# ENHANCEMENT OF HEAT TRANSFER USING TURBULENCE PROMOTERS

**A Thesis**

**Submitted to the College of Engineering**

**of Nahrain University in Partial Fulfillment of the**

**Requirements for the Degree of Master of Science**

**in**

**Chemical Engineering**

**by**

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**February 2011**

# Certification

I certify that this thesis entitled **"Enhancement of Heat Transfer Using Turbulence Promoters"** was prepared by **Abbas Nawar Znad** under my supervision at Nahrain University/College of Engineering in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering..

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# ABSTRACT

Three cases of heat transfer enhancement by turbulence promoters were adopted in order to increase the thermal performance of a double pipe heat exchanger of 1245 mm effective length, 28 mm outer diameter and changeable inner diameter (11 or 14 mm). Wire coils of 1 mm diameter and 10, 20, 30 and 40 mm coiling pitches were used as turbulence promoters to augment heart transfer inside the inner tube of heat exchanger at a Reynolds number range of 5000 to 40000 based on smooth tube diameter. Two new types of turbulence promoters are used to enhance heat transfer in the annulus of the same double pipe heat exchanger for a Reynolds number range of 3000 to 10000 based on smooth annulus equivalent diameter. The first was by wire coils of 1 and 2.2 mm diameters and 10, 20, 30 and 40 mm coiling pitches set up on the outer surface of the inner tube. The second was by circular ribs of 2.2 mm diameter and the same pitches and position. Water was used as the working fluid in the two sides. Variation in the experimental conditions was attained by changing the mass flowrates of unenhanced side and changing the inlet temperature of hot fluid. These conditions were followed in order to increase the data points in addition to observe the effect of these conditions.

Heat transfer is increased inside the inner tube by 2.43 folds compared to smooth tube at the same Reynolds number accompanied by friction factor increase of 4.75 folds. For the annulus-side enhancement, heat transfer is increased by 3.25 folds, compared to smooth annulus with an increase of friction factor of 2.63 folds. New correlations of Nusselt number and friction factor for the tube and annulus sides were proposed as functions of Reynolds number, Prandtl number and geometrical characteristics of inserts and sizes of tubes and annuli. In addition, performance evaluation criteria (PEC) were applied to the results, in order to determine the most beneficial method.

# List of Contents

# Notations

| Symbols | Description |
|---|---|
| $A$ | Heat exchange surface area [$m^2$] |
| $A_c$ | Cross-sectional area [$m^2$] |
| $C_f$ | Fanning friction factor **[—]** |
| $Cp$ | Heat capacity [J/kg.°C] |
| $d$ | Tube diameter [m] |
| $D'_e$ | Equivalent diameter of annulus based on fluid flow [m] |
| $D_e$ | Equivalent of annulus [m] |
| $D_i$ | Inner diameter of annulus[m] |
| $D_o$ | Outer diameter of annulus [m] |
| $e$ | Wire or rib diameter [m] |
| $E_h$ | Enhancement ratio [—] |
| $f$ | Darcy friction factor **[—]** |
| $G$ | Mass flux [$kg/m^2s$] |
| $h$ | Convective heat transfer coefficient [$W/m^2.°C$] |
| $j$ | Colburn factor ($Nu/Re\ Pr^{1/3}$) [—] |
| $k$ | Thermal conductivity [W/m.°C] |
| $L$ | Length [m] |
| $\dot{m}$ | Mass flowrate [kg/s] |
| $N$ | Number of tubes of shell and tube heat exchanger |
| $Nu$ | Nusselt number (hd/k) **[—]** |
| $p$ | Coiling or ribbing pitch [m] |
| $P$ | Pumping Power [W] |
| $Pr$ | Prandtl number ($Cp\mu/k$) **[—]** |
| $q$ | Heat transfer rate [W] |
| $r$ | Radius [m] |
| $Re$ | Reynolds number ($\rho\ d\ \nu/\mu$) [—] |

| | |
|---|---|
| $Re_o$ | Reynolds number in smooth tube for PEC calculations [—] |
| St | Stanton number (Nu/Re Pr) [—] |
| T | Temperature [°C] |
| U | Overall heat transfer coefficient |
| y | Twist ratio (twisted tape insert) **[—]** |
| $\Delta H$ | Enthalpy difference [kJ/kg] |
| $\Delta p$ | Pressure drop [$N/m^2$] |
| $\Delta T_i$ | Approach temperature difference [°C] |
| Q | Volumetric flowrate [$m^3/s$] |

## Greek Symbols

| | |
|---|---|
| $\mu$ | Dynamic viscosity [Pa.s] |
| $\beta$ | Coiling angle (Bergles equation) |
| $\delta$ | Tape thickness (twisted tape) [m] |
| $\theta$ | Disruption shape corner (Bergles equation) |
| $\nu$ | Fluid Velocity [m/s] |
| $\rho$ | Density [$kg/m^3$] |

## Subscripts

| | |
|---|---|
| 1,2,3,4 | The four temperatures of the heat exchanger |
| a | Augmented |
| b | Bulk, both |
| c | Cold, cross-sectional, corrected |
| e | Equivalent |
| h | Hot, hydraulic |
| i | Inner, inlet |
| m | Mean |
| o | Outer, outlet, smooth in PEC calculations |
| p | Pass |

| | |
|---|---|
| s | Smooth |
| w | Wall |

## Superscript

| | |
|---|---|
| n | exponent of Prandtl number |

## Abbreviations

| | |
|---|---|
| ID | Inner diameter of tube |
| OD | Outer diameter of tube |
| PEC | Performance Evaluation criteria |
| LMTD | Logarithmic Mean Temperature Difference |

# List of Tables

# List of Figures

# CHAPTER ONE

# Introduction

## 1.1 Introduction

The conversion, utilization, and recovery of energy in every industrial, commercial, and domestic application involve a heat exchange process. Some common examples are steam generation in power plants; sensible heating and cooling of viscous media in thermal processing of chemical, pharmaceutical, and agricultural products; refrigerant evaporation and condensation in air conditioning and refrigeration; gas flow heating in manufacturing and waste-heat recovery; air and liquid cooling of engine and turbomachinery systems; and cooling of electrical machines and electronic devices. Improved heat exchange, can significantly improve the thermal efficiency in such applications as well as the economics of their design and operation.

Enhancement techniques essentially reduce the thermal resistance in a conventional heat exchanger by promoting higher convective heat transfer coefficient with or without surface area increases. As a result, the size of a heat exchanger can be reduced, or the heat duty of an existing exchanger can be increased, or the pumping power requirements can be reduced, or the exchanger's operating approach temperature difference can be decreased [1].

## 1.2 Classification of Heat Transfer Enhancement Techniques

Generally, enhancement techniques can be classified either as passive or active methods. In the first class, no direct application of external power is required, but, to the surface configuration, the enhancement of heat transfer belongs. Treated or roughened surfaces are used for boiling and condensation by coating the surface with fine-scale roughness which also might be beneficial, when its height is larger to enhance heat transfer in single-phase. The latter might be produced in many configurations ranging from random sand-grain type roughness to discrete protuberances, all to disturb the laminar sublayer rather than increasing the heat transfer surface area.

Displaced enhancement devices, such as in fig. 1-1are inserted into the flow channel, in forced flow operation, so as indirectly to improve energy transport at the heated surface. A category of those is Swirl-flow devices which include a number of geometric arrangements or tube inserts that create rotating and secondary flow, for example coiled tubes, inlet vortex generators, twisted-tape inserts, wire coils.

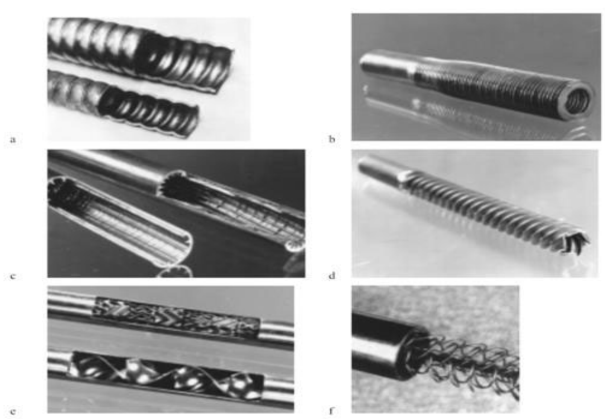


**Figure 1-1:** Enhanced tubes for augmentation of single-phase heat transfer.

The second class of enhancement techniques requires external power. It might include Mechanical aids which involve stirring the fluid by mechanical means or by rotating the surface especially in batch processing of viscous liquids in the chemical process industry; vibration of surface at either low or high frequency or vibration of fluid itself with a range from pulsations of about 1 Hz to ultrasound. Single-phase fluids are of primary concern; AC or

DC electrostatic fields; injection of particular gas to the stagnant or flowing liquids; and suction or removal of vapors in nucleate boiling [1, 2].

In many cases heat transfer enhancement in tubes can be supplemented by heat transfer enhancement on the outside wall of tubes, as for double pipe heat exchangers. An application is in vapor compression hot-water heat pumps. The condensing refrigerant may typically flow in the inner tube and the water to be heated in a counter flow direction in the annulus. In this case, heat transfer enhancement on the outer wall is also important. Like these heat exchangers are suitable when one or both of the fluids is at very high pressure because containment in the small-diameter pipe or tubing is less costly than containment in a large-diameter shell. Furthermore, double pipe exchangers are generally used for small-capacity applications where the total heat transfer surface area required is 50 $m^2$ or less [3, 4].

## 1.3 Scope of the present work

The present work aims to study the application of wire coil inserts and circular ribs as turbulence promoters to enhance heat transfer, with different conditions and assembling positions of a double pipe heat exchanger. It is comprised of three parts; the first is using the coiled wire insert as a turbulence promoter inside the inner tube of heat exchanger using a wire with one diameter; the second part is using a coiled wire with two diameters on the outer surface of the inner tube; and finally using circular rib turbulence promoters on the outer surface of the inner tube.

All experiments would be implemented using the same double pipe heat exchanger but with two inner tubes. Different experimental conditions and dimensions are employed to obtain large quantity of data to be used to obtain empirical correlations for heat transfer and pressure drop.

# CHAPTER TWO

# Literature Review

## 2.1 The Problem of Turbulence

Turbulent fluid flow is a complex, nonlinear multiscale phenomenon, which poses some of the most difficult and fundamental problems in classical physics. It is also of tremendous practical importance in making predictions, for example, about heat transfer in nuclear reactors, drag in oil pipelines, the weather, and the circulation of the atmosphere and the oceans. Many generations of scientists have struggled valiantly to understand both the physical essence and the mathematical structure of turbulent fluid motion. **Leonardo da Vinci in (1507)** named the phenomenon observed in swirling flow “la turbolenza” [5].

The scientific study of turbulence had generally begun with the work of **Osborne Reynolds in (1883)**. The problem that Reynolds had studied was the classic one of flow through long straight pipes of constant diameter and circular cross-section. Using his “method of color bands”, he was the first person to show that, for a given fluid and pipe, the flow would be orderly (laminar) for velocities below a certain critical speed. At the critical speed, the flow abruptly became turbulent at some distances from the pipe entrance.

Reynolds found that the criterion for the transition from laminar to turbulent flow could be expressed in universal form in the terms of the value taken by dimensionless group

$$\mathrm{Re} = \frac{\rho d v}{\mu} \qquad \ldots (2.1)$$

where Re is what is now called the Reynolds number [6].

Reynolds noted that the main motion of the flow took place in the direction of the axis of the pipe. Because of the flow fluctuations, a great amount of mixing occurred in the turbulent flow, leading to a transverse motion perpendicular to the main motion. Reynolds discovered that the transition from laminar to turbulent flow always took place at almost exactly the same Reynolds number ($Re_{crit}$=2300). For $Re < Re_{crit}$, the flow is laminar, and turbulent for $Re > Re_{crit}$. He already suspected that the critical Reynolds number will be larger if the disturbances in the incoming flow are smaller [7].

## 2.2 Enhancement of Heat Transfer.

Here, a brief survey for the most recent works performed in the field of heat transfer enhancement in single-phase flow is included concentrating on those that depends on turbulence caused by devices or inserts installed in the flow passage which may be referred to as “turbulence promoters”. Some studies, stated here, ascribe the enhancement of heat transfer to vortices or swirls generated by these devices; the present survey will include, for the reason that such phenomena may occur together with turbulence.

### 2.2.1 Enhancement of Heat Transfer by Turbulence Promoters

To make it easy to understand and compare the different types of turbulence promoters, a simple classification, built on the basis of similarity in configuration and the manner of work for each group, is introduced in the following sections.

#### 2.2.1.1 Wire coil inserts.

Wire coils inserts are currently used in applications as oil cooling devices, preheaters or fire boilers. They showed several advantages with respect to other enhancement techniques:

1. Low cost.
2. Easy installation and removal.
3. Preservation of original plain tube mechanical strength.
4. Possibility of installation in an existing smooth tube heat exchanger [8].

Many correlations had been set for predicting the heat transfer and pressure drop. **Ravigururajan and Bergles in (1985) [1, 2]** proposed what might be the most famous method for predicting heat transfer and pressure drop inside internally ribbed tubes and plain tubes with coiled wire inserts.

**Kumar et al., in (1970) [9]** examined the influence of wire coils inserted in a tube on the heat transfer and the pressure drop. Water was used as the test fluid. The pitch ($p/d_i$=1.05-5.5) and the wire size ($e/d_i$=0.1-0.15) were employed. They had maximum increase of heat transfer of 280% with a large increase of pressure drop. They developed the following relation:

$$\frac{Nu_a}{\mathrm{Pr}^{1/3}} = 0.0554\left(f\ \mathrm{Re}^3\right)^{0.286} \qquad \ldots (2.2)$$

This equation was found to be independent of the tube diameter $d_i$, the wire diameter $e$, the pitch $p$ and the test fluid [9].

**Zhang et al., in (1991) [10]** investigated heat transfer and friction factor of hot air, regarding the influence of pitches and wire diameter of the helical coils in tubes. They used air as the flowing fluid, heated to 200±5°C, and obtained the following correlation

$$Nu_a = 0.253\,\mathrm{Re}^{0.716}\left(\frac{e}{d_i}\right)^{0.372}\left(\frac{p}{d_i}\right)^{-0.171} \qquad \ldots (2.3)$$

which was considered to be valid for: $6000 \le Re \le 100000$, $0.037 \le e/d_i \le 0.10$ and $0.35 \le p/d_i \le 2.50$.

**Viedma, et al. in (2005) [8]**, had experimentally studied wire coils inserted in a round tube in order to obtain their thermodynamic behavior in laminar, transition and turbulent flows. They used water and propylene glycol mixtures at different concentrations, for a range of Reynolds number of 100 to 90,000 and Prandtl number from 2.8 to 200. They tested six wire coil inserts with different geometric range of helical pitch and wire diameter. Their results showed that the wire coil increased pressure drop up to 9 times and heat transfer up to 4 times compared to the empty smooth tube. Their proposed correlation for Nusselt number was:

$$Nu_a = 0.132(p/d_i)^{-0.372} \,\mathrm{Re}^{0.72}\, \mathrm{Pr}^{0.37} \qquad \ldots (2.4)$$

They concluded that the wire coil diameter had a slight influence on heat transfer. The corresponding correlation of friction factor for Reynolds numbers from 2000 to 30000 was:

$$C_{f\,a} = 5.76\,(e/d_i)^{0.95}\,(p/d_i)^{1.21}\, \mathrm{Re}^{\,0.217} \qquad \ldots (2.5)$$

They recommended that equation (2.5) might overpredict up to 15 % the experimental values.

**Eiamsa-ard et al., in (2010) [11]** studied experimentally heat transfer, friction factor and thermal performance behaviors in a tube equipped with the combined devices between the twisted tape and constant and periodically varying wire coil pitch ratio. The experiments were conducted in a turbulent flow regime with Reynolds numbers ranging from 4600 to 20000 using air as the test fluid. They found that heat transfer rate was further augmented by the compound devices by 3.65 times compared to plane tube, 1.39 times compared to wire coil insert and 2.34 times compared to tube inserted with twisted tape. Correspondingly, the friction factor augmentation was about 28.8, 2.24 and 8.37 respectively.

**Figure 2-1:** Compound wire coil/ twisted tape insert tested by Eiamsa-ard et al [11].

### 2.2.1.2 Twisted tapes, helical inserts and twisted angles.

Twisted tape inserts cause the flow to spiral along the tube. Their potential performance is diminished because the thermal contact of the tape and the tube wall is not ideal, so they do not perform as "wall-attached roughness". They enhance the heat transfer due to the increased tangential velocity component and reduced flow cross section [51].

**Manglik and Bergles in 1992 [12]** proposed the following friction factor correlation for tubes with twisted tape inserts in turbulent flow regime:

$$C_{fa} = \frac{0.0791}{\mathrm{Re}^{0.25}}\left[\frac{\pi}{\pi - 4(\delta/d_i)}\right]^{1.75}\left[\frac{\pi + 2 - 2(\delta/d_i)}{\pi - 4(\delta/d_i)}\right]^{1.25}\left[1 + \frac{2.752}{y^{1.29}}\right] \quad \text{... (2.6)}$$

where:

$$y = \frac{p}{2d_i} \quad \text{… (2.7)}$$

Their corresponding heat transfer correlation for turbulent flows was:

$$\frac{Nu_a}{Nu_{y=\infty}} = 1 + \frac{0.769}{y} \quad \text{... (2.8)}$$

and $Nu_{y=\infty}$ for straight tape:

$$Nu_{y=\infty} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}\left(\frac{\pi}{\pi - 4\delta/d_i}\right)^{0.8}\left(\frac{\pi + 2 - 2t/d_i}{\pi - 4\delta/d_i}\right)^{0.2}\left(\frac{\mu_b}{\mu_w}\right)^{n}$$

… (2.9)

where the exponent $n$ is equal to 0.18 for heating and 0.30 for cooling.

**Promvonge, et al., in 2004 [13]** studied experimentally the influence of helical tapes inserted in a tube on heat transfer enhancement, fig. 2-2. Their swirling flow devices were a full-length helical tape with or without a centered-rod, and a regularly-spaced helical tape, inserted in the inner tube of a concentric tube heat exchanger. Hot air was passed through the inner tube, whereas cold water flowed in the annulus. They concluded that full-length helical tape with rod provides the highest heat transfer rate about 10% better than that without rod but with increased pressure drop. They found that regularly spaced helical tape inserts at spacing ratio=0.5 yielded the highest Nusselt number which was about 50% above the plain tube.

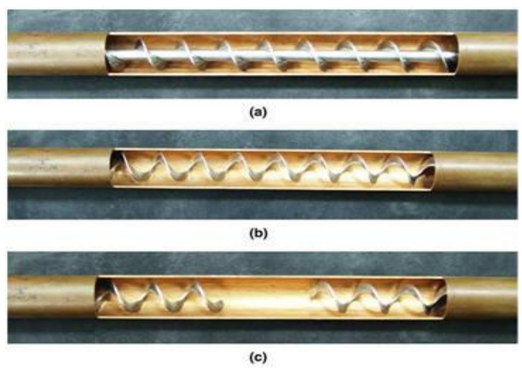



**Figure 2-2:** Devices used by Promvonge, et al., [13].

**Ahmed et al., in 2005 [14]** performed an experimental investigation on heat transfer and pressure drop characteristics in a circular tube fitted with twisted tape inserts, at three different twist ratios (y=23, 11.5 and 8). They concluded that the average heat transfer coefficient was about 1.3 to 3 times higher than that of the smooth tube.

**Promvonge et al., in 2006 [15]** studied experimentally the influence of the twisted tape insertion on heat transfer and flow friction in double pipe heat exchanger. In the experiments, the swirling flow was introduced by using twisted tape placed inside the inner test tube of the heat exchanger with different twist ratios, y=5 and 7. Over the range investigated, they found that the maximum increase in Nusselt number was for using the enhancement devices with y=5 became 188% higher than that for plain tube.

**Eiamsa-ard and Promvonge in 2006 [16]** investigated the heat transfer and pressure drop characteristics in a circular wavy-surfaced tube with a helical-tape insert, fig. 2-3. In the experiment, the turbulence flow near the tube wall was produced by using wavy surfaced wall while the swirling flow was generated by inserting the helical-tape along the core region. The Nusselt numbers for the tube with wavy-surfaced wall was found 1.9 to 2.0 times that for the plain tube, while for the tube combined with wavy-surfaced wall and a helical-tape insert, were 2.48 to 2.67 times, and pressure drops were seen to be 9.3 to 22.3 times the plain tube.

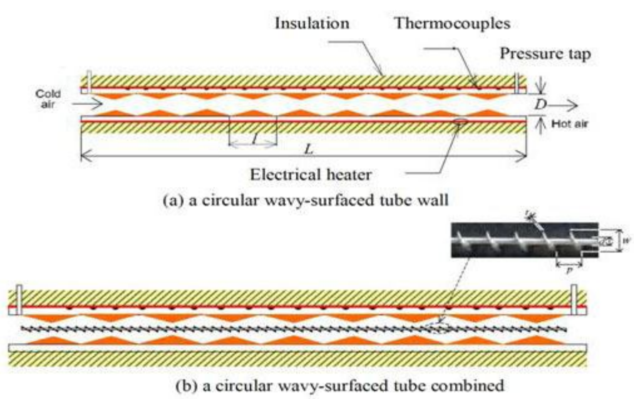



**Figure 2-3:** Test tube used by Eiamsa-ard and Promvonge [16].

**Kumar et al., in 2008 [17]**, studied the development and testing of modified solar water heater having twisted tape inserted inside the tubes along with plain one for the range of flow Reynolds number as 4000 < Re < 20000, and twist pitch ratio of between 3 and 12. Experimental results showed that in the range of parameters investigated, thermal enhancement factor varied between 1.18 to 2.7 and the maximum value of collector efficiency increased by about 30% compared to that of plain ones at same operational conditions.

**Gouda and Bikram in 2008 [18]** studied the determination of friction factor and heat transfer coefficient for various twisted angles, fig. 2-4, having different twist ratios. They observed that the heat transfer coefficient could vary from 1.16 to 2.87 times the smooth tube value but the corresponding friction factor increased by 4 to 9.6 times the smooth tube values.

**Figure 2-4:** A twisted angle [18].

**Yadav in 2009 [19]** investigated experimentally influences of the half length twisted tape inserted inside the inner tube of a U-bend double pipe heat exchanger. The heat transfer coefficient was found to increase by 40% with half-length twisted tape inserts when compared with plain heat exchanger. It was found that on the basis of equal mass flow rate, the heat transfer performance of half-length twisted tape was better than plain heat exchanger.

**Thianpong et al. in 2009 [20]** investigated experimentally the friction factor heat transfer behaviors in a dimpled tube fitted with a twisted tape swirl generator using air as working fluid in the range of Reynolds number of 12000 to 44000. They found that both heat transfer coefficient and friction factor in the dimpled tube fitted with the twisted tape, were higher than those in the dimple tube acting alone and plain tube.

### 2.2.1.3 Rod-pin inserts and louvered strips.

**Nazrul Islam et al., in 2007 [21]** investigated experimentally the pressure drop and heat transfer in a tube with rod-pin, fig. 2-5 with air as the working fluid. They indicated that heat transfer increased by three folds.

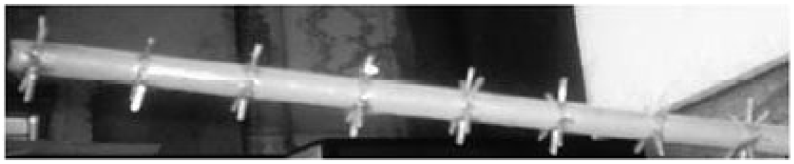


**Figure 2-5**: Rod-pin inserts used by Nazrul Islam et al., [21].

**Promvonge et al., in 2007 [22]** investigated experimentally, heat transfer and friction characteristics, employing louvered strips inserted in a concentric tube heat exchanger, fig. 2-6 with water used as working fluid. They obtained increases in average Nusselt number and friction loss for the inclined forward louvered strip about 284% and 413% while those for the backward louvered strip were 263% and 233% over the plain tube, respectively.

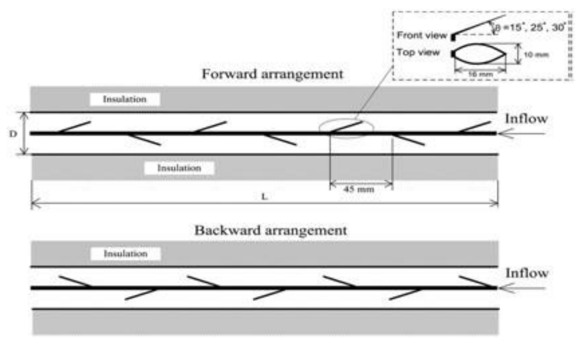



**Figure 2-6:** Louvered strips with forward and backward arrangements [22].

### 2.2.1.4 Disk and mesh inserts

**Alemrajabi et al., in 2006 [23]** studied experimentally the effects of insertion of disks with different geometries on heat transfer in the flow of air in a tube. The disks were elliptic in shape with an elliptical or rectangular hole in the center and were either perpendicular to the flow or at angle relative to the flow. They found that disks were more effective at higher Reynolds numbers.

**Raju et al., in 2009 [24]** investigated experimentally the augmentation of turbulent flow heat transfer in a horizontal tube by means of mesh inserts, fig. 2-7, with air as the working fluid with different types of mesh inserts with different screen diameters and distances between the screens in the porosity range of 99.73 to 99.98 were considered for experimentation. It was observed that the enhancement of heat transfer by using mesh inserts when compared to plain tube at the same mass flow rate was more by a factor of 2 times, where as the pressure drop was only about a factor of 1.45 times.

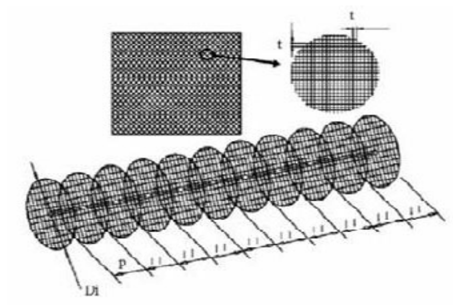


**Figure 2-7:** Mesh inserts [24].

### 2.2.1.5 Conical nozzles.

**Promvonge et al., in 2009 [25]** investigated experimentally the enhancements of heat transfer characteristics in a uniform heat flux circular tube fitted with conical nozzles and swirl generator. The conical nozzles, assumed as a turbulator/reverse flow generator, were placed in a model pipe line through which air was flowing as working fluid. In addition, the snail was also employed to provide swirling flow at the inlet of the test tube. They found that application of the conical nozzle and the snail could help to increase heat transfer rate over that of the plain tube by about 278% and 206%, respectively. The use of the conical nozzle with the snail led to a maximum heat transfer rate that was up by 316%.

### 2.2.1.6 Twisted and corrugated tubes

A new innovation or developed technology, known as twisted tube technology, fig. 2-8, which has been able to overcome the limitations of the conventional technology, and in addition, provide superior overall heat transfer coefficients through tube side enhancement. The twisted tube exchanger consists of a bundle of uniquely formed tubes assembled in a bundle without the use of baffles. That type is giving 40% increase in heat transfer coefficient compared to a conventional shell and tube heat exchanger with the same pressure drop [26].

**Figure 2-8**: Completed twisted tube bundle [26].

**Rainieri, et al., [27]** investigated experimentally the effect of the internal helical ridging tubes on the heat transfer coefficient and friction factor for laminar flow forced convection to. They found that in the spirally enhanced geometries the transition to the turbulent flow might occur at Reynolds number values much lower than 2000. This early transition is accompanied by a significant heat transfer enhancement values between 1.1 and 6 in the Reynolds number range 300-1800.

**Zimparov et al., [28]**, studied performance evaluation criteria, used to assess the benefit of replacing the smooth tubes with deeper corrugated tubes in shell and-tube heat exchangers in the case of condensers with steam condensing on the outside of the vertically or horizontally mounted tubes and water in forced convection (non-boiling) flow being pumped through the tubes. It was concluded that in all the cases considered, corrugated tubes with large pitches and small helix angle have low thermal efficiency.

#### 2.2.1.7 Ribbed surfaces and channels

**Kotcioglu et al., in 1998 [29]** studied experimentally heat transfer using winglet-type vortex generators in the range of Reynolds number between 3,000 and 30,000. The installation of wings was organized, in such a way that periodically interrupted enlarged and contracted channel flow domains could be established. Wings were aligned at various angles of 7-20° positively and negatively with the direction of main air flow direction. They concluded an increase of heat transfer coefficient was observed with accompanying large pressure drops, increasing with the inclination angle.

**Layek, et al., in 2006 [30]** studied the effect of compound turbulator on heat transfer coefficient and friction factor in rectangular ducts with repeated transverse integral chamfered rib groove roughness on one broad uniformly heated. They found that heat transfer performance of chamfered rib-groove roughened ducts was much better than the ribbed ducts only, and compared to smooth duct the chamfered rib-groove roughened walls enhanced the Nusselt number and friction factor 3.03 and 3.6 folds respectively.

**Naphon in 2006 [31]** tested the heat transfer characteristics and pressure drop in a channel with V corrugated upper and lower plates under constant heat flux, fig. 2-9. They concluded that the corrugated surface had higher heat transfer as well as pressure drop, and that was because of the presence of recirculation zones.

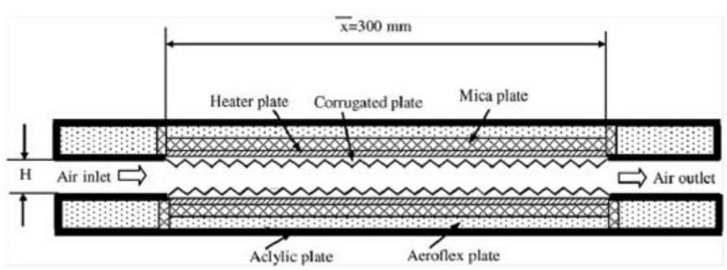



**Figure 2-9:** The V corrugated plates used by Naphon [31].

**Fletcher et al., in 2008 [32]** conducted an investigation to determine whether dimpled surfaces (spherical and elliptical or trenched dimples) could improve the heat transfer in a heat sink under laminar airflows. They found that heat transfer enhancement was up to a 6% relative to a flat plate were consistently observed for Reynolds number (based on channel height) in the range of 500 to 1650 on both circular and oval dimples. The pressure drop over the dimpled plates was either equivalent to or less than that of the flat plate with no dimples.

### 2.2.2 Enhancement of heat transfer in the annulus of a double-pipe heat exchanger.

**Agrawal et al., in 1992 [33]** investigated numerically the laminar forced convection in a double pipe heat exchanger which with an isothermal tube with periodic enhancements (promoters) placed concentrically inside an insulated circular tube; fig. 2-10. Comparing to an unenhanced tube annulus of identical length and heat transfer surface area and mass flow rate and Reynolds number kept the same, they found that the effects of promoter length and spacing on the pressure drop and heat transfer were small and the pressure drop was influenced significantly by the promoter height and the annular gap, while the promoter height was the only significant geometric parameter affecting the heat transfer.

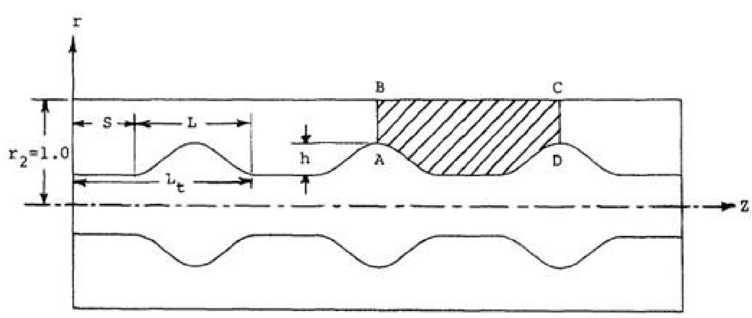



**Figure 2-10**: Enhanced annulus adopted by Agrawal et al. [33]

**Coetzee in 2001 [34]** studied the heat transfer and pressure drop characteristics of an angled spiraling tape used in the annulus of a double pipe heat exchanger, fig. 2-11 to induce swirl and then increase heat transfer. Three heat exchangers were tested with angled spiraling tape in the annulus with different pitches. It was determined that the heat exchanger with the smallest pitch of the angled spiraling tape and with flow against the curvature of the tape resulted in the highest increase in the Nusselt number of 206%. As penalty this heat exchanger also had the highest increase of the pressure drop of 203%.

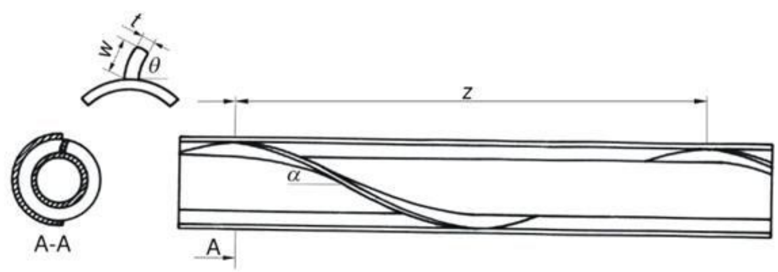



**Figure 2-11**: Schematic representation of angled spiraling tape heat exchanger [34].

The second and third parts of the present work fall into this type of enhancement inserts, where a wire coil and circular ribs with different diameters, different coiling pitches and different experimental conditions have been used to enhance heat transfer in the annulus of a double pipe heat exchanger. The first part is a conventional method which is the coiled wire insert in the inside of the inner tube of the double pipe heat exchanger but with new conditions and with exploiting the most recent correlations in calculating heat transfer and pressure drop in smooth tubes which had undergone numerous developments in the last decades.

# CHAPTER THREE

# Theoretical Background

## 3.1 Introduction

The subject of enhanced heat transfer has developed to the stage that it is of serious interest for heat exchanger application. The refrigeration and automotive industries routinely use enhanced surfaces in their heat exchangers. The process industry is aggressively working to incorporate enhanced heat transfer surfaces in its heat exchangers. Virtually, every heat exchanger is a potential candidate for enhanced heat transfer. However, each potential application must be tested to see if enhanced heat transfer "makes sense". Heat exchangers were initially developed to use plain (or smooth) heat transfer surfaces. An "enhanced heat transfer surface" has a special surface geometry that provides a higher ($hA$) value, per unit base surface area than a plain surface. The term "enhancement ratio" ($E_h$), is the ratio of the ($hA$) of an enhanced surface to that of a plain surface [35]. Thus:

$$E_h = \frac{hA}{(hA)_s} \qquad \dots (3.1)$$

## 3.2 Turbulent Fluid Flow and Heat Transfer

### 3.2.1 Fluid Flow and Heat Transfer in Circular Tubes

Turbulent flow is commonly utilized in practice because of the higher heat transfer coefficients that is associated with. Most correlations for the friction and heat transfer coefficients in turbulent flow are based on experimental studies because of the difficulty in dealing with turbulent flow theoretically.

For smooth tubes, the friction factor in turbulent flow can be determined from the first Petukhov equation [36]

$$f = (0.79 \ln \mathrm{Re} - 1.64)^{-2} \qquad \dots (3.3)$$

or from the well-known Moody diagram. The friction factor considered in equation (3.3) is the Darcy friction factor that is used to calculate the pressure drop using the equation

$$\Delta p = f \frac{L}{d_i} \rho \frac{v^2}{2} \qquad \dots (3.4)$$

which is well-known as Darcy-Weisbach equation [37, 38].

The Nusselt number in turbulent flow is related to the friction factor through the Chilton–Colburn analogy [39] expressed as:

$$Nu = 0.125 f \,\mathrm{Re}\,\mathrm{Pr}^{(1/3)} \qquad \dots (3.5)$$

With the friction factor is available, equation (3.5) can be used conveniently to evaluate the Nusselt number for both smooth and rough tubes. For fully developed turbulent flow in smooth tubes, a simple relation for the Nusselt number can be obtained by substituting the simple power law relation

$$f = 0.184\,\mathrm{Re}^{-2} \qquad \dots (3.6)$$

for the friction factor into equation (3.5), it gives

$$Nu = 0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3} \quad (0.7 \le \mathrm{Pr} \le 160,\ \mathrm{Re} > 10{,}000) \qquad \dots (3.7)$$

which is known as the Colburn equation. The accuracy of this equation can be improved by modifying it as:

$$Nu = 0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n} \qquad \dots (3.8)$$

where n = 0.4 for heating and 0.3 for cooling of the fluid flowing through the tube. This equation is known as the Dittus–Boelter equation [40], with properties of the fluid concerned evaluated at the bulk mean fluid temperature $T_b = (T_i - T_o)/2$. When the temperature difference between the fluid and the wall is very large, a correction factor is used to account for the different viscosities near the wall and at the tube center. **Sieder and Tate [41]** suggested a correction factor to be used with all the equations above

$$Nu_c = Nu\left(\frac{\mu_b}{\mu_w}\right)^{0.14} \qquad \dots (3.9)$$

where $\mu_b$ is evaluated at bulk mean temperature while $\mu_w$ at the temperature of the wall. The Nusselt number relations above are fairly simple, but they may give errors as large as 25% [42].

Comparing a great number of experimental data on heat transfer in tubes with the correlations included in the literature, **Gnielinski** [43] found that a semiempirical type of equation similar to that proposed by Prandtl correlates the data best. The equation of Prandtl for fully developed turbulent flow is of the form

$$Nu = \frac{(f/8)\mathrm{Re}\,\mathrm{Pr}}{1 + 8.7(f/8)^{0.5}(\mathrm{Pr} - 1)} \qquad \dots (3.10)$$

A number of modifications of equation (3.10) are to be found in the literature and may be summarized by the equation

$$Nu = \frac{(f/8)\mathrm{Re}\mathrm{Pr}}{k_1 + k_2(f/8)^{0.5}(\mathrm{Pr}^n - 1)} \qquad \dots (3.11)$$

For it, **Petukhov and Popov [44]** had suggested that $k_1 = 1$, $k_2 = 12.7$ and $n = 2/3$, where data were correlated best in the region of fully developed turbulent flow by this expression. Since equation (3.11) is based on a model for fully developed turbulent flow ( Re > 10000), it does not account for entrance effects and it is not applicable in the transition range between laminar and fully developed turbulent flow where the Reynolds numbers are between 2300 and $10^4$. To overcome these disadvantages of Eq. (3.11), Gnielinski modified it by replacing Re by (Re −1000) and by multiplying with the entrance correction factor derived by **Hausen [45]**. The equation becomes

$$Nu = \frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/8)^{0.5}(\mathrm{Pr}^{2/3}-1)}\left[1+\left(\frac{d_i}{L}\right)^{2/3}\right] \qquad \dots (3.12)$$

For estimation purposes, Gnielinski suggested the following simplified forms for equation (3.12);

$$Nu = 0.0214\left(\mathrm{Re}^{0.8}-100\right)\mathrm{Pr}^{0.4}\left[1+\left(\frac{d_i}{L}\right)^{2/3}\right] \qquad \dots (3.13)$$

for 0.5 < Pr < 1.5; and $10^4$ < Re < 5 × $10^6$ and

$$Nu = 0.012\left(\mathrm{Re}^{0.87}-280\right)\mathrm{Pr}^{0.4}\left[1+\left(\frac{d_i}{L}\right)^{2/3}\right] \qquad \dots (3.14)$$

for 1.5 < Pr < 500; and 3000 < Re < 5 × $10^6$

Nowadays equation (3.12) is known as Gnielinski equation where *f* is Darcy friction factor for turbulent flow in smooth tubes obtained using equation (3.3). The viscosity correction, equation (3.9) also can be used to correct for the difference between the temperature of the wall of tube and the bulk temperature of the fluid.

Equation (3.3) in connection with equation (3.12) has been shown to represent the majority of the experimental data within 20%. This equation is valid for developing or fully developed turbulent flow 2300 < $Re$ < 5 x $10^6$, 0.5 < Pr < 2000 and $d_i/L$ < 1[43].

### 3.2.2 Fluid Flow and Heat Transfer in the Annulus of Concentric Tubes.

When a fluid flows in a conduit having a non-circular cross section, such as an annulus, it is convenient to express heat transfer coefficients and friction factors by the same types of equations and curves used for pipes and tubes. To permit this type of representation for annulus heat transfer, it has been found advantageous to employ an equivalent diameter $D_e$. The equivalent diameter is four times the hydraulic radius, and the hydraulic radius is, in turn, the radius of a pipe equivalent to the annulus cross section.

The hydraulic radius is obtained as the ratio of the flow area to the wetted perimeter. For a fluid flowing in an annulus the flow area is $(\pi/4)(D_o^2 - D_i^2)$ but the wetted perimeters for heat transfer and pressure drop are different. For heat transfer the wetted perimeter is the outer circumstance of the inner tube

$$D'_e = 4r_h = \frac{4 \times (\text{flow area})}{(\text{heat transfer wetted perimeter})} = \frac{4\pi\left(D_o^2 - D_i^2\right)}{4\pi D_i} = \frac{D_o^2 - D_i^2}{D_i} \qquad \ldots (3.15)$$

In pressure drop calculations the friction not only results from the resistance of the outer tube but it is also affected by the outer surface of the inner tube. The total wetted perimeter is $\pi(D_o + D_i)$ and the equivalent diameter for pressure drop calculations in the annulus is:

$$D_e = 4r_h = \frac{4 \times (\text{flow area})}{(\text{frictional wetted perimeter})} = \frac{4\pi\left(D_o^2 - D_i^2\right)}{4\pi\left(D_o + D_i\right)} = D_o - D_i \qquad \ldots (3.16)$$

This leads to the anomalous result that the Reynolds numbers for the same flow conditions are different for heat transfer and pressure drop. Since Reynolds number evaluated using $D'_e$ might be above 2100 while that using $D_e$ is below 2100. Actually, both Reynolds numbers should be considered only approximations, since the sharp distinction between streamline and turbulent flow at the Reynolds number of 2100 is not completely valid in annuli [46].

The details above are very decisive, if equations like that of Dittus and Boelter, equation (3.8), are used in calculating the Nusselt number, where two values for Reynolds number must be estimated, one for friction factor calculations and another for heat transfer calculations [4, 46, 47, 48, 49]. As an effort in the field, **Davis** [50] has proposed the equation;

$$\frac{hD_i}{k} = 0.031\left(\frac{D_i G}{\mu}\right)^{0.8} \mathrm{Pr}^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14}\left(\frac{D_o}{D_i}\right)^{0.15} \quad \dots (3.17)$$

to be used to estimate the Nusselt number in the annulus of $D_i$ and $D_o$ as the inner and outer diameter of the annulus respectively, using the outer diameter of the inner tube as the characteristic dimension, which is the surface through which heat transfer occurs.

Heat transfer in turbulent flow of gases and liquids in concentric annuli may be obtained using a modified form of equation (3.12) in tubes using the hydraulic or equivalent diameter $D_e = D_o - D_i$ to evaluate *Nu*, *Re* and *D/L* in equation (3.12). According to **Petukhov and Roizen** [51], the Nusselt number in case of heat transfer at the inner wall, and the outer wall insulated, might be calculated using

$$\frac{Nu_i}{Nu_{tube}} = 0.86\left(\frac{D_i}{D_o}\right)^{-0.16} \quad \dots (3.18)$$

for cases, the heat transfer at the outer wall, and the inner wall insulated

$$\frac{Nu_o}{Nu_{tube}} = 1 - 0.14\left(\frac{D_i}{D_o}\right)^{0.6} \quad \dots (3.19)$$

The third case is when heat transfer on both walls of the passage, and equal temperatures on both walls, Nusselt number is calculated using

$$\frac{Nu_b}{Nu_{tube}} = \frac{0.86\left(\frac{D_i}{D_o}\right)^{0.84} + \left[1 - 0.14\left(\frac{D_i}{D_o}\right)^{0.6}\right]}{1 + \frac{D_i}{D_o}} \qquad \ldots (3.20)$$

Nowadays numerous studies [42, 52, 53, 54, and 55] do ignore the physical fact of what surface in the annulus is concerned with heat transfer and use the Reynolds number value, based on the equivalent diameter $D_e = D_o - D_i$ in both heat transfer and pressure drop calculations regardless of what correlation is used.

Since all calculations of the present work are based on equation (3.12), then no need for obtaining two values for Reynolds number, i.e. friction factor as well as Nusselt number calculations in the annulus will include the same Reynolds number with the hydraulic diameter defined by $D_e = D_o - D_i$. By equation (3.18), the use of equation (3.12) for the annulus is acceptably accurate. Furthermore, for the two sides, equation (3.12) includes the entrance effect term as well as working in larger range of Reynolds number.

### 3.2.3 Empirical Correlations of Turbulent Fluid Flow and Heat Transfer in Tubes Inserted with Wire Coils

Many correlations had been set for predicting the heat transfer and pressure drop. **Ravigururajan and Bergles in (1985) [56]** proposed what might be considered to be the most general and accurate method for predicting heat transfer and pressure drop inside internally ribbed tubes (and plain tubes with coiled wire inserts). Figure 3-1 depicts the rib geometries and profiles (and wire geometry) that were included in their study. The $n_{corners}$ here is the number of sharp corners of the rib facing the flow (two for triangular or rectangular cross-section ribs and infinity for smoother profiles). The profile contact angle for a circular sector and circular profiles is taken as 90°. Their method is applicable to the following range of parameters: $0.01 < e/d_i < 0.02$, $0.1 < p/d_i < 7.0$, $0.3 < \beta/90 < 1.0$, $5000 < Re < 250000$ and $0.66 < Pr < 37.6$. Their ribbed tube heat transfer correlation is:

$$\frac{Nu_a}{Nu_s} = \left\{1 + \left[2.64\,\mathrm{Re}^{0.036}\left(\frac{e}{d_i}\right)^{0.212}\left(\frac{p}{d_i}\right)^{-0.21}\left(\frac{\beta}{90}\right)^{0.29}\mathrm{Pr}^{-0.024}\right]^{7}\right\}^{1/7}$$

… (3.21)

The friction factor is correlated as a ratio to the value for a smooth tube of the same internal diameter as:

$$\frac{f_a}{f_s} = \left\{1 + \left[29.1\mathrm{Re}^{a1}\left(\frac{e}{d_i}\right)^{a2}\left(\frac{p}{d_i}\right)^{a3}\left(\frac{\beta}{90}\right)^{a4}\left(1 + \frac{2.94}{n_{corners}}\right)\sin\theta\right]^{15/16}\right\}^{16/15}$$

… (3.22a)

$$a1 = 0.67 - 0.06\left(\frac{p}{d_i}\right) - 0.49\left(\frac{\beta}{90}\right) \quad a2 = 1.37 - 0.157\left(\frac{p}{d_i}\right)$$

$$a3 = -1.66\times10^{-6}\,\mathrm{Re} - 0.33\left(\frac{\beta}{90}\right) \quad a4 = 4.59 + 4.11\times10^{-6}\,\mathrm{Re} - 0.15\left(\frac{p}{d_i}\right)$$

... (3.22b)

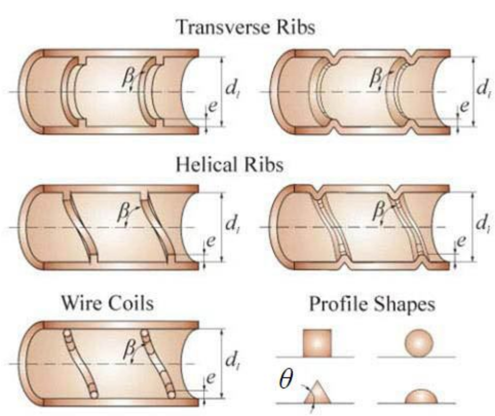



**Figure 3-1**: Internal enhancement geometries and profile shapes considered by Ravigururajan and Bergles (1985) [57].

In equations (3.21) and (3.22), equations (3.3) and (3.11) are used to determine the friction factor and Nusselt number of the reference tube (smooth, plain surface tube) [1, 2, 57, 35, and 58]. But because the friction factor correlation above reported to predict 96% of the data within ±50%, and the heat transfer correlation to predict the 99% of the data within ±50%, these correlations are not recommended for general use [35].

## 3.3 Mechanisms of Heat Transfer Augmentation by Turbulence Promoters

One of the most important mechanisms of augmenting heat transfer is the displacement of the turbulent boundary layer. Figure 3-2 depicts a diagram that **Arman and Rabas [59, 60]** used to illustrate this process, showing the separation of the flow as it passes over a transverse rib (creating a small recirculation zone in front of the rib), the formation of a recirculation zone behind the rib, flow reattachment on the base wall, and then flow up and over the next rib. Recirculation eddies are formed above these flow regions. They commented as follows on a rib's effect on the heat transfer process:

1. There are six distinct heat transfer regions, although some are more important than others (the upstream recirculation zone, the rib's upstream, top and downstream faces, the downstream recirculation zone, and finally the boundary layer reattachment zone);
2. Two peaks in local heat transfer occur, one at the top of the rib and the other in the downstream recirculation zone just before the reattachment point;
3. Heat transfer enhancement increases substantially with increasing Prandtl number, so that for large Prandtl number, fluids heat transfer is dominated by flow around the rib surfaces;

4. The surface-averaged heat transfer performance is directly proportional to the maximum enhancement at the rib;
5. The point of the local maximum in the heat transfer coefficient on the base wall between ribs moves upstream towards the back of the rib with increasing Reynolds and Prandtl numbers, and is located on the base wall between the reattachment point and the point of maximum wall shear stress;
6. The Prandtl number has the same influence on thermal performance in the downstream recirculation region as at the rib;
7. The high heat transfer augmentation in the downstream recirculation region is due to the high turbulence levels near the surface;
8. Two more local maximums in heat transfer occur at large Reynolds numbers in the front recirculation zone before the rib and on the rear face of the rib **[59, 60].**

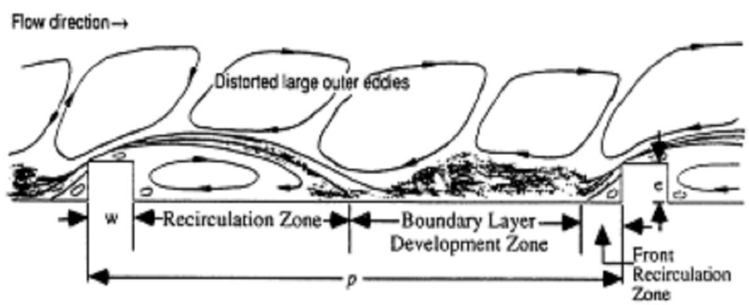



**Figure 3-2:** An enhanced tube with the separation and reattachment mechanism [59].

**Webb, Eckert and Goldstein in 1971 [61]** have presented an interesting composite diagram of the recirculation and reattachment zones as a function of rib spacing for ribs oriented normal to the flow. Figure 3-3 shows this diagram where the flows are characterized by the axial rib pitch to rib height (*p/e*) ratio. For closely spaced ribs (at bottom of diagram), one large recirculation eddy is trapped between two successive ribs with two small eddies in the corners. As the (*p/e*) ratio increases, the large recirculation eddy elongates until it is broken and a reattachment zone is formed, such that two dominant eddies exist at larger ratios. The separation occurs at the ribs, which leads to the formation of a shear layer and finally reattaches at about 6-8 times the rib height, downstream of the rib. The reverse flow boundary was found to originate from the reattachment point and had grown in thickness. The wall shear stress is zero at the reattachment point and was found to increase in the reverse flow region. Webb had shown that reattachment does not take place below a particular (*p/e*) ratio [61].

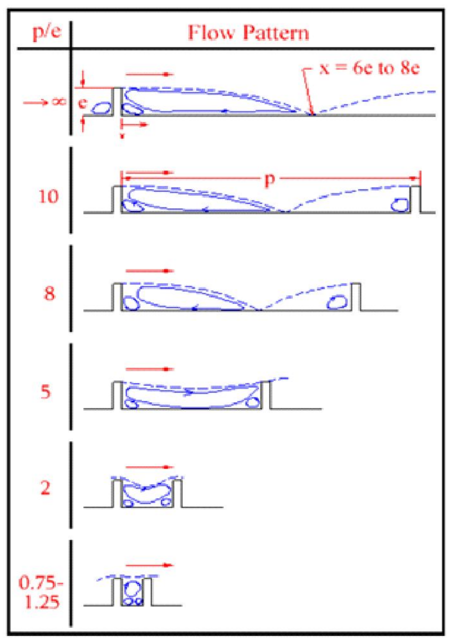



**Figure 3-3**: Recirculation flow patterns over transverse ribs as a function of rib spacing [61].

Similarly, but using an advanced technique, **Acharya et al., [62, 63]** adopted a laser-Doppler measurement system to investigate the effect of the rib on local heat transfer. They reported a peak in stream-wise turbulence intensity that occurred directly above the rib. Cross-stream turbulence intensity profiles were found to reach a maximum downstream of the rib as well as a peak in heat transfer upstream of the point of flow reattachment.

## 3.4 Performance Evaluation Criteria (PEC)

It is impossible to establish an absolute applicable selection criterion for the use of enhancement techniques, because numerous factors influence the designer's decision. In addition to the relative thermal-hydraulic performance improvements brought about by the enhancement devices, there are many factors that must be considered. They include economic (capital, installation, maintenance, etc.), manufacturability (machining, forming, etc.), reliability (material compatibility, and long-time performance), and finally safety.

Common thermal-hydraulic goals include reducing the size of a heat exchanger required for a specified heat duty, increasing the heat duty of an existing heat exchanger, reducing the approach temperature difference for the process streams, or reducing the pumping power. The presence of system and design constraints leads to a number of performance evaluation criteria (PECs). The geometric variables for tube-side flow in a shell-and-tube heat exchanger are tube diameter, tube length, and number of tubes per pass. The heat exchanger performance is represented by two dependent variables: heat transfer rate ($q$) and pressure drop ($\Delta p$) or pumping power ($P$), as

$$q = (UA)\Delta T_m \qquad \ldots (3.23)$$

$$\Delta p = f \frac{L}{d_i} \frac{G^2}{2\rho} \qquad \ldots (3.24)$$

$$P = \Delta p \frac{G A_c}{\rho} \qquad \ldots (3.25)$$

The primary independent operating variables are the approach temperature difference and the mass flow rate ($\dot{m}$), and in the case of the tubular geometry, the design variables (heat transfer surface area ($A$) or exchanger size) are the diameter ($d_i$) and length ($L$) of tubes and number of tubes ($N$) per pass. PECs are established for the process stream of interest by selecting one of the operational variables for the performance objective and applying the design constraints on the remaining variables [1, 2, 35, 58].

### 3.4.1 Objective Functions and Constraints

For single-phase flow heat transfer inside enhanced and smooth tubes of the same diameter, PECs for 12 different cases outlined by Webb and Bergles are listed in table 3-1. They represent criteria for comparing the enhanced performance on the basis of three broad geometry constraints [35, 58].

**Table 3-1**: Performance Evaluation Criteria for Single-Phase Forced Convection in Enhanced Tubes Diameter ($d_i$) as the Smooth Tube [58].

| Fixed | | | | | | | Consequences | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Case | Geom. | $\dot{m}$ | P | $q$ | $\Delta T_i$ | Objective | $\frac{Nu_a}{Nu_s}$ | $\frac{L_a}{L_s}$ | $\frac{\dot{m}_a}{\dot{m}_s}$ | $\frac{Re_a}{Re_s}$ | $\frac{P_a}{P_s}$ | $\frac{q_a}{q_s}$ | $\frac{\Delta T_{ia}}{\Delta T_{is}}$ |
| FG-1a | $N, L$ | X | — | — | X | $\uparrow q$ | 1 | 1 | 1 | 1 | >1 | >1 | 1 |
| FG-1b | $N, L$ | X | — | X | — | $\downarrow \Delta T_i$ | 1 | 1 | 1 | 1 | 1 | 1 | <1 |
| FG-2a | $N, L$ | — | X | — | X | $\uparrow q$ | 1 | 1 | <1 | <1 | 1 | >1 | 1 |
| FG-2b | $N, L$ | — | X | X | — | $\downarrow \Delta T_i$ | 1 | 1 | <1 | <1 | 1 | 1 | <1 |
| FG-3 | $N, L$ | — | — | X | X | $\downarrow$P | 1 | 1 | <1 | <1 | <1 | 1 | 1 |
| FN-1 | $N$ | — | X | X | X | $\downarrow L$ | 1 | <1 | <1 | <1 | 1 | 1 | 1 |
| FN-2 | $N$ | X | — | X | X | $\downarrow L$ | 1 | <1 | 1 | 1 | <1 | 1 | 1 |
| FN-3 | $N$ | X | — | X | X | $\downarrow$P | 1 | <1 | 1 | 1 | <1 | 1 | 1 |
| VG-1 | — | X | X | X | X | $\downarrow NL$ | >1 | <1 | 1 | <1 | 1 | 1 | 1 |
| VG-2a | $NL$ | X | X | — | X | $\uparrow q$ | >1 | <1 | 1 | <1 | 1 | >1 | 1 |
| VG-2b | $NL$ | X | X | X | — | $\downarrow \Delta T_i$ | >1 | <1 | 1 | <1 | 1 | 1 | <1 |
| VG-3 | $NL$ | X | — | X | X | $\downarrow$P | <1 | <1 | 1 | <1 | <1 | 1 | 1 |

**1. FG criteria**. The cross-sectional envelope area (N and $d_i$) and tube length (L) are held constant. This would typically be applicable for retrofitting the smooth tubes of an existing exchanger with enhanced tubes. That means maintaining the same basic geometry and size (N, $d_i$, and L). The objectives then could be to increase the heat load capacity (q) for the same approach temperature ($\Delta T_i$) and mass flow rate ( $\dot{m}$ ) or pumping power (P); that is (FG-1a) and (FG-2a) respectively; or decrease ($\Delta T_i$) or (P) for fixed (q) and ($\dot{m}$), i.e. (FG-1b) or (P), i.e. (FG-2b); or reduce (P) for fixed (q), i.e. (FG-3).

**2. FN criteria**. These criteria maintain fixed cross-sectional area (N and $d_i$) and allowing the heat exchanger length to vary. Here the objectives are to seek a reduction in either the heat transfer surface area (A → L), i.e. (FN-1) and (FN-2); or the pumping power (P), i.e. (FN-3) for a fixed heat load.

**3. VG criteria**. In many cases, a heat exchanger is sized for a required thermal duty with specified flow rate. In these situations the FG and FN criteria are not applicable. Because the tube-side velocity must be reduced to accommodate the higher friction characteristics of the enhanced surface, it is necessary to increase the flow area to maintain constant flow rate. This is accomplished by using a greater number of parallel flow circuits. Maintaining a constant exchanger flow rate eliminates the penalty of operating at higher thermal effectiveness encountered in the previous FG and FN cases [58].

### 3.4.2 Algebraic Formulation of the PEC

Calculation of the performance evaluation criteria for any of the 12 cases in Table 3-1 requires algebraic relations that quantify the objective function and constraints. It is convenient to develop the algebraic relations relative to a smooth surface operating at the same fluid temperature. This allows cancellation of the fluid properties from the equations.

The different cases listed in table 3-1 are derived for flow inside enhanced and smooth tubes of the same inside diameter. Considering a shell and tube heat exchanger of length *L,* having *N* tubes in each pass, and $N_p$ passes. The total tube-side surface area in the heat exchanger is

$$A = \pi d_i L N N_p \quad \text{... (3.26)}$$

The basic heat transfer and friction performance characteristics of the enhanced and smooth tubes are normally presented as Colburn factor (*j*) defined as $j = St\,\mathrm{Pr}^{2/3} = Nu/\mathrm{Re}\,\mathrm{Pr}^{1/3}$ and $f$ vs. $\mathrm{Re} = d_i G/\mu$. Because the tube inside diameter is held constant, one may write

$$h = \frac{C_p jG}{\mathrm{Pr}^{2/3}} \qquad \ldots (3.27)$$

The value of ($hA$) of the enhanced surface, as in equation (3.1), relative to that of the smooth surface is the aim of interest. Writing equation (3.27) as the ratio, relative to a smooth surface gives

$$\frac{hA}{h_s A_s} = \frac{j}{j_s}\frac{A}{A_s}\frac{G}{G_s} \qquad \ldots (3.28)$$

Substituting equation (3.24) in (3.25) and replacing $A_c$ by $[(\pi/4)d_i^2]$ gives equation (3.29) for pumping power

$$P = \frac{fAG^3}{8\rho^2} \qquad \ldots (3.29)$$

Writing equation (3.29) as the ratio, relative to the smooth surface, gives

$$\frac{P}{P_s} = \frac{f}{f_s}\frac{A}{A_s}\left(\frac{G}{G_s}\right)^3 \qquad \ldots (3.30)$$

Elimination of the term $G/G_s$ from equations (3.28) and (3.30) gives

$$\frac{hA/h_s A_s}{(P/P_s)^{1/3}(A/A_s)^{2/3}} = \frac{j/j_s}{(f/f_s)^{1/3}} \qquad \ldots (3.31)$$

To apply one of the PECs, one of the variables on the left side of equation (3.31) is set as the objective function, and the remaining two are set as operating constraints (equal to unity). It is necessary to determine the $G/G_s$ ratio that satisfies Equation (3.31). The equations of the $j_s$ and $f_s$ as a function of $\mathrm{Re}_s$ and the $j$ and $f$ as a function of Re must be known [35]. Accordingly, in the present work, these equations would be created from the experimental data to accommodate the requirements of these PECs either for the tube-side or annulus-side heat transfer enhancement.

## 3.5 Thermal Design of the Double Pipe Heat Exchangers

Only two important relationships constitute the entire thermal design procedure of a heat exchanger. These are:

1. Heat transfer rate for a non-adiabatic single-phase flow:

$$q = \dot{m}\Delta H = \dot{m}Cp(T_o - T_i) \qquad \dots (3.32)$$

2. Heat transfer rate equation:

$$q = UA\,\Delta T_m \qquad \dots (3.33)$$

Equation (3.33) reflects a convection–conduction heat transfer phenomenon in a two-fluid heat exchanger. Heat transfer rate is proportional to the heat transfer area ($A$) and mean temperature difference ($T_m$) between the fluids. This mean temperature difference is a log-mean temperature difference (LMTD), for counterflow and parallelflow exchangers, it is

$$\Delta T_m = LMTD \equiv \frac{(T_{h2} - T_{c2}) - (T_{h1} - T_{c1})}{\ln[(T_{h2} - T_{c2})/(T_{h1} - T_{c1})]} \qquad \dots (3.34)$$

If a wall of a hollow cylinder (like a double pipe heat exchanger) is considered, the overall heat transfer coefficient (U) in equation (3.33) may be based on either the inside or outside area of the tube. Accordingly,

$$U_i = \frac{1}{\dfrac{1}{h_i} + \dfrac{A_i \ln(r_o/r_i)}{2\pi kL} + \dfrac{A_i}{A_o}\dfrac{1}{h_o}} \qquad \dots (3.35)$$

$$U_o = \frac{1}{\dfrac{A_o}{A_i}\dfrac{1}{h_i} + \dfrac{A_o \ln(r_o/r_i)}{2\pi kL} + \dfrac{1}{h_o}} \qquad \dots (3.36)$$

Equations (3.35) and (3.36) include three thermal resistances, heat is transferred through. Two are concerned with convection heat transfer in the two sides of the exchanger and the other is caused by the wall itself [4, 64].

# CHAPTER FOUR

# Experimental Work

## 4.1 Experimental Rig Design and Assembly.

An experimental rig was designed and assembled to carry out the experiments that require particular fluid temperatures, particular fluid flow rates, and for each run, temperatures of four points and pressure drop in specific sections, which represent the heart of the present work, must be measured in acceptable accuracy.

Simply, the concerned rig is an assembly of several parts when operated, the result is two streams of fluids having particular temperatures that the study needs, flowing separately and sometimes mixed for specific tasks. In addition, two specialized streams were used in the isothermal pressure drop experiments, which might stop the working as a heat exchange system and mixing the two streams to work under constant temperature conditions. No automatic temperature control devices are available, so manual control is widely adopted to regulate temperatures of fluid streams. Figure 4-1 shows a photograph of the rig whose parts are detailed in the schematic flow diagram depicted in fig. 4-2.

Water was used as the working hot fluid and cold fluid streams for its availability; high heat capacity, which enables easy control of temperature; and conventionality of using it as the cold fluid in many actual heat exchange processes.


**Figure 4-1:** A photograph of the experimental rig.

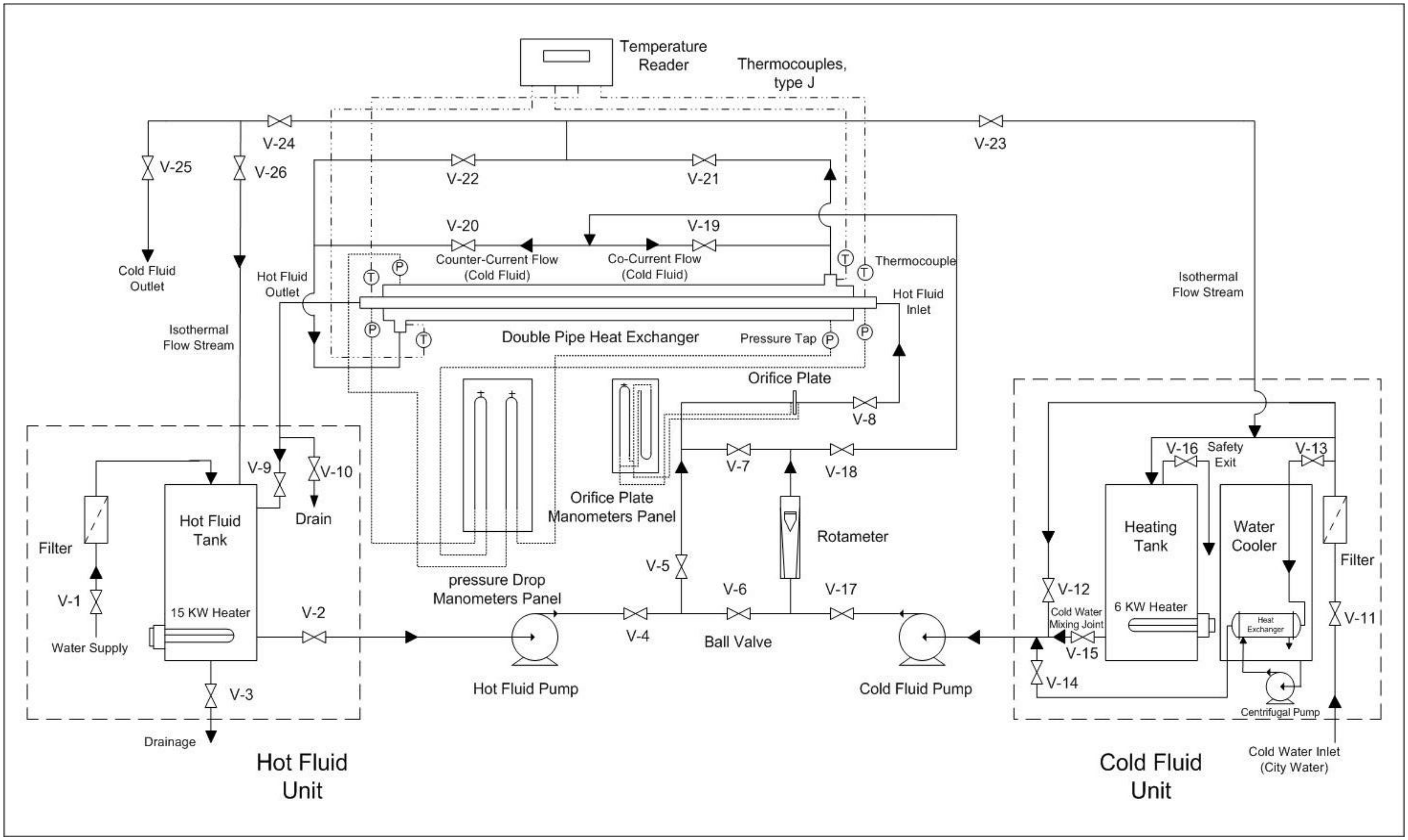



**Figure 4-2**: A schematic flow diagram of the experimental rig.

### 4.1.1 Components of the Experimental Rig.

#### 4.1.1.1 Hot Fluid Unit.

As depicted in fig. 4-2 the hot fluid unit consists mainly of the following:

**( i ) Insulated Tank:** A tank of (50×50×100 cm) dimensions well-insulated using 5 cm thick of mineral wool insulation to forbid loss of heating energy.

**( ii ) Electric heaters:** 4 electric heaters with 3 kW power for each in addition to a 3.5 kW power supplied by 1500, 1000, and 500 W heaters and 500 W heater controlled by a variac are used to supply thermal energy needed for heat transfer. The partitioned 3.5 kW power is exploited to control temperature of the hot stream to the required value, where the heat transferred from the hot to cold stream through the heat exchanger at any time, is guessed by calculations as shown later.

Hot fluid unit is supplied with water (as the working fluid) after passing through a filter assembled at the inlet of the system. Hot water is circulated throughout the system and returned to the hot fluid tank. Water is replaced periodically so as to keep it free from salts which may be concentrated as a result of continuous heating.

#### 4.1.1.2 Cold Fluid Unit

The cold fluid unit consists of the following:

**( i ) Main Stream of Tap Water**: The cold fluid used throughout the system is filtered tap water used for one pass without circulating, but since it may come in different temperatures during the different seasons of the year, its temperature must be maintained to the required temperature which is 20 °C.

**( ii ) Heating Tank**: To maintain tap water at 20 °C which may arrive in temperature less than this degree (during winter), a heating tank provided with a 6 kW electric heater is used for the task. In most cases, tap water is divided into two streams before entering the unit; one is passed through the heating tank. The two streams are mixed in a joint point before entering the system. The flowrates of the two streams are maintained manually till the temperature of the "mixture" is being settled at the required value.

**( iii ) Water Cooler:** In summer, the task may be different where the tap water is arriving in temperature more than 20 °C, so it is necessary to lower to this temperature. The task is carried out in a manner similar to that used in the preceding case but instead of passing one of the two streams, the water have been divided into the heating tank, it is now passed through a water cooler. The concerned stream is passed through a shell-and-tube heat exchanger immersed inside the pool of the water cooler and exchanging heat with cold water (its temperature is below 5 °C, pumped by a centrifugal pump) without mixing. This exit stream is mixed with the other stream and again controlled manually to produce water at the required temperature. Depending on the techniques discussed above and enough experience, temperature of cold water was controlled to 20 ± 0.5.

#### 4.1.1.3 Flow Measurement Instrumentation

Two flow measurement devices have been used, one for each stream:

**( i ) Rotameter:**

A rotameter type (FLOWTECH, LZS-25) with flowrate range between 0.16 and 1.5$m^3$/hr, were used to measure the flowrate of cold water (20 °C). But in case of isothermal pressure drop experiments, which would be explained later, the rotameter was used to measure the flowrate of hotter water, reaches 70 °C, so an accurate calibration was required in order to ensure obtaining results as acceptable as possible. Calibration of rotameter was performed to produce calibration curves for flowrate of water, at four temperatures (20, 40, 60, and 70 °C). Details of calibration of the rotameter and calibration curves, produced are fixed in appendix B.

**( ii ) Orifice plate.**

An orifice plate was designed and manually fabricated to be used in measuring hot water flowrate. This device is supplied with two manometers, an inverted manometer filled with mercury to be used in measuring relatively high flowrates (between 0.3 and 0.9 $m^3/hr$), and the other is an ordinary water manometer to be used in measuring low flowrates (0.3 $m^3/hr$ and lower). Design and calibration of the orifice plate for the two temperatures (60 and 70 °C) is detailed in appendix B. The mercury manometer graduation is directly fixed on the orifice manometer panel, while the water manometer must be treated differently. That is by using a computer program written for the purpose because the water manometer readings cannot be adjusted directly.

### 4.1.1.4 Pressure Measurement Instrumentation

One of the most important data to be obtained in the present work is the pressure drop inside the test section (double-pipe heat exchanger), so four pressure taps were fixed in the inlet and exit of the hot and cold fluid streams to measure pressure drop inside the inner tube and the annulus. Three manometers were used. Two of the manometers-that use water-are employed to measure low pressure drops and the third that uses mercury is employed to measure high pressure drops. The latter is connected to each of the others if needed. When working together, the water manometer must be closed, when measuring high flowrates, or else it might overflow.

#### 4.1.1.5 Temperature Measurement Instrumentation

Four thermocouples type (J) fixed at the inlet and outlet of the hot and cold fluid streams to measure temperature of the intended fluids at specific points. The ends of thermocouples are screwed to be tightly fixed in the external tubes near the inlet and outlet points. The thermocouples are connected to a temperature reader device type (DORIC) with five buttons.

Since these temperature values play a decisive role in calculating the Nusselt number, and to ensure that the temperatures obtained are as accurate as possible, an accurate calibration for the four thermocouples and the temperature reader device were carried out using a mercury thermometer. The latter was calibrated using boiling distilled water and a mixture of distilled water and ice [65]. The result of the calibration process was converted to four calibration curves to be used to predict the actual values of temperature. Details of calibration are fixed in appendix B.

#### 4.1.1.6 Pipes, Pumps, and Valves

All pipes used in the construction of the rig are made of galvanized iron pipes of ID=16mm, well-insulated to save energy. Three centrifugal pumps, with maximum volumetric flowrate of 4 $m^3$/hr, are included, one for the cold fluid unit and the others are employed to pump the hot and cold fluids in concerned streams. 26 ball valves are used in the rig. This type of valve had been used because it could be easily and rapidly opened and sealed and easily used in controlling the volumetric flowrates of the two streams.

#### 4.1.1.7 Test Section (Double-Pipe Heat Exchanger)

The most important part of the experimental rig is the test section which is a double pipe heat exchanger. Figure 4-3 illustrates its main parts:

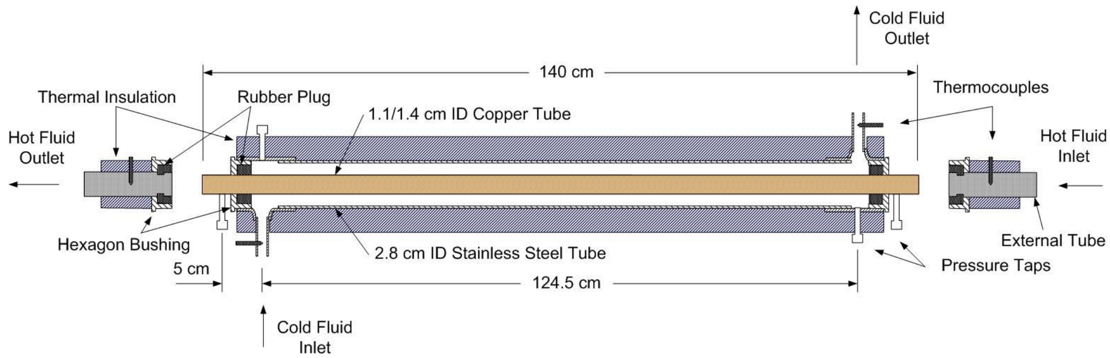



**Figure 4-3:** Sketch of the double-pipe heat exchanger used in the present work.

**( i ) The outer tube:** It is made of stainless steel to avoid corrosion during operation. It is 1.2 m length, ID=2.8 cm and OD=3.0 cm.

**( ii ) The inner tube:** It is made of pure copper (South African Origin) for its low thermal resistance with two sizes used. The first is 1.4 m length, ID=1.1 cm and OD=1.25 cm. The second has the same length but with ID=1.4 cm and OD=1.55 cm.

**( iii ) Pipe fittings:** Two 1-½ inch reducing tee lateral fits are connected to the two ends of the stainless steel tube with making their branches in opposite directions. In addition, four hexagon bushings with their hollows filled with rubber plugs, were used. These were perforated in a way can hold the inner tube without leakage. Two were used to conjoin the inner with the outer tube in a manner enables the operator to disassemble the two tubes in order to change the inner tube easily after each experiment. The other two were used to connect the two ends of the inner tube to the external pipes of the rig [66].

**( iv ) Pressure taps:** Four pressure taps are installed in four points around the double-pipe heat exchanger, and connected to the manometer panel detailed above. Two pressure taps concerning the pressure drop in the inner tube are fixed directly in that tube by perforating it carefully near the two ends keeping a distance of 134.5 cm between the two perforations. This distance was larger than the effective heat transfer length (124.5 cm) which equals to the distance between the inlet and outlet of cold water or the two centers of the tee fittings, so all pressure drop values registered for the tube side would be multiplied by the ration of (124.5/134.5) to obtain the real value of pressure drop. To avoid leakage in these points, an adhesive material was used, taking into consideration that no protrusion was left inside the tube which may cause an error in reading the actual pressure drop. The annulus side pressure taps were fixed in the centre of the tee lateral body. That was in order to calculate the actual pressure drop in the annulus without that caused by the entrance. The registered value in that case was adopted directly without correction. These taps not like those of the inner tube, they were not removable because the outer tube connected to the reducing tee laterals were left without disassembling all the experimental work. Fig. 4-4 shows the pressure taps.

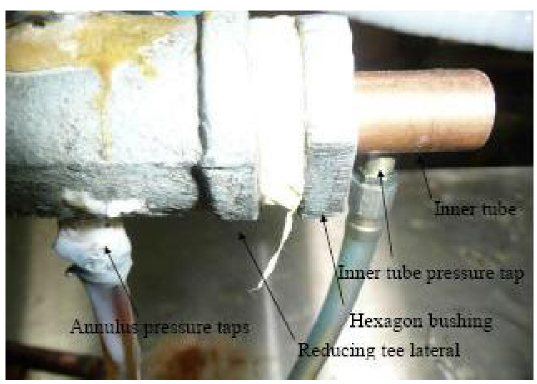



**Figure 4-4:** Pressure taps.

The temperature thermocouples installation was easier because they were fixed in the external tubes belonging to the rig itself and left without removing all the experimental work.

The whole body of the heat exchanger was insulated with a layer of mineral wool insulation to avoid heat loss.

### 4.1.2 Turbulence Promoter Selection and Fabrication

Three types of inserts with different pitch length and wire diameter, (defined in fig. 4-5a), was used in the present work:

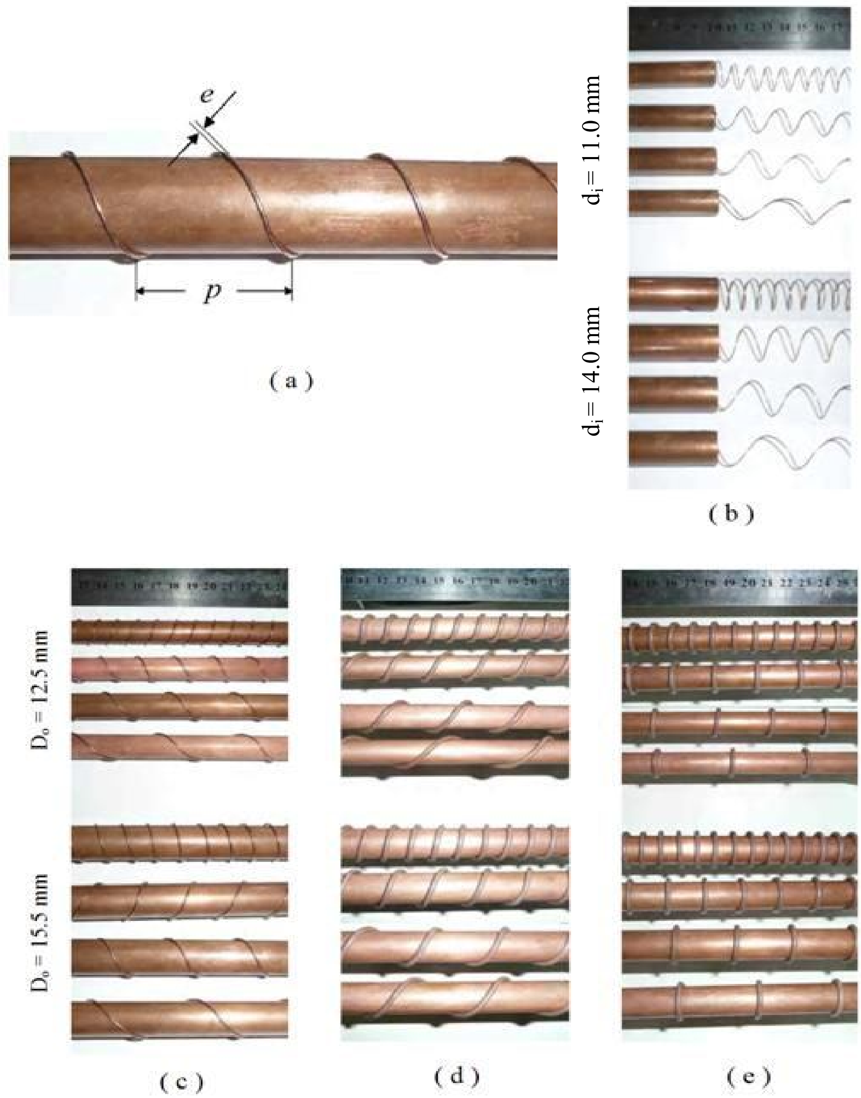



**Figure 4-5:** Turbulence promoters used in the present work, (a) Definition of pitch length *p* and wire diameter *e*, (b) Inner coiled wire inserts, (c) Coiled wire on the outer surface of the inner tube *e* =1 mm, (d) Coiled wire on the outer surface of the inner tube *e* =2.2 mm, (e) Circular rib on the outer surface of the inner tube *e* =2.2 mm.

**( i ) Wire coil insert inside the inner tube:** 1 mm diameter copper wire was coiled around a steel bar of about 8.5 and 12 mm diameter to produce wire coils with outside coiling diameters of 11 and 14 mm. Four coiling pitches had been studied (10, 20, 30, and 40 mm), as in fig.4-5b.

**( ii ) Wire coil insert on the outer surface of the inner tube:** Two copper wire sizes were used (1 and 2.2 mm diameter). That was by coiling the interested wires around the copper tubes directly with keeping four coiling pitches to be used (10, 20, 30, and 40 mm), fig. 4-5c, and d.

**( iii ) Circular ribs on the outer surface of the inner tube:** A copper wire with diameter of 2.2 mm was used in fabricating circular ribs to be used as turbulence promoters on the outer surface of the inner tube with four pitch lengths (10, 20, 30, and 40 mm).

## 4.2 Operation of the System

In the present work, experiments were divided into two kinds, isothermal pressure drop experiments and heat exchange experiments:

### 4.2.1 Isothermal Pressure Drop Experiments

The aim of the isothermal pressure drop experiments is to obtain the friction factor or pressure drop, in mm $H_2O$, for the range of Reynolds numbers of working fluid flowing through the tube or annulus side of the heat exchanger at constant temperature (no heat exchange). In the present work experiments were performed at four temperatures 20, 40, 60, and 70 °C, which give a satisfactory variety of physical properties, with 8 values for Reynolds number, from 5000 through 40000 for the tube-side enhancement experiments and from 3000 through 10000 based on the equivalent diameter for annulus-side enhancement experiments. The operation of isothermal pressure drop, in case, if the tube side is intended to study the pressure drop inside, can be summarized in the following steps (referring to fig. 4-2):

- The first step was filling the hot water tank with water at one of the temperatures above. Then temperature is changed to the next.
- The isothermal pressure drop operation was a closed-loop process. That was by sealing valves V-17, V-23, and V-25.
- The interested loop of water was being determined according to its temperature. For 20 and 40 °C water circulated the loop was started from the hot water tank passing through V-2, pumped by the hot water centrifugal pump through V-4, V-6, passing through the rotameter and then V-7 entering the inner tube of the heat exchanger and returning to the tank. V-5 and V-18 was tightly sealed. That loop was decided because the orifice plate was designed and calibrated to work at 60 and 70 °C, while that was accessible in the rotameter. For 60 and 70 °C, the loop was different, starting from the hot water tank, through V-2, V-5 pumped through the orifice plate to the inner tube of the heat exchanger and finally returned to the tank. V-6 and V-7 was tightly sealed.
- Flowrate measured by the rotameter was the wanted one in case of 20 and 40 °C temperatures while that measured by the orifice plate for 60 and 70 °C. For each case, the pressure drop was registered. Then the flowrate was raised for the next using valve V-4.
- Valves V-18, V-20, V-21, V-24, and V-26 were left open, while V-19 and V-22 there was no problem if were being forgotten open.

If the annulus side was intended to study the pressure drop inside, with the aid of fig. 4.2, the main steps are summarized by the following points:

- Filling the hot water tank with water at a specific temperature.
- Sealing valves V-17, V-23, and V-25.

- Valve V-7 should be tightly sealed.
- Valves V-19 and V-22 were left sealed.
- In the present case the path of water was: the hot water tank, V-2, the hot water pump, V-7, the rotameter, V-18, V-20, V-21, V-24, V-26, and returning to the tank. The flowrate measured by the rotameter was the intended flowrate. Then, pressure drop was registered.
- V-5 was left slightly open and V-8 and V-9 were being left open to permit some of water to pass through the inner tube to ensure that no heat exchange was happening.

### 4.2.2 Heat Exchange Experiments

The second part of the present work was the heat transfer experiments. Cold water was flowing in open cycle, through the annulus of the double pipe heat exchanger, counter-currently with hot water stream which was flowing in closed cycle through the inner tube. The implementation of a heat transfer experiment can be summarized in the following steps:

- Valves V-23 and V-26 were kept sealed during all the work.
- Valves V-6 and V-7 should be tightly sealed to keep the two streams separated.
- V-11 was the inlet of the water, so it should be opened.
- The cold fluid unit work was depending on whether the water was coming with temperature less or greater than 20 °C (working temperature of cold water for all heat transfer experiments). If less than 20 °C, V-13 and V-14 were both sealed, i.e., the water cooler and its accessories were shut down, while the heating tank was being used (V-15 opened). If the water temperature was greater than 20 °C, then the

water cooler and its accessories were being operated (V-13 and V-14 open), while the heating tank was shut down (V-15 sealed).

- In the mixing point, two streams were mixed, the fresh stream of water and either that coming from the cooling or the heating tank, manually controlled to obtain a water stream at 20 ± 0.5 °C to be used as the cold fluid.
- V-19 and V-22 were always left sealed.
- The cold water path was: the mixing point, pumped by the cold water pump through V-17, the rotameter, V-18, V-20, counter-currently through the annulus of the heat exchanger, V-21, V-24, and through V-25 water was drained outside the system.
- The volumetric flowrate assigned by the rotameter is the flowrate of cold water under study.
- Valves V-1, V-3, and V-10 were left sealed.
- In the present work, all experiments were performed with two temperatures for the hot water stream, 60 and 70 °C. These temperatures were controlled manually. Heat transferred in the exchanger was always known due to the computer program employed, so, by using the variety of heaters, provided to the hot water tank especially those controlled by the variac, temperature of the produced water would be controlled to 60 or 70 ± 0.5 °C. The large volume of the hot water tank was widely helping in forbidding the fluctuations in these temperatures.
- The path of hot water was: the hot water tank, V-2, pumped by the hot water pump through V-4 and V-5, and then through the orifice plate and V-8 entering into the inner tube of the double pipe heat exchanger, and finally through V-9 returning to the hot water tank.

- Two divisions of heat exchange experiments were performed, the first was carried out for the case of enhancement of heat transfer inside the inner tube. In that kind, the cold water mass flowrate was kept constant at two values (0.1 and 0.15 kg/s) and hot water was changed for 8 values of Reynolds number in the inner tube starting from 5000 through 40000. The second kind was performed when the annulus as the enhanced side, where constant mass flowrates for the hot water stream (0.1125 and 0.2 kg/s), while the cold water was changed for 8 values of Reynolds number starting from 3000 through 10000.
- Valves V-4 and V-17 were used as control valves of the hot and cold flowrates respectively.
- All steps stated above were in need to wait for few minutes until the steady state conditions were reached for each change in the hot or cold flowrate. When the approval value of volumetric flowrate (determined by using the computer program) was reached, four temperatures of the inlet and outlet points, as well as the pressure drop in the two sides, read on the manometers panel, were being registered.

## 4.3 Calculation Procedure

### 4.3.1 Prediction of Physical Properties

The use of a computer program (fig. 4-6) to perform calculation of the system which includes widely the properties of water like density, dynamic viscosity, conductivity, and heat capacity, needs to deduce equations for these properties to be used in the computer program. Appendix A includes tabulated properties of water which have been converted by curve fitting to polynomial equations. Equations (A.1), (A.2) and (A.3) would be used in the computer program to predict the physical properties of water instead of direct use of table A-1.

### 4.3.2 Isothermal Pressure Drop Calculations

This class of calculations includes the calculation of Darcy-Weisbach friction factor for all cases studied using the values of isothermal pressure drop obtained during the experiments of isothermal pressure drop, discussed previously, using the equation (3.4). Thus, a large number of points would be available to be used in predicting an isothermal friction factor correlation.

### 4.3.3 Heat Transfer Calculations

The more complicated calculations are that of heat transfer which includes:

**( i ) Calculation of Reynolds number:** It is an implicit problem where Reynolds number was intended to be calculated with unknown physical properties and mass flowrate in order to appear in the form of an integer (5000, 10000, 15000, etc.) in addition to the great physical meaning might be included if all readings had been taken for particular Reynolds numbers instead of volumetric or mass flowrates. In other words, a specified Reynolds number at particular temperature (particular physical properties) might mean a mass flowrate, different from that at another temperature. A trial and error procedure is adopted for the purpose which may be explained as: an initial volumetric flowrate $Q$ is assumed as the required value for the Reynolds number under study, using the temperatures of the inlet and outlet streams of the double pipe heat exchanger resulted to predict physical properties which would lead to a new value for $Q$ for the interested stream, repeating the process until convergence would be reached as illustrated in fig. 4-6 which represents an algorithm for a computer program. Figure 4-6 was written for tube-side enhancement, similar one for annulus enhancement, easily could be imitated by excluding the part of the orifice plate operation which was unnecessary in that case, with some changes in the equations used for calculations to be suitable for the annulus instead of the inner tube.

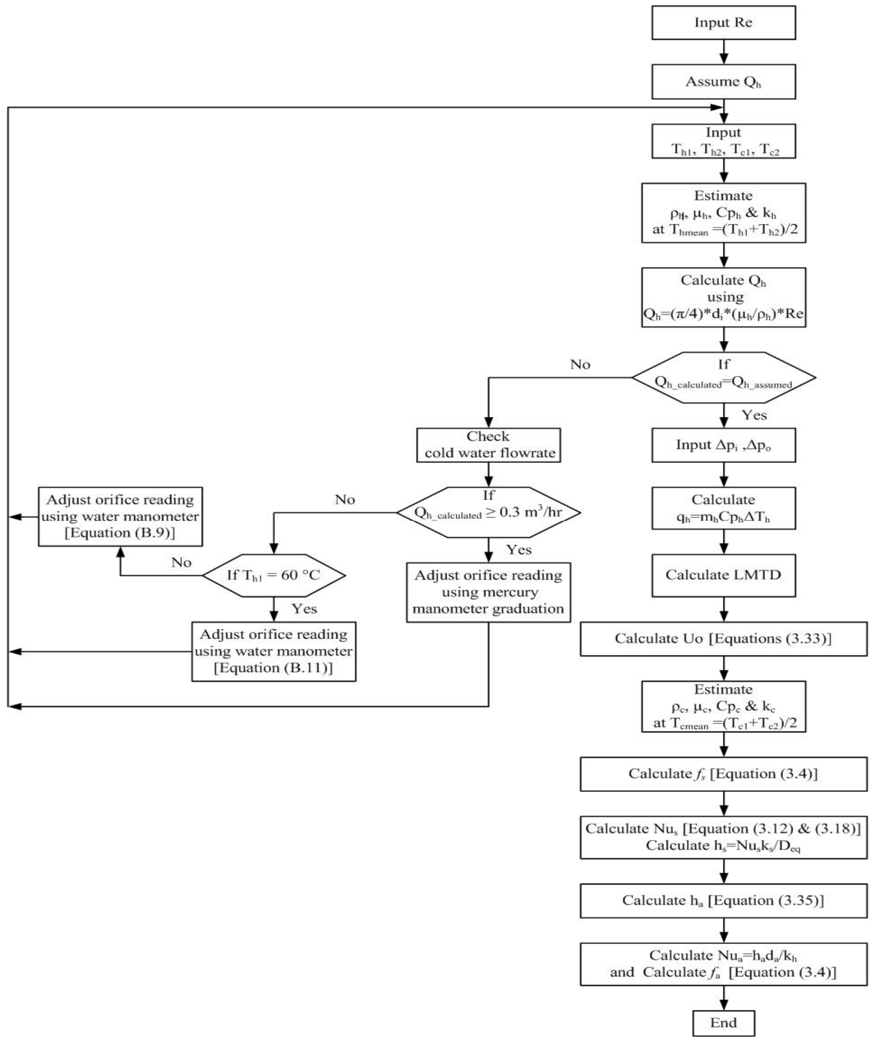



**Figure 4-6:** An algorithm for calculations of tube-side heat transfer enhancement.

**( ii ) Friction factor calculations:** For both enhanced or unenhanced sides of the heat exchanger, friction factor was calculated directly by using equation (3.4) adopting the pressure drop measured by the manometer,

**( iii ) Nusselt number calculations:** The procedure of calculating Nusselt number might be summarized as:

1. Heat Transfer rate is calculated by equation (3.32) for the two sides and the average value is considered.
2. The overall heat transfer coeff. $U_o$ was calculated by eq. (3.33).

3. Friction factor for the unenhanced side is predicted by equation (3.4).
4. Nusselt number (and then the heat transfer coefficient) for the unenhanced side is calculated by equation (3.12), alone, if it is the tube side or with equation (3.18), if it is the annulus side.
5. By equation (3.36), the heat transfer coefficient is obtained for the enhanced side, and then Nusselt number for that side.

## 4.4 Error Sources and Uncertainty

In the present work, some of the error sources which may be fixed as the sources of uncertainty in predicting volumetric flowrates, temperatures and pressure drops which might lead to errors in the predicted values:

1- Electric power instability.
2- Uncertainty in temperature reading resulted from manufacturing defects in the thermocouples and temperature reader device.
3- Errors in flow measurements.
4- Temperature control difficulties.

The first three might lead to that the heat transfer calculated by $q = \dot{m}Cp\Delta T$ be not equal, so the average value was used in all calculations with an acceptable deviation ratio defined as:

$$\text{Deviation ratio} = \frac{|q_h - q_c|}{q_{avg.}} \times 100 \qquad \leq 5\%. \qquad \text{... (4.1)}$$

The fourth source was constrained to ± 0.5 °C for the inlet temperatures with keeping the inlet temperature approach as close to 40 or 50 °C as possible.

# CHAPTER FIVE
# Experimental Results

## 5.1 Introduction

Experiments on thirty six cases of smooth and augmented tubes and annuli were carried out in order to study the effect of different types of inserts on heat transfer and pressure drop in a double pipe heat exchanger. The primary experimental data taken are temperatures of the four inlets and outlets, pressure drop in the two sides and heat transfer rate at different experimental conditions. Tables C-1 through C-18 includes the experimental results for the smooth, as well as augmented tubes and annuli. In addition, experiments on isothermal pressure drop for all cases have been performed. Their results are displayed in tables C-37 through C-40.

## 5.2 Test of Authenticity of Using the Present Heat Exchanger.

First of all calculations and comparisons among the heat transfer and pressure drop or friction factor for augmented and smooth tubes annuli, these smooth tubes and annuli must be tested for authenticity to be used in the experimental work. For heat transfer authenticity test, a comparison between Nusselt number calculated empirically by Gnielinski equation (equation 3.12) and that calculated by using the experimental data obtained, has been performed. For the pressure drop authenticity test a comparison between the friction factor calculated theoretically by Petukhov equation (equation 3.3) and that obtained by experimental work (equation (3.4)). Theoretical and experimental Nusselt number and friction factor (for heat exchange and isothermal conditions) are presented in tables C-19, C-24, C-37 and C-38 and plotted in figs. 5-1 through 5-4.

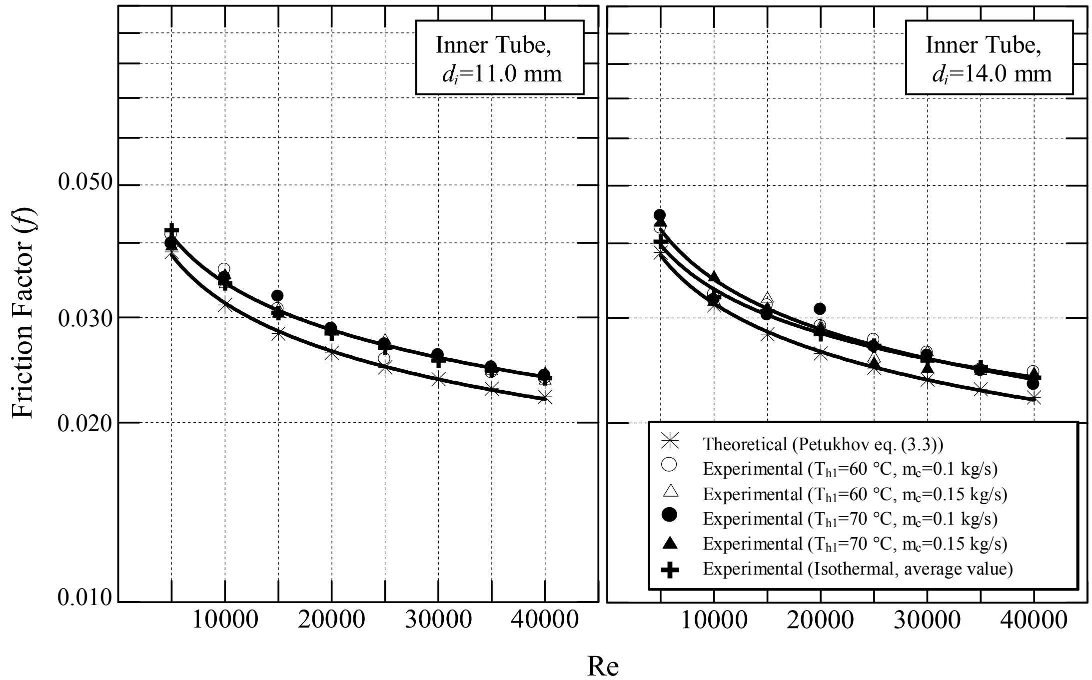



**Figure 5-1:** Comparison of empirical (eq. (3.3)) and experimental friction factor of smooth tubes used in tube-side heat transfer enhancement experiments for two tube sizes.

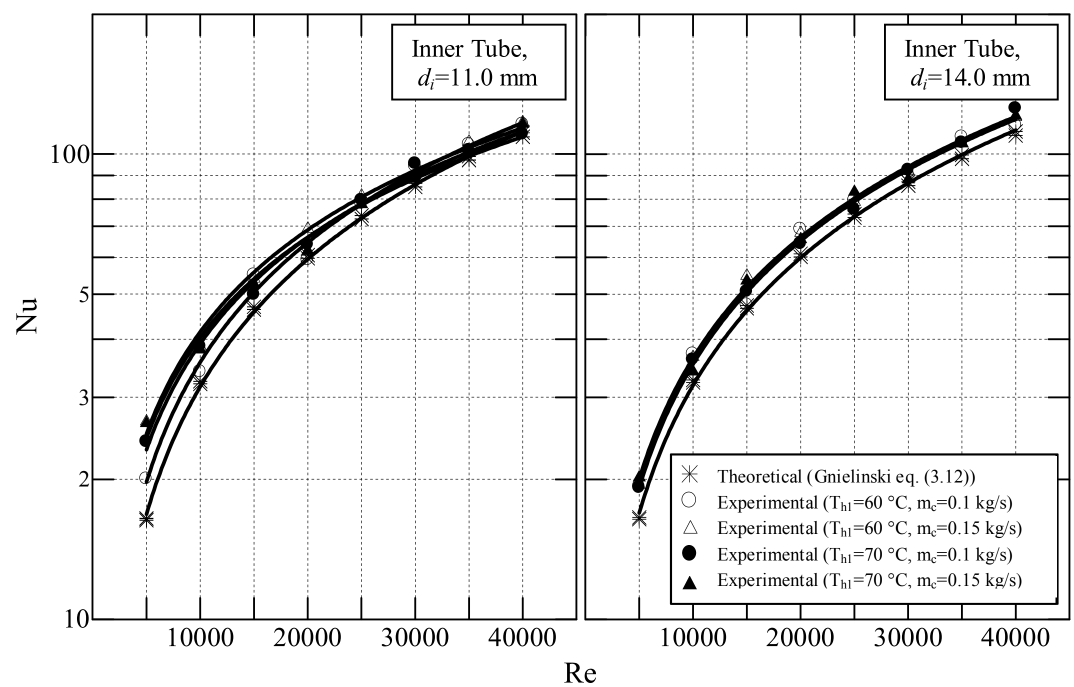



**Figure 5-2:** Comparison of empirical (eq. (3.12)) and experimental Nusselt number inside the smooth tubes used in tube-side heat transfer enhancement experiments.

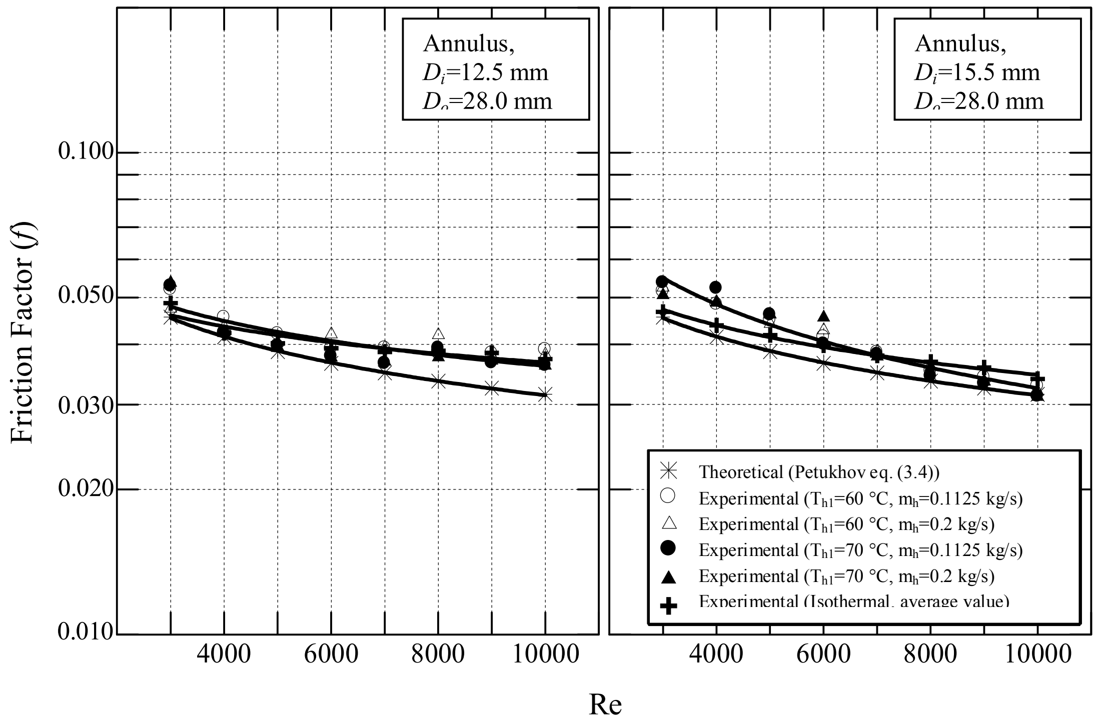



**Figure 5-3:** Comparison of theoretical and experimental friction factor of smooth annuli used in annulus-side heat transfer enhancement experiments.

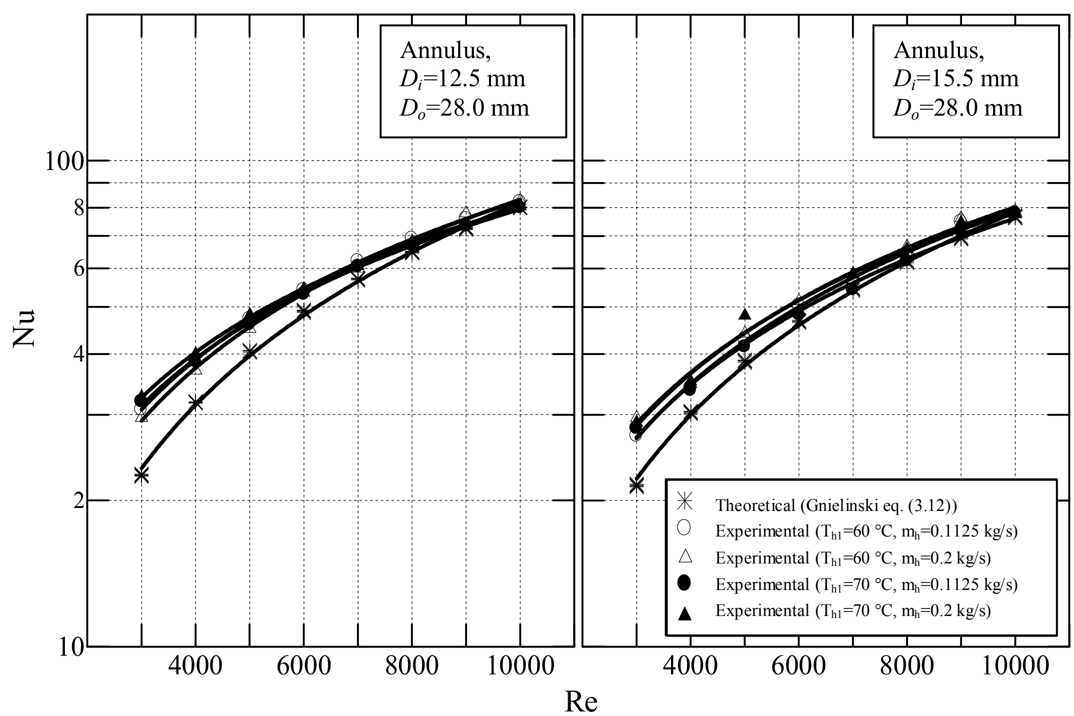



**Figure 5-4:** Comparison of theoretical and experimental Nusselt number of smooth annuli used in annulus-side heat transfer enhancement experiments.

Deviations from theoretical values are fixed in table 5-1. These values were obtained by dividing the absolute difference of the experimental and theoretical value by the theoretical value for all values of the friction factor and Nusselt number and then the average value is considered.

**Table 5-1:** Deviations of Experimental Nusselt and Friction Factor from Values obtained from empirical equations for Smooth Inner Tubes and Annuli.

| Type of experiment | Inner tube | | | | Annulus | | | |
|---|---|---|---|---|---|---|---|---|
| | $d_i = 11$ | | $d_i = 14$ | | $D_i = 12.5$ $D_o = 28.0$ | | $D_i = 15.5$ $D_o = 28.0$ | |
| | % dev. in Nu | % dev. in $f$ | % dev. in Nu | % dev. in $f$ | % dev. in Nu | % dev. in $f$ | % dev. in Nu | % dev. in $f$ |
| Dev. in heat exch. exp. | + 8.66 | + 8.36 | + 8.55 | + 9.18 | + 8.88 | + 10.79 | + 7.77 | + 11.35 |
| Dev. in isothermal pressure drop exp. | — | + 8.12 | — | + 6.96 | — | + 9.79 | — | + 7.46 |
| Average deviation | + 8.66 | + 8.24 | + 8.55 | + 8.07 | + 8.88 | + 10.29 | + 7.77 | + 9.41 |

## 5.3 The Effect of Turbulence Promoters on Heat Transfer Rate and Pressure Drop.

To have a general view of the effect of turbulence promoters, used in the present work, on heat transfer rate and pressure drop in the inner tube and annulus, values of heat transfer rate and pressure drop (tables C-1 through C-18) are plotted versus Reynolds number in figs. 5-5 through 5-8 for all cases.

Figures 5-5 through 5-8 reveals an expected increase of pressure drop with decreasing the coiling or ribbing pitches either in tube-side or annulus-side heat transfer enhancement. On the other hand, the heat transfer rate does not behave in a similar manner except in case of tube-side heat transfer enhancement (fig. 5-5) where the above description becomes valid only for the wire coil of $e$ =1 mm used on the outer surface of the inner tube (fig. 5-6) for the two annulus sizes, while this fact becomes invalid for the $e$ =2.2 mm wire coil or circular rib where decreasing the coiling or ribbing pitch for that wire or rib diameter means decreasing heat transfer rate (fig. 5-7 and 5-8).

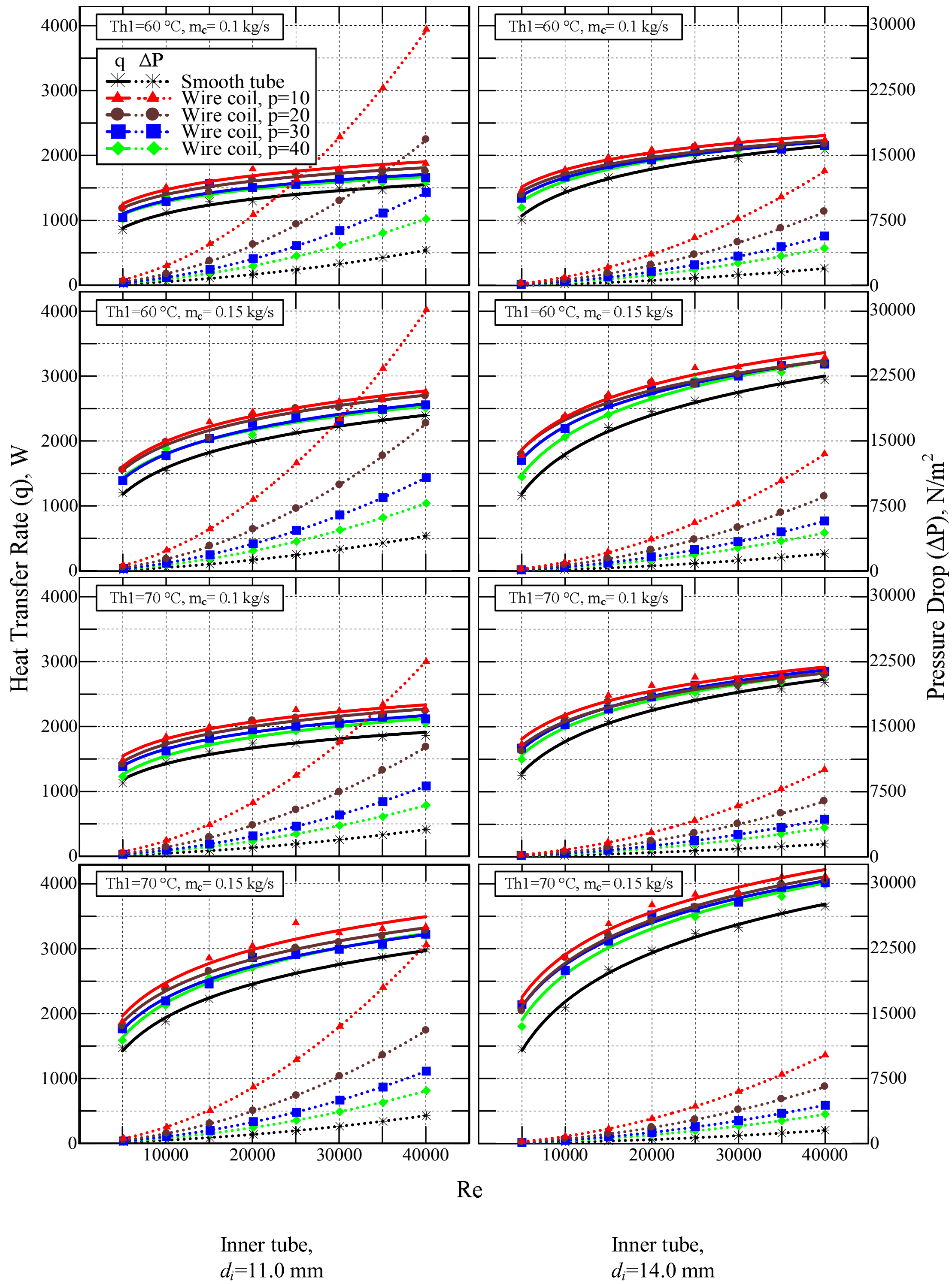



**Figure 5-5:** Heat transfer rate (W) and pressure drop (N/m$^2$) vs. Reynolds number for tube-side heat transfer enhancement using a wire coil of $e$ = 1 mm for two inner tube sizes and four experimental conditions (Notation above belongs to all cases).

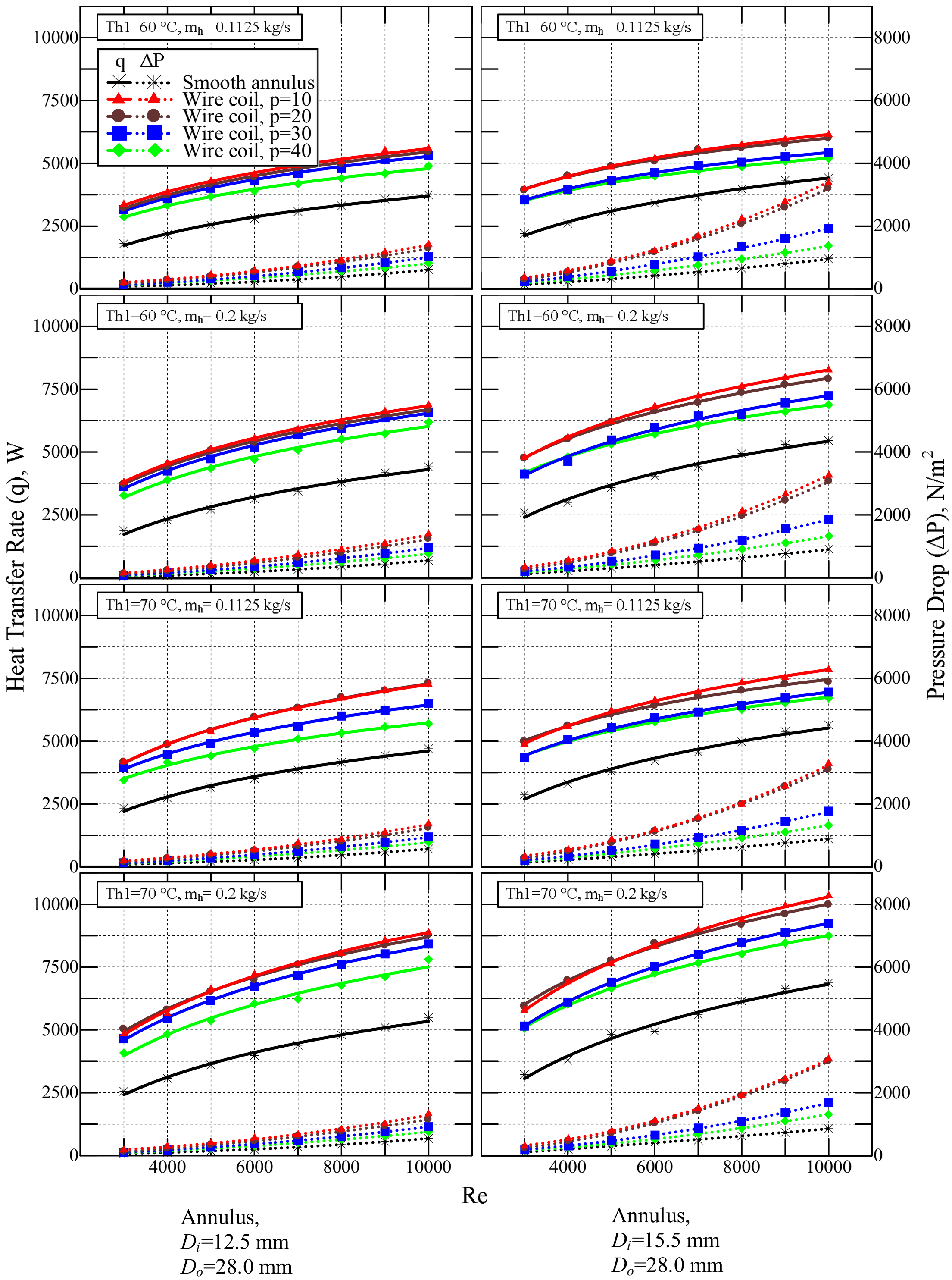



**Figure 5-6:** Heat transfer rate (W) and pressure drop ($N/m^2$) vs. Reynolds number for annulus-side heat transfer enhancement by wire coils of $e$ = 1 mm for two annulus sizes and four experimental conditions (Notation above belongs to all cases).

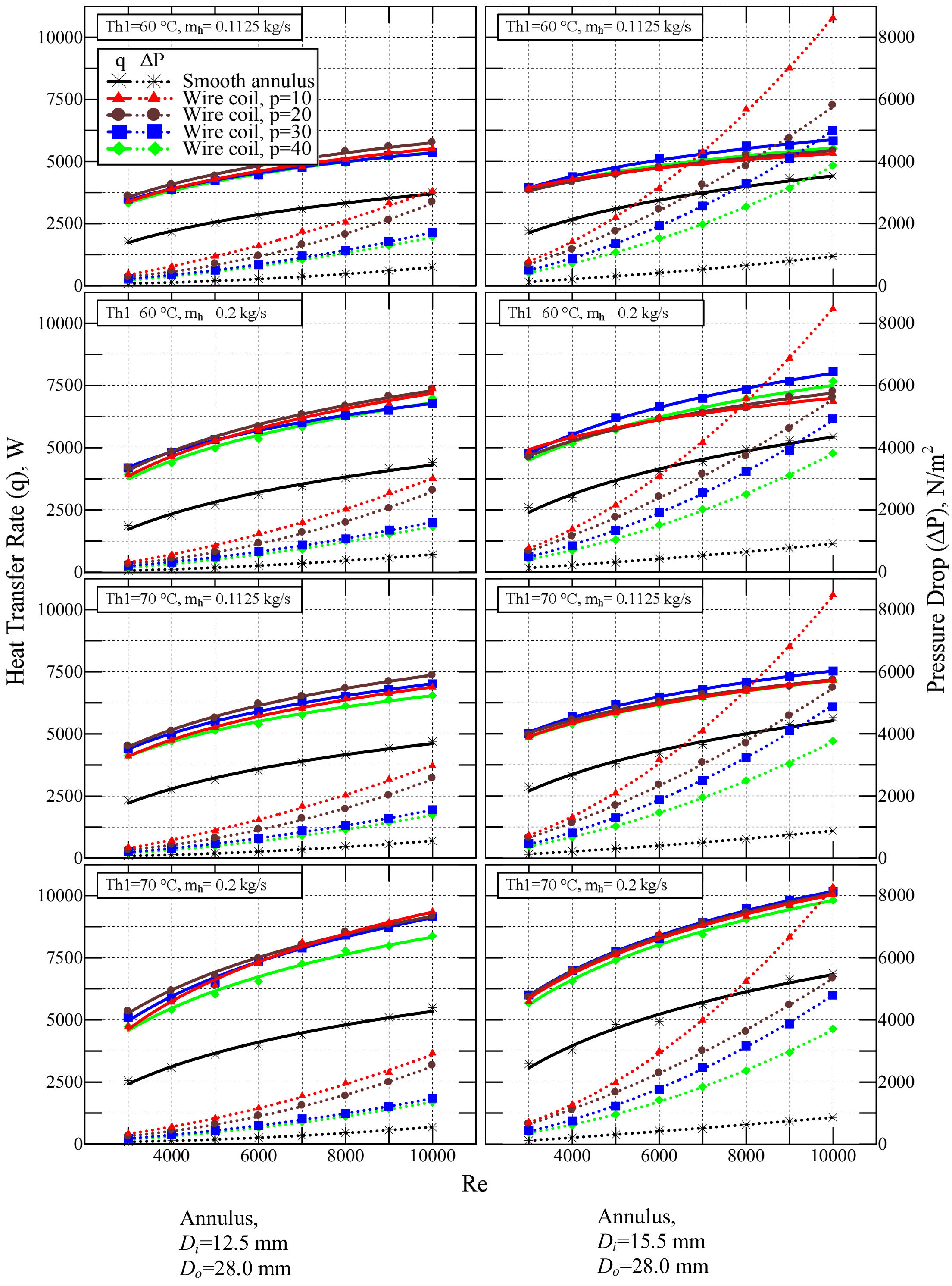



**Figure 5-7:** Heat transfer rate (W) and pressure drop (N/m$^2$) vs. Reynolds number for annulus-side heat transfer enhancement by wire coils of $e$ = 2.2 mm for two annulus sizes and four experimental conditions (Notation above belongs to all cases).

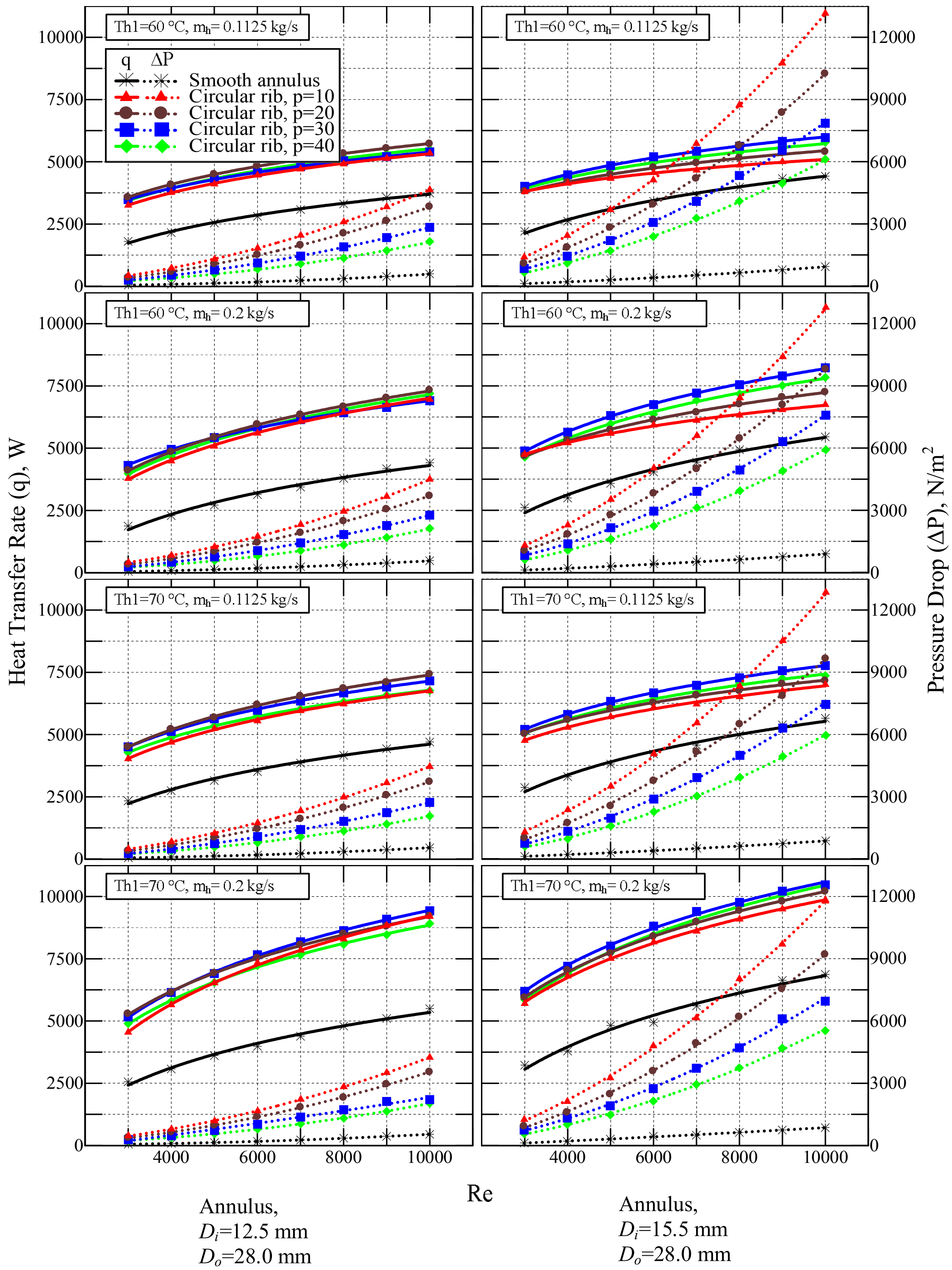



**Figure 5-8:** Heat transfer rate (W) and pressure drop (N/m$^2$) vs. Reynolds number for annulus-side heat transfer enhancement by circular ribs of $e$ = 2.2 mm for two annulus sizes and four experimental conditions (Notation above belongs to all cases).

## 5.4 Effect of Turbulence Promoters on Friction Factor

Two collections of friction factor were obtained for each promoter used to augment heat transfer. The first is that for real heat exchange process. These values of friction factor, graphically or in correlation form, would be used for comparisons and PECs to study the effect and usefulness of each insert. The second is that for isothermal operation conditions. The latter might be converted to correlations to be used in design of heat exchangers.

### 5.4.1 Friction Factor in Heat Exchange Process

Friction factor inside the inner tube and annulus either smooth or with wire coil inserts (for all wire diameters adopted), have been calculated using the experimental values of pressure drop using equation (3.4), as tabulated in tables C-19 through C-36 and plotted in fig. 5-9 through 5-12 versus Reynolds number.

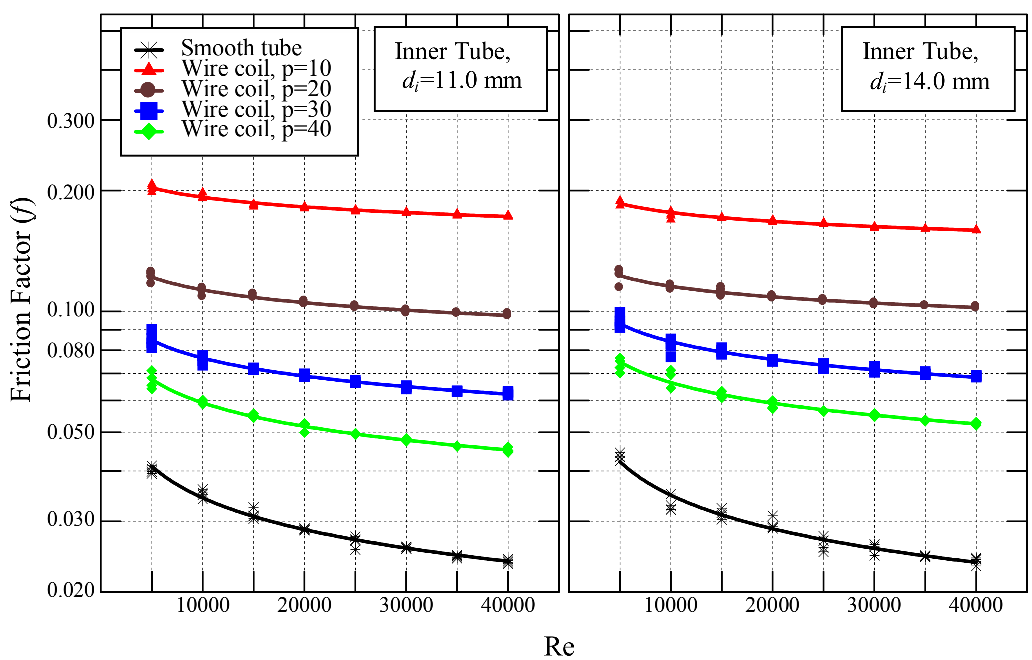



**Figure 5-9:** Friction factor vs. Reynolds number for heat exchange process inside the inner tube inserted with a wire coil of $e$ = 1 mm for two inner tube sizes.

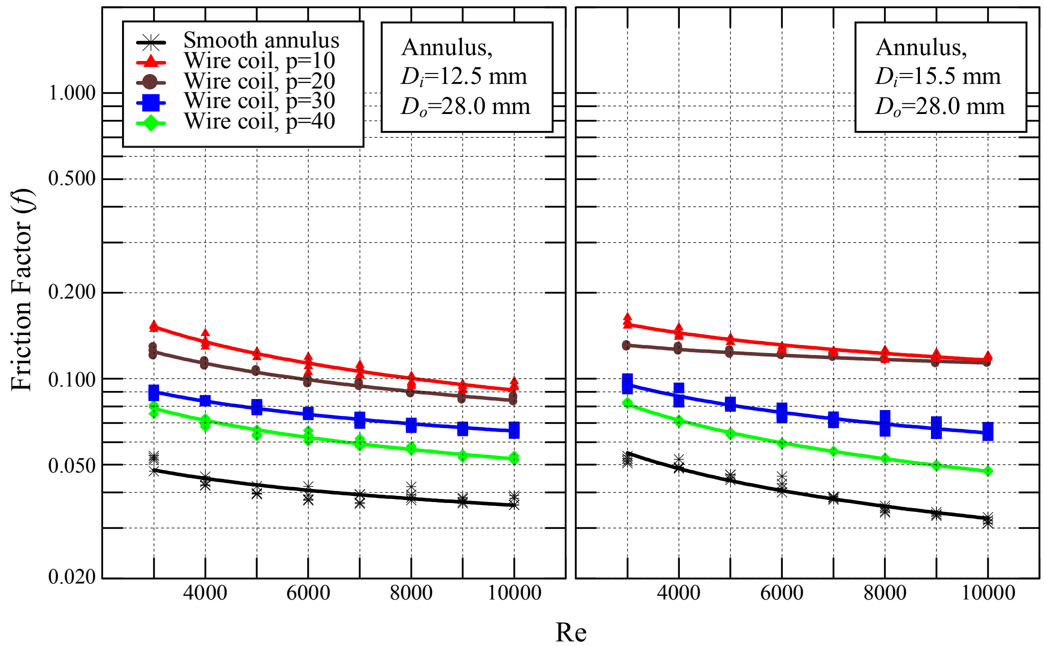



**Figure 5-10:** Friction factor vs. Reynolds number for annulus-side heat transfer enhancement by wire coils of $e$ = 1 mm (heat exchange process) for two annulus sizes.

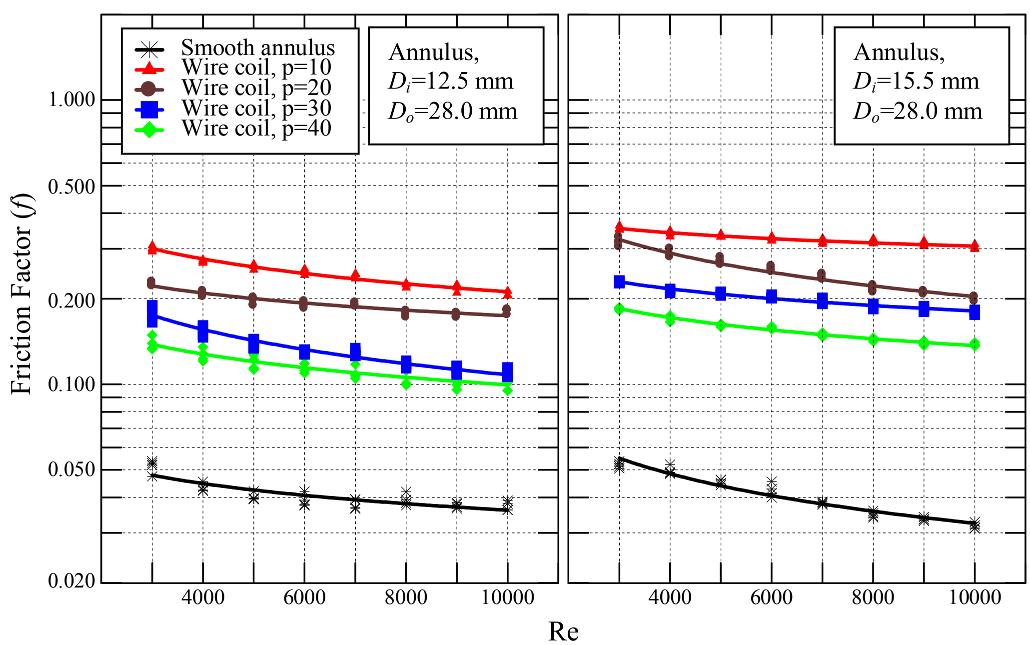



**Figure 5-11:** Friction factor vs. Reynolds number for annulus-side heat transfer enhancement by wire coils of $e$ = 2.2 mm (heat exchange process) for two annulus sizes.

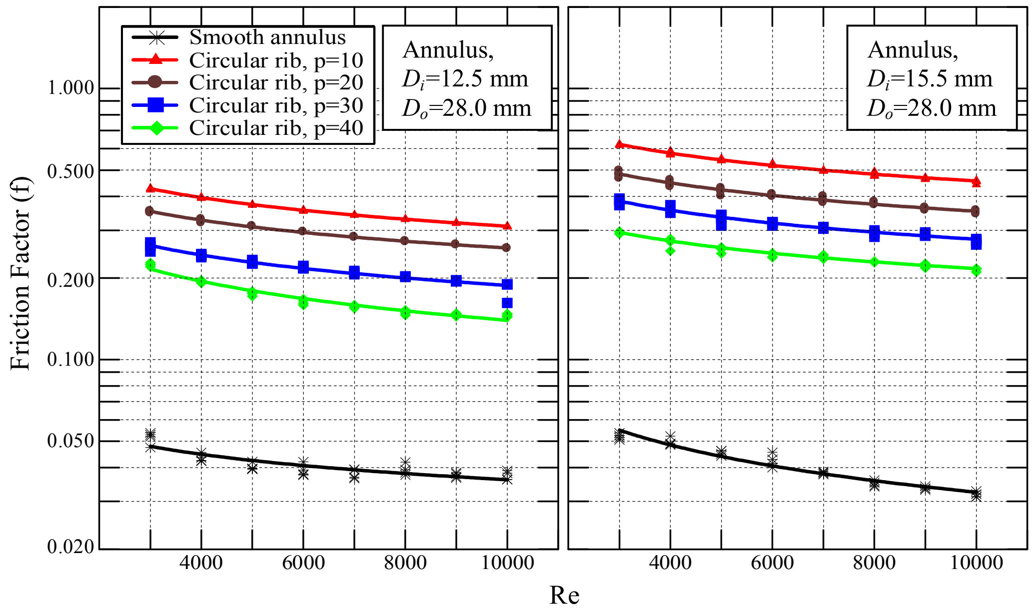



**Figure 5-12:** Friction factor vs. Reynolds number for annulus-side heat transfer enhancement by circular ribs of $e$ = 2.2 mm (heat exchange process) for two annulus sizes.

In figs. 5-9 through 5-12, no sign for the operational conditions have been included and the curve fit represented the average value of friction factor for the four operation conditions for each case considered, because only the geometrical parameters, in addition to Reynolds number, would be included in the proposed correlations produced in the present work. That would be in a similar manner to those appearing in Petukhov equation for smooth tubes or the previous works [1, 2, 8, 9, 10, 11, 35, 51, and 52] for augmented tubes.

### 5.4.2 Friction Factor in Isothermal Process.

That was performed by using similar calculations to that adopted in heat exchange process but with using the isothermal pressure drop values. Isothermal pressure drop and friction factor obtained are tabulated in tables C-37 through C-40) and plotted in figs. 5-13 through 5-16 versus Reynolds number.

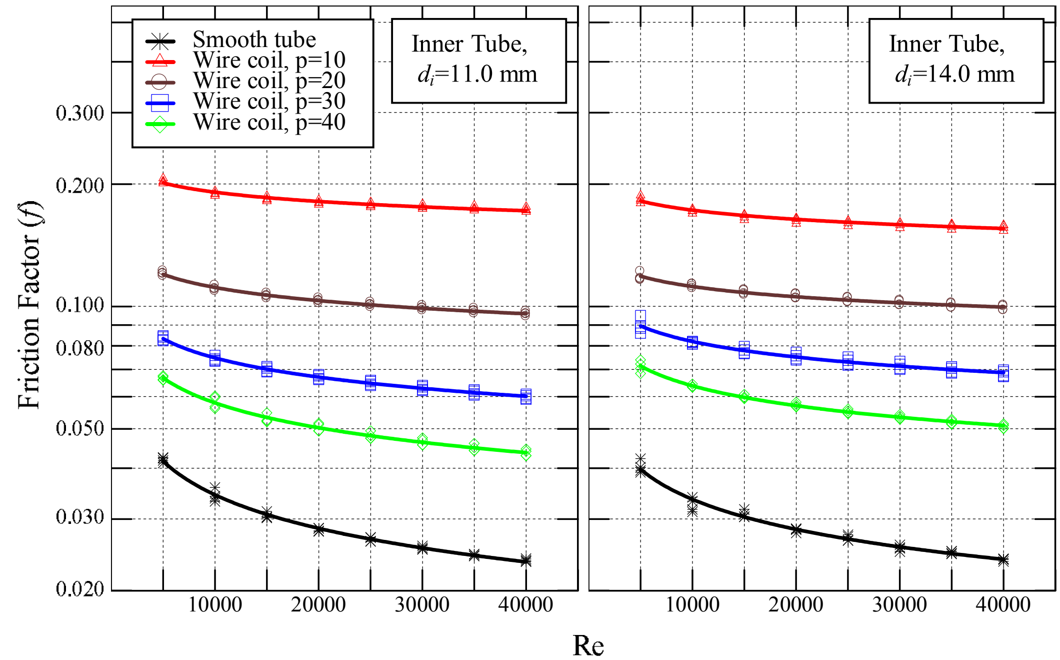



**Figure 5-13:** Friction factor vs. Reynolds number for smooth tube and roughened by a wire coil of $e$ = 1 mm in isothermal conditions for two inner tube sizes.

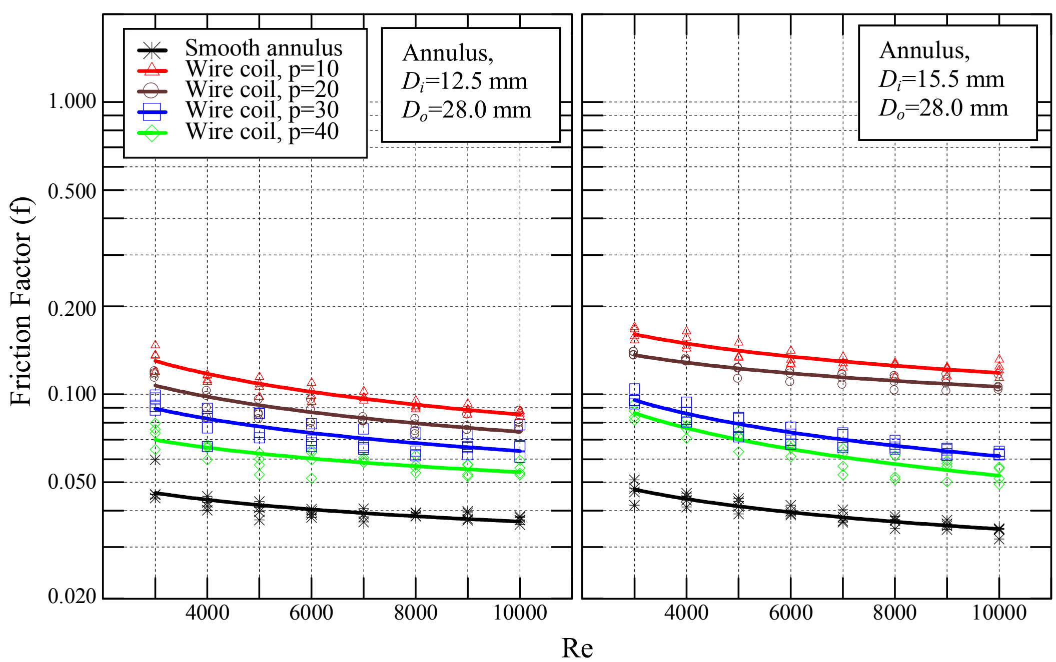



**Figure 5-14:** Friction factor vs. Reynolds number for smooth annulus and with a wire coil of $e$ = 1 mm in isothermal conditions for two annulus sizes.

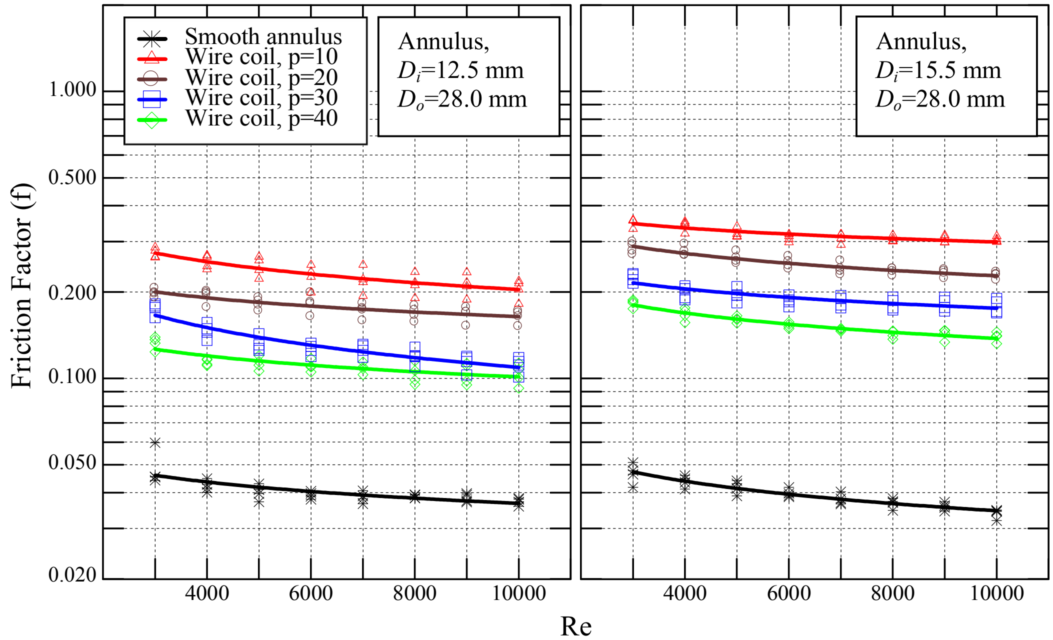



**Figure 5-15:** Friction factor vs. Reynolds number for smooth annulus and with a wire coil of $e$ = 2.2 mm in isothermal conditions for two annulus sizes.

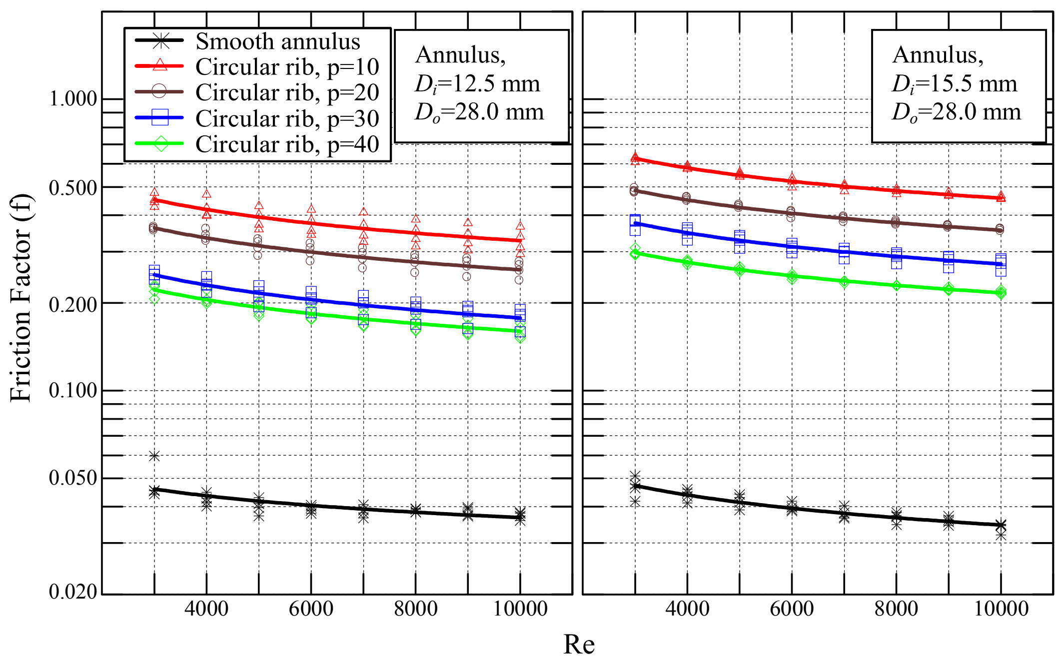



**Figure 5-16:** Friction factor vs. Reynolds number for smooth annulus and with circular ribs of $e$ = 2.2 mm in isothermal conditions for two annulus sizes.

## 5.5 Effect of Turbulence Promoters on Heat Transfer

In addition to friction factor, heat transfer represented by Nusselt number is the most important factor might be studied in a heat transfer enhancement study, because it might be considered as the real indication to the variations in heat transfer in smooth tubes or those obtained by using turbulence promoters, rather than heat transfer rate plotted in figs. 5-5 through 5-8. Nusselt number values for different types of inserts, different positions, different tube or annulus sizes, and operational conditions are tabulated in tables C-19 through C-36 and plotted in figs. 5-17 through 5-20.

In these plots, the adopted operation conditions are strictly considered because they are the only way to indicate to the Prandtl number which is importantly included in all Nusselt number relationships either for smooth or roughened tubes and annuli.

Similar to relationships of heat transfer rate, the Nusselt number versus Reynolds number curve fits behave, where Nusselt number, for different conditions, increases with Reynolds number and coiling pitch in case of tube-side heat transfer enhancement while that does not occur in the other two cases and the same statement can be said for the variation in wire diameter.

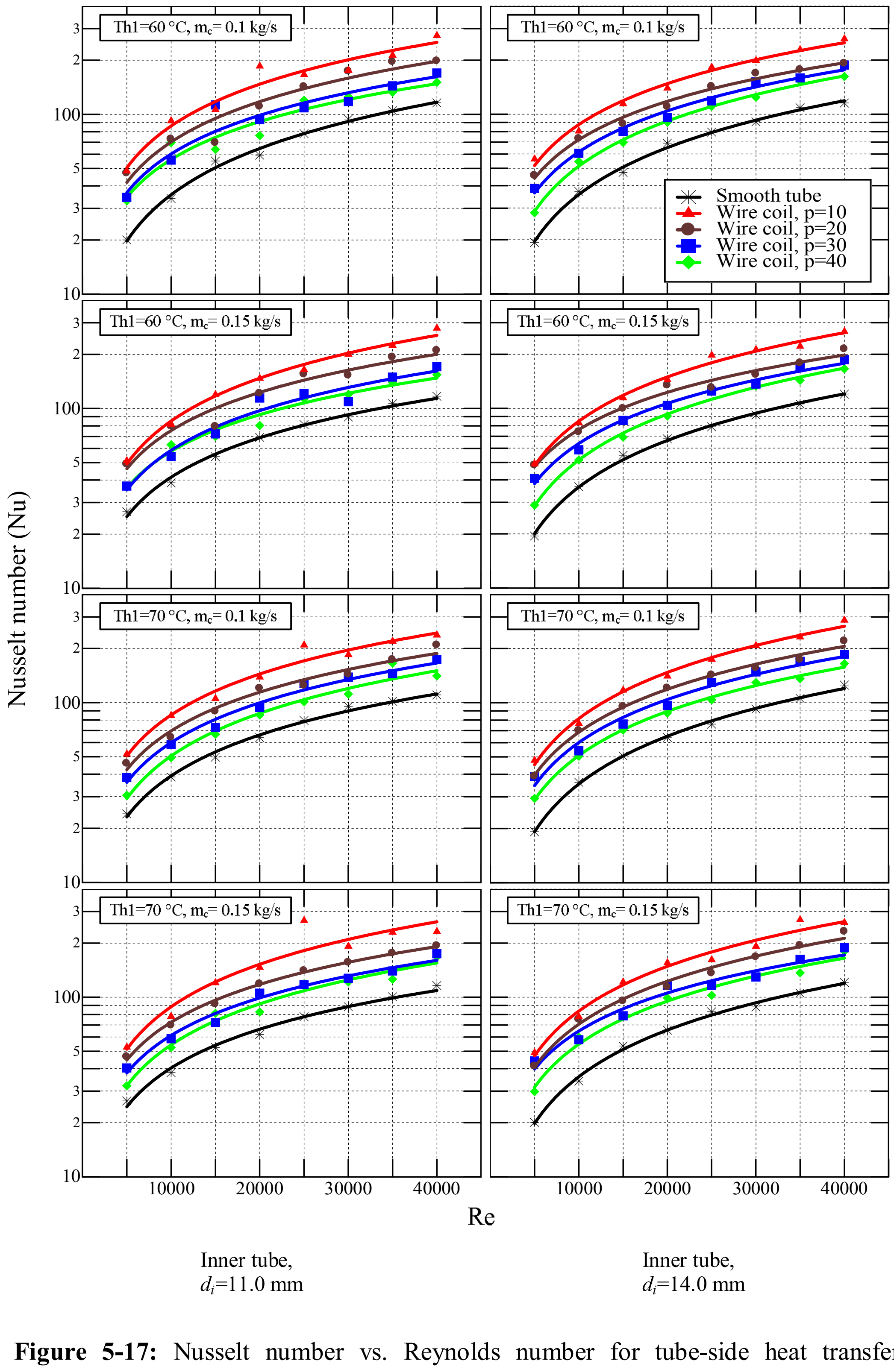



**Figure 5-17:** Nusselt number vs. Reynolds number for tube-side heat transfer enhancement using a wire coil of $e$ = 1 mm for two inner tube sizes and four experimental conditions (Notation above belongs to all cases).

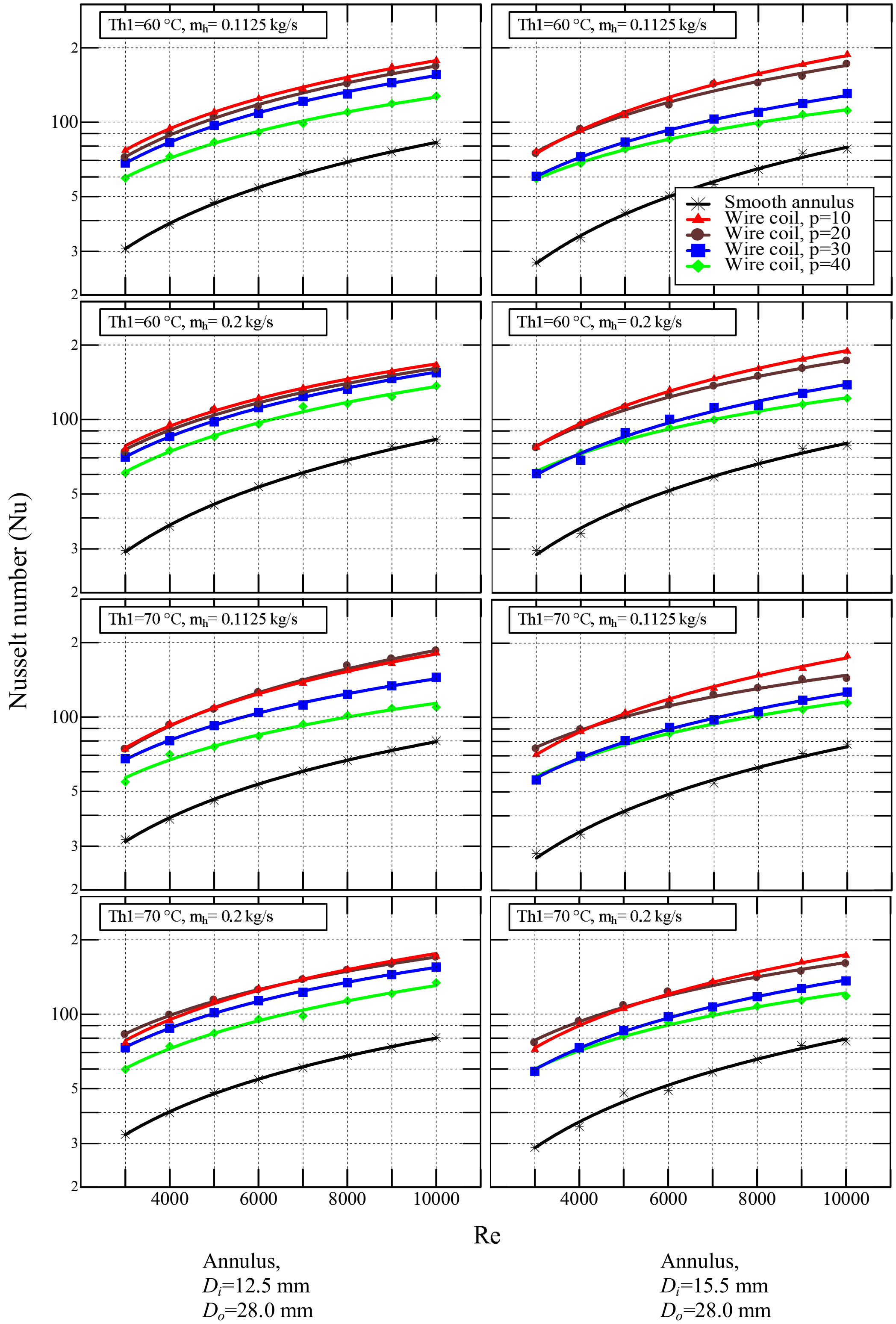
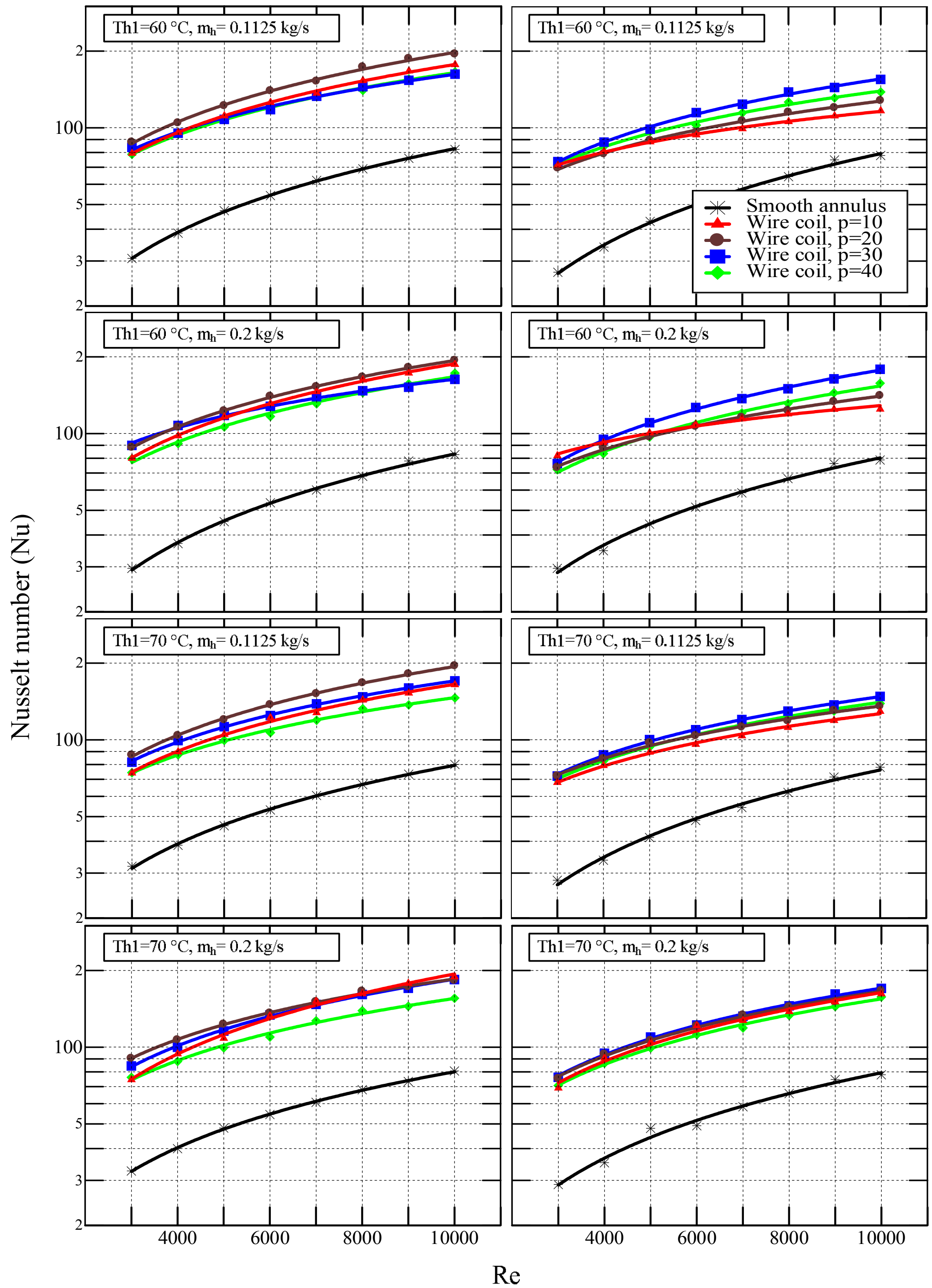


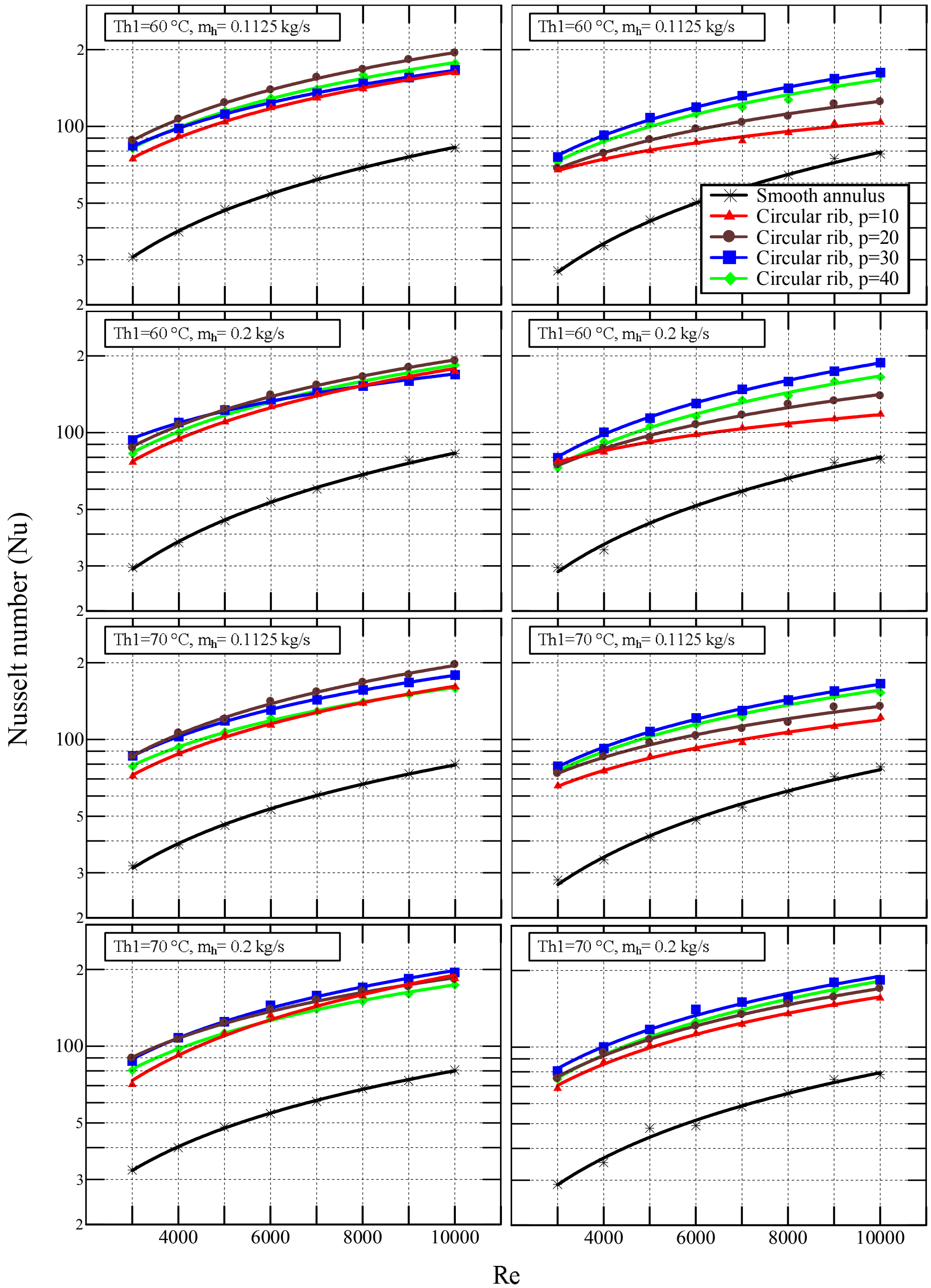

**Figure 5-18:** Nusselt number vs. Reynolds number for annulus-side heat transfer enhancement using a wire coil of $e$ = 1 mm for two annulus sizes and four experimental conditions (Notation above belongs to all cases).




Annulus,
$D_i$=12.5 mm
$D_o$=28.0 mm

Annulus,
$D_i$=15.5 mm
$D_o$=28.0 mm

**Figure 5-19:** Nusselt number vs. Reynolds number for annulus-side heat transfer enhancement using a wire coil of $e$ = 2.2 mm for two annulus sizes and four experimental conditions.




Annulus,
$D_i$=12.5 mm
$D_o$=28.0 mm

Annulus,
$D_i$=15.5 mm
$D_o$=28.0 mm

**Figure 5-20:** Nusselt number vs. Reynolds number for annulus-side heat transfer enhancement using circular ribs of $e$ = 2.2 mm for two annulus sizes and four experimental conditions.

## 5.6 Proposed Correlations of Friction Factor and Nusselt Number.

Comprehensive correlations of friction factor and Nusselt number can be proposed for the three heat transfer enhancement methods. Like these correlations must include all geometrical parameters and operation conditions which are thought to influence the friction factor and Nusselt number. The first step is describing the studied inserts concisely in terms of the most effective geometrical parameters.

### 5.6.1 Concise Description of Inserts.

A concise description of inserts used in the present work has been accommodated in terms of the most effective geometrical parameters which can be summarized as:

$\left(\frac{e}{d_i}\right)$ or $\left(\frac{e}{D_e}\right)$: This parameter represents the effect of the wire or circular rib diameter related to the inner diameter of the tube or the equivalent diameter of the annulus.

$\left(\frac{p}{d_i}\right)$ or $\left(\frac{p}{D_e}\right)$: This parameter represents the effect of the coiling or ribbing pitch related to the inner diameter of the tube or the equivalent diameter of the annulus.

The values of these parameters are set in table C-41.

### 5.6.2 Proposed Correlations of Friction Factor

Curve fits in figures 5-9 through 5-16 each apart represents a correlation for friction factor versus Reynolds number for the intended inner tube or annulus with particular insert type, position of installation, size of tube or annulus or operation conditions. To have more useful correlations of friction factor to be used in comparing the efficiency of different turbulence promoters in augmenting heat transfer or to be used in heat transfer equipment design, 256 points of friction factor versus Reynolds number for four heat exchange conditions inside the inner tube of the double pipe heat exchanger which have been used in plotting the mentioned figures ware admitted together into the STATISTICA software package (a computer software concerned with statistical calculations) to produce a comprehensive empirical correlation of friction factor as a function of Reynolds number, and the two parameters ($e/d_i$) and ($p/d_i$) whose values are calculated for tube-side in table C-41. The correlation proposed is:

$$f_a = 3.6346 \,\mathrm{Re}^{-0.0964} \left(\frac{e}{d_i}\right)^{0.8912} \left(\frac{p}{d_i}\right)^{-0.7856} \qquad \text{... (5.1)}$$

Equation (5.1) has a coefficient of determination of 0.9915. The latter may be defined as the criterion often used to judge the adequacy of a regression model [67].

Using the 256 friction factor points obtained for isothermal pressure drop experiments (plotted in fig. 5-13 except those for smooth tube), a similar correlation with a coefficient of determination equal to 0.9912 was obtained for isothermal operation conditions. That is:

$$f_a = 4.1497 \,\mathrm{Re}^{-0.0945} \left(\frac{e}{d_i}\right)^{0.9576} \left(\frac{p}{d_i}\right)^{-0.7963} \qquad \text{... (5.2)}$$

The validity of equations (5.1) and (5.2) is in the range of Reynolds number of 5000 to 40000, $e/d_i$ = 0.0714 to 0.0909 and $p/d_i$ = 0.7143 to 3.6364. Of course, equation (5.2) is more authenticable than equation (5.1), because the latter has been created using points fixed in isothermal conditions which mean real physical properties to be used in calculating the Reynolds number, while Reynolds number calculated using physical properties at arithmetic mean temperature.

For the case of annulus-side heat transfer enhancement using a wire coil set up on the outer surface of the inner tube, 512 friction factor versus Reynolds number points (used in fig. 5-10 and 5-11 except those for smooth tube) are available to be used in correlating an empirical equation for the friction factor as a function of Reynolds number and ($e/D_e$) and ($p/D_e$). That is

$$f_a = 16.0619\,\mathrm{Re}^{-0.2491}\left(\frac{e}{D_e}\right)^{1.0872}\left(\frac{p}{D_e}\right)^{-0.4652} \qquad \ldots (5.3)$$

Equation (5.3) has a coefficient of determination of 0.9709. An attempt to improve the value of that criterion (or enhancing the accuracy of equation (5.3)), may be by enforcing a new parameter which may be thought to be an influence in the friction factor in the annulus. That is the ratio of the inner to outer diameter of the annulus or ($D_i/D_o$), which has the value of 0.4464 and 0.5536 for the annulus of $D_i$= 12.5 mm and $D_o$=28.0 mm and $D_i$= 15.5 mm and $D_o$=28.0 mm respectively. The resulting correlation is

$$f_a = 21.8417\,\mathrm{Re}^{-0.2467}\left(\frac{e}{D_e}\right)^{1.0126}\left(\frac{p}{D_e}\right)^{-0.4870}\left(\frac{D_i}{D_o}\right)^{0.6875} \qquad \ldots (5.4)$$

with a coefficient of determination something larger than that of equation (5.3) to be equal to 0.9820. For the isothermal operation conditions, also the 512 points (used in fig. 5-14 and 5-15 except those for smooth tube) are available to be used to obtain an equation similar to equation (5.3). That is:

$$f_a = 11.5288\,\mathrm{Re}^{-0.2088}\left(\frac{e}{D_e}\right)^{1.1142}\left(\frac{p}{D_e}\right)^{-0.4479} \qquad \ldots (5.5)$$

which has a coefficient of determination of 0.9636, but inserting the parameter ($D_i/D_o$) enables having an equation with larger coefficient of determination of 0.9829 with producing the following equation

$$f_a = 17.4238\,\mathrm{Re}^{-0.2069}\left(\frac{e}{D_e}\right)^{1.0108}\left(\frac{p}{D_e}\right)^{-0.4774}\left(\frac{D_i}{D_o}\right)^{0.9179} \qquad \ldots (5.6)$$

Equations (5.4) and (5.6) are valid for the range of Reynolds number of 3000 to 10000, $D_i/D_o$=0.4464 to 0.5536, $e/D_e$= 0.0645 to 0.176 and $p/D_e$ = 0.6452 to 3.2.

The third part of the present work was using circular ribs set up on the outer surface of the inner tube. Using the 256 points of friction factor versus Reynolds number plotted in fig. 5-12 except those of smooth tube gives the equation:

$$f_a = 204.7049\,\mathrm{Re}^{-0.2666}\left(\frac{e}{D_e}\right)^{2.1579}\left(\frac{p}{D_e}\right)^{-0.4821}\left(\frac{D_i}{D_o}\right)^{0.0001} \qquad \ldots (5.7)$$

with a coefficient of determination of 0.9833 while the empirical correlation for friction factor under isothermal conditions is obtained by adopting the 256 points plotted in fig. 5-16 (except those for smooth annulus) to obtain equation (5.8) with a coefficient of determination of 0.9803

$$f_a = 169.1513\,\mathrm{Re}^{-0.2657}\left(\frac{e}{D_e}\right)^{2.0482}\left(\frac{p}{D_e}\right)^{-0.4967}\left(\frac{D_i}{D_o}\right)^{0.0001} \qquad \ldots (5.8)$$

Equations (5.7) and (5.8) look not greatly dependent on the parameter ($D_i/D_o$) as its power seems. They are valid for the range of Reynolds number of 3000 to 10000, $D_i/D_o$= 0.4464 to 0.5536, $e/D_e$ = 0.1419 to 0.1760 and $p/D_e$= 0.6452 to 3.2.

In the subsequent calculations, correlations of friction factor for smooth tube and annulus under heat exchange conditions are needed. For the smooth tube, friction factor as a function of Reynolds number could be obtained using data depicted in table C-1. The best fit is

$$f_s = 0.4185 \,\mathrm{Re}^{-0.2708} \quad \text{... (5.9)}$$

having a coefficient of determination of 0.9847 and validity for water with the range of Reynolds number of 5000 to 40000. For smooth annulus, the friction factor correlation using the data in table C-5 is

$$f_s = 0.8168 \mathrm{Re}^{-0.3395} \left( \frac{D_i}{D_o} \right)^{0.0672} \quad \text{... (5.10)}$$

with a coefficient of determination of 0.9123. Equation (5.10) is valid for water flowing in an annulus of ($D_i/D_o$) of 0.4464 to 0.5536 for the range of Reynolds number of 3000 to 10000.

### 5.6.3 Proposed Correlations of Nusselt Number

Making use of the STATISTICA software, empirical equations for the Nusselt number as a function of Reynolds number, geometrical characteristics of inserts (table C-41) and the inner tube and annuli, and Prandtl number which plays a vital role in heat transfer can be obtained for the three cases studied in the present work. In case of the tube-side heat transfer enhancement, it is expected that the affecting factors in the final correlation of Nusselt number are the Reynolds number, Prandtl number, and the geometrical parameters ($e/d_i$) and ($p/d_i$). Using the 256 points of Nusselt number plotted in fig. 5-17 give equation (5.11) which has a coefficient of determination of 0.9796.

$$\overline{N}u_a = 0.0668\,\mathrm{Re}^{0.7938}\,\mathrm{Pr}^{0.2741}\left(\frac{e}{d_i}\right)^{0.2049}\left(\frac{p}{d_i}\right)^{-0.3532} \quad \ldots (5.11)$$

Equation (5.11) is valid for the range of Reynolds number of 5000 to 40000, $e/d_i$ = 0.0714 to 0.0909 and $p/d_i$ = 0.7143 to 3.6364. In addition, this equation is valid for water only in the range of temperatures employed in the hot fluid stream of the present work which is about 50 to 70 °C.

For the case of annulus-side heat transfer enhancement using wire coil set up on the outer surface of the inner tube, the form of the correlation of Nusselt number is expected to be more complicated than that of tube-side heat transfer enhancement. The best curve fit of the 512 points of Nusselt number plotted in figs. 5-18 and 5-19 that might be suggested is the equation

$$\overline{N}u_a = 0.002\,\mathrm{Re}^{1.1462\left(\frac{e}{D_e}\right)^{0.2464}\left(\frac{p}{D_e}\right)^{0.1475}}\,\mathrm{Pr}^{0.3} \times\left[\frac{\left(\frac{e}{D_e}\right)^{-0.8156}}{\left(\frac{e}{D_e}\right)^{2.5892}+0.01}\right]\left[\frac{\left(\frac{p}{D_e}\right)^{-0.5503}}{\left(\frac{p}{D_e}\right)^{1.515}+3.8717}\right]\left(\frac{D_i}{D_o}\right)^{-0.3823} \quad \ldots (5.12)$$

which has a coefficient of determination of 0.9563. This correlation is considered to be valid for the range of Reynolds number of 3000 to 10000, $D_i/D_o$=0.4464 to 0.5536, $e/D_e$= 0.0645 to 0.176 and $p/D_e$ = 0.6452 to 3.2.

For the case of annulus-side heat transfer enhancement using circular ribs set up on the outer surface of the inner tube the best curve fit of the 256 points plotted in fig. 5-20 is the following equation:

$$\overline{Nu}_a = 0.1006\,\mathrm{Re}^{0.3298\left(\frac{e}{D_e}\right)^{-0.4696}\left(\frac{p}{D_e}\right)^{-0.0645}}\,\mathrm{Pr}^{0.29}$$

$$\times\left[\frac{\left(\dfrac{e}{D_e}\right)^{0.0527}}{\left(\dfrac{e}{D_e}\right)^{-2.3452}+0.5044}\right]\left[\frac{\left(\dfrac{p}{D_e}\right)^{0.51}}{\left(\dfrac{p}{D_e}\right)^{0.001}-0.983}\right]\left(\frac{D_i}{D_o}\right)^{-0.12} \quad \text{... (5.13)}$$

which has a coefficient of determination of 0.9503 and valid for the range of Reynolds number of 3000 to 10000, $D_i/D_o$=0.4464 to 0.5536, $e/D_e$= 0.1419 to 0.1760 and $p/D_e$ = 0.6452 to 3.2. Equations (5.12) and (5.13) are valid to be used for water in the range of temperature of about 20 to 35 °C.

For smooth tube, the empirical correlations of Nusselt number corresponding to equation (3.12) is

$$\overline{Nu}_s = 0.013\,\mathrm{Re}^{0.833}\,\mathrm{Pr}^{0.265} \quad \text{... (5.14)}$$

with a coefficient of determination of 0.9952, and for the smooth annulus, it is

$$\overline{Nu}_s = 0.0124\,\mathrm{Re}^{0.843}\,\mathrm{Pr}^{0.45}\left(\frac{D_i}{D_o}\right)^{-0.2392} \quad \text{... (5.15)}$$

having a coefficient of determination of 0.9947 and valid for $D_i/D_o$=0.4464 to 0.5536. The last two correlations are valid for water with the ranges of Prandtl and Reynolds number adopted in the present work.

It is important to mention that equations (5.9) and (5.10) and equations (5.14) and (5.15) are assumed to be more accurate than Petukhov and Gnielinski equation respectively, for the double pipe heat exchanger used in the present work including the deviation values depicted in table 5-1.

# CHAPTER SIX

# Discussion

## 6.1 Introduction

The study of heat transfer enhancement in heat exchangers by mechanical methods, like those adopted in the present work, consists of two principal results; the first is the gain of the enhancement process represented by augmentation of heat transfer (Nusselt number), and the second is the penalty paid for this gain; it is the growth of friction factor which is axiomatically followed by increasing pumping power. In general, implementation of the aim for which, one suggests to enhance or design an enhanced heat exchanger, is based on the judgment whether the followed method is beneficial or not.

## 6.2 The Influence of the Experimental Conditions

In the present work, the variation of the operational conditions, represented by the mass flow rate of the unenhanced side and the inlet temperature of the hot fluid stream (60 or 70 °C) have given the chance to have a large quantity of experimental data to correlate as accurate relationships as possible, either for friction factor or Nusselt number. These variations are the only way available to have a variety in the physical properties especially in the calculations of Nusselt number. These properties are briefly expressed by Prandtl number which has a vital role in heat transfer since it relates the convective and conductive heat transfer in the fluid as being a function of temperature [64]. Prandtl number in the present work has been varied from 2.6 to 3.4 in hot fluid stream in tube-side heat transfer enhancement experiments and from 5.5 to 6.5 in cold fluid stream in annulus-side heat transfer enhancement experiments. So these ranges do not represent wide scopes to consider that the experimental results, obtained assess the proper influence of Prandtl number. Hence, using different liquids as the working fluid or by adding different quantities of a particular substance like propylene glycol to water may produce an enough variation of Prandtl number [8].

The change of the experimental conditions represented by changing the mass flow rate of cold fluid stream in case of tube-side enhancement or by changing the mass flow rate of hot fluid stream in case of annulus-side enhancement, both at a given inlet temperature of hot fluid stream, have given an observable change in heat transfer rate as shown in figs. 5-5 through 5-8. That is axiomatic since that any change in the mass flow rate of the unenhanced side would affect the heat transfer coefficient in that side and then affect the heat transfer coefficient leading to influence heat transfer rate in the enhanced side through equation (3.35) or (3.36). Accidentally that change is leading to a slight change in Prandtl number which could not be considered as an effective influence on heat transfer.

On the other hand, changing the hot fluid temperature, for both enhancement cases, affects directly Prandtl number which leads to affect the heat transfer not only in the hot fluid stream but also in the other side. In another word, raising the hot fluid inlet temperature (in case of tube-side enhancement) leads to lower Prandtl number which leads to lower heat transfer, represented by Nusselt number and not the heat transfer rate which axiomatically increases due to the increase in temperature difference. This is obvious in fig. 5-17, where for the two tube sizes, values of Nusselt number in case of hot fluid temperature is70 °C, are lower than those when it is 60 °C.

The same behavior happens, but with lesser magnitude, when the case is the annulus-side enhancement, where raising the hot fluid inlet temperature means making the other side working at higher temperature which leads to lower the Prandtl number and then lowering the Nusselt number as shown in figs. 5-18 through 5-20, i.e., relatively lowering heat transfer. The whole situation is agreeing with the information concerning heat transfer in smooth tubes or annuli as in equations (3.8) and (3.12) or with that of Arman and Rabas [59, 60] for ribbed surfaces to enhance heat transfer as discussed in chapter three but to a lesser degree that cannot be considered as picturing the relationship between the heat transfer and Prandtl number.

What happens for the pressure drop or friction factor, either in heat exchange or isothermal conditions, starting with the tube-side enhancement (fig. 5-5), is that raising the mass flowrate of the unenhanced side (in heat exchange conditions) means raising heat transfer and then lowering the mean temperature of the other side. That means that the enhanced side fluid density will be increased, but with larger manner the viscosity will do (that is obvious in the density or viscosity versus temperature relationships as shown in appendix A). That means that the Reynolds number at which the reading is taken needs larger mass flowrate which means larger velocity, and then larger pressure drop according to equation (3.4).

The reverse occurs for the annulus-side enhancement case (figs. 5-6 through 5-8), where increasing the hot stream mass flowrate leads to increase the mean temperature of the annulus side fluid which means lowering the mass flowrate required for a particular Reynolds number and lowering the pressure drop in that stream. On the other hand, raising the inlet temperature of hot fluid, in both enhancement cases, means lowering the mass flowrate required for a particular Reynolds number leading to lower the pressure drop.

The friction factor, in both heat exchange and isothermal processes, has been intended to be calculated as a function of geometrical parameters in addition to Reynolds number without granting an importance to the physical properties outside the Reynolds number. As a result, the curves in figs. 5-9 through 5-16 represent the average value for each case. To reduce complexity in the coming calculations, the experimental conditions would be reduced to only two conditions that concern the working at a particular hot stream inlet temperature (60 or 70 °C), considering the average values for the two groups working at a specified mass flowrate of unenhanced side.

## 6.3 Friction Factor in Enhanced Tubes and Annuli

It is important to point out that the heat transfer enhancement by turbulence promoters is simply an action to disturb the laminar sublayer which prevents or decreases heat transfer. Such enhancement always is accompanied by pressure drop or drag due to the obstruction created by adding these turbulence promoters. So, looking for a suitable promoter, one must take into consideration reducing the pressure drop might be reached by investigating an affluent passage through which the fluid could pass with keeping the promoter to work as efficient heat transfer enhancer as possible.

### 6.3.1 The Effect of the Wire or Rib Diameter and Coiling or Ribbing Pitch on Friction Factor.

In the tube-side heat transfer enhancement, fast propagation of pressure drop or friction factor with increasing the intensity of coils or decreasing the coiling pitches of the wire coil is observed. A glance at figs. 5-9 and 5-13 shows that the friction factor in the inner tube inserted with a wire coil is developing non-linearly; for example, increasing the wire coiling from $p$=20 to $p$=10 leads to increase the friction factor about three times that when increasing the wire coiling from $p$=40 to $p$=30 with slightly greater propagation at large Reynolds numbers than that at lower ones. This fact emphasizes an attention to avoid the exaggeration in increasing the intensity of coils inside the tube even when that leads to increase heat transfer.

The friction factor recorded in case of the annulus-side enhancement using wire coil set up on the outer surface of the inner tube (figs. 5-10, 5-11, 5-14, and 5-15) is affected by the wire diameter or ($e/D_e$) as well as coiling pitches or ($p/D_e$) giving friction factor values in case of wire coil of $e$= 2.2 mm twice that of $e$=1 mm with the same coiling pitch and at the same Reynolds number. That is for the annulus of $D_i$=12.5 mm and with greater magnitude in case of the $D_i$=15.5 mm annulus which has a narrower annular gap. Here, the wire coil works as roughness installed on the outer surface of the inner tube helping the friction factor to increase, especially in case of $e$=1 mm. This action might be one of two causes of increasing the friction factor in case of using the $e$=2.2 mm wire, which might be considered as swirl generator around the inner tube lengthening the path of fluid flow in a similar manner to the method of enhancing heat transfer in the annulus by using a spiraling tape to induce swirl leading to more friction [34]. Also, the wire of this size might work as a series of obstacles standing in that path increasing the friction factor, especially in case of the 10 mm coiling pitch, where fluid crosses over “ribs” that the close coils might formulate [68].

The obstruction encountered in the case of using the $e$=2.2 mm wire coil becomes larger in case of using circular ribs with the same diameter giving a huge friction factor values especially in case of the annulus of $D_i$=15.5 mm where the passage of flowing becomes relatively very narrow with consecutive obstacles (circular ribs) blocking the way of fluid flow without permitting to the fluid to flow spirally around the inner tube producing, as a result, greater friction factor, reaching to one fold as compared to that of the wire coil of 2.2 mm at the same Reynolds number, as shown in figs. 5-11 and 5-12. The last observation gives an urgent fact that the spiral coil permits the fluid to flow more easily than the ribs which work as obstacles, granting no chance to the fluid to flow in ease fluency [68].

In fact, each of the two sides of figs. 5-9 or 5-13 represents an ($e/d_i$) ratio, so comparing the act of the coiling pitch in case of the tube-side heat transfer enhancement, is simply by seeing the curve fits of the same colors in the two sides of each of these figures, while comparing the effect of the coil pitch ratio ($p/d_i$) at a particular ($e/d_i$) is accessible by comparing the curve fits in the same figure side. The same description might be said for the annulus-side heat transfer enhancement methods.

### 6.3.2 The Effect of the Annulus Diameter Ratio ($D_i/D_o$)

In addition to the geometrical parameters of inserts, another parameter, ($D_i/D_o$), had appeared in the friction factor correlations in the annulus-side heat transfer enhancement, to distinguish between the two annuli used giving an importance to the extent of the annular gap. This parameter might be simply considered as a correction factor concerned with the double pipe heat exchanger, used in the present work. But, since it had appeared in values greater than the deviation values fixed in table 5-1 for the two annuli used in the present work (that can be proved easily by predicting the values of ($D_i/D_o$) with the exponents appearing in the concerned correlations). In addition, that factor had appeared in both friction factor and Nusselt number correlation, so it is apt to consider it in fluid flow and heat transfer in annulus.

In order to use this factor safely the whole boundary conditions concerning the present heat exchanger must be mentioned to give a perfect image about the authenticity of using this parameter. The boundary condition that might be absent in describing the annuli in chapter five is the effective length of the present heat exchanger which is 1.245 m, so a boundary condition including this length might be ($L/D_e$) having a value of between 80.32 and 99.60. Indeed, the parameter ($D_i/D_o$) had appeared in all correlations of friction factor belonging to the annulus either smooth or enhanced but with dissimilar exponents, so ignoring that parameter in case of the friction factor correlation for the annulus-side enhancement by circular ribs, where its exponent is close to zero, might be considered as a good approximation. Also, appearing in slight power in equation (5.10) for smooth annulus might lead to consider it as a correction factor for the present annuli.

### 6.3.3 The Effect of Disruption Shape of Insert on Friction Factor

In the three methods of heat transfer enhancement, adopted in the present work, a circular section of the enhancement devices (circular wires and ribs), have been used. This shape produces smaller friction factor than that given by a rectangular one or a shape with sharp corners but, unfortunately, produces smaller Nusselt number. This is due to the disruption effect of the owned corners [69].

### 6.3.4 The Dependency of Friction Factor on Reynolds Number

In general, dependency of friction factor on Reynolds number in the tube-side heat transfer enhancement using wire coil, as revealed in the present work, is low as compared to the dependency on the geometrical characteristics of the wire coil itself as shown in figs. 5-9 and 5-13 which are typified in equations (5.1) and (5.2). The relationship between friction factor and Reynolds number is slightly different in case of the two types of the annulus-side enhancement where the friction factor is more dependent on Reynolds number as obviously seen in figs 5-10 through 5-12 and 5-14 through 5-16 and presented in equations (5.3) through (5.8). Such observations might be considered as an agreement with the well-known Moody diagram, where the wire coil or the circular ribs might be considered as roughness on the inner or outer surface of the tube. It is to be admitted that the Reynolds number range adopted in the tube-side enhancement is larger than that adopted in the annulus-side enhancement where the dependency on Reynolds number decreases with increasing the relative roughness [38].

### 6.3.5 Friction Factor Augmentation

The friction factor augmentation is one of the most important purposes of heat transfer enhancement study, because it represents the magnitude of penalty, one might pay if he followed a specified enhancement method. It is defined by the ratio between the friction factors of enhanced (augmented) tube or annulus and that of smooth ones at the same Reynolds numbers [8,35].

#### 6.3.5.1 Friction Factor Augmentation for Tube-Side Heat Transfer Enhancement

For the tube-side heat transfer enhancement, the equation of friction factor augmentation is obtained by dividing equation (5.1) by equation (5.9). The latter represents the actual friction factor relationship of smooth tube in the present work. The produced equation is:

$$\frac{f_a}{f_s} = 8.6848\,\mathrm{Re}^{0.1744}\left(\frac{e}{d_i}\right)^{0.8912}\left(\frac{p}{d_i}\right)^{-0.7856} \quad \text{... (6.1)}$$

Inserting values of the dimensionless parameters into equation (6.1) gives values of friction factor augmentation as listed in tables C-20 through C-23 and plotted in fig. 6-1 which shows the friction factor augmentation of tube-side heat transfer enhancement by wire coil in the adopted ranges.

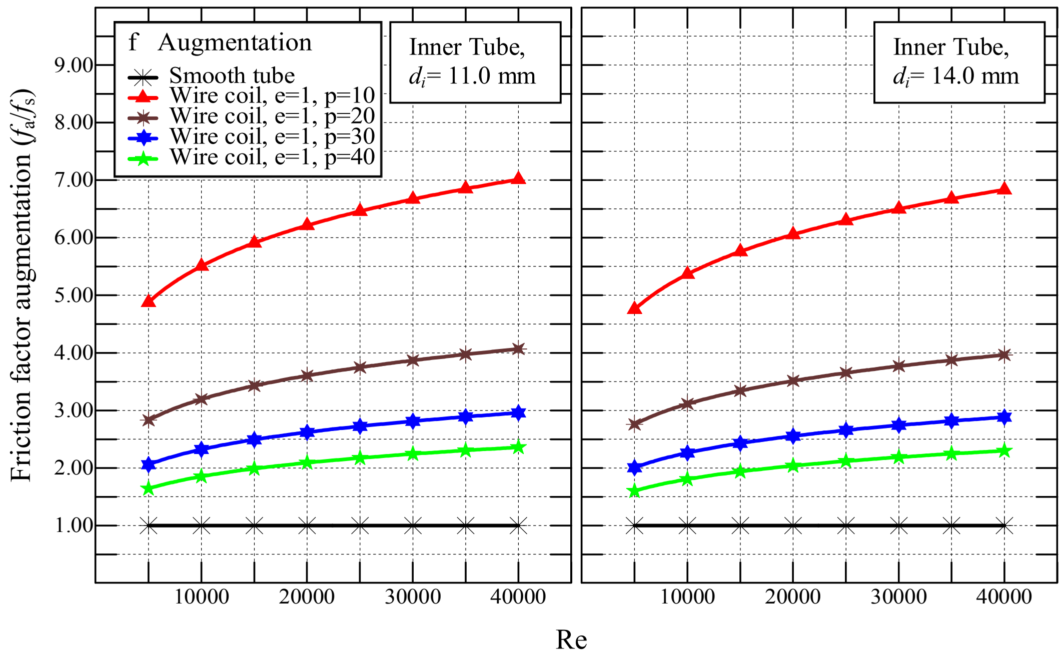



**Figure 6-1:** Friction factor augmentation vs. Reynolds number for tube-side heat transfer enhancement using a wire coil of $e$ = 1 mm for two inner tube sizes.

The maximum value recorded for friction factor augmentation is 7 times that for smooth tube. That value is for friction factor in the tube of $d_i$=11 mm inserted with a wire coil of $e$=1 mm and $p$=10 mm at Reynolds number of 40000, as compared to that of smooth tube, i.e., $e/d_i$=0.0909 and $p/d_i$=0.9091, and something less for the same values of $e$ and $p$ for the other tube size. It is obvious that the friction factor augmentation, like the friction factor itself, greatly affected by the coiling pitch or ($p/d_i$) depending largely upon Reynolds number at high ($p/d_i$) values and slightly at lower ones.

The values of friction factor augmentation calculated using equation (6.1) is agreeing with the experimental values of friction factor plotted in fig. 5-9. To have an idea about the agreement of the values obtained for the friction factor of the tube inserted with a wire coil, studied in the present work, a comparison with previous works at least for specified values of dimensionless parameters and physical properties can be performed.

As a one of the most well-known studies in the field of heat transfer enhancement by wire coils was that of Ravigururajan and Bergles in (1985) [56] which led to equation (3.22), for friction factor, and (3.21), for Nusselt number, in (1996). The friction correlation predicted 96% of the data within ±50%, and the heat transfer correlation predicted 99% of the data within ±50%. Because of the high deviation, recently, these correlations are not recommended for general use [35]. Moreover, these equations cover ranges outside those adopted in the present work.

Viedma et al., in (2005) [8] showed a comparison between their results and correlations proposed by Sethumadhavan and Rao (1982), Zhang et al., (1991), and Inaba et al., (1994) for a wire coil of $e/d_i$= 0.1 and $p/d_i$= 1.2 for turbulent flow regime. The ranges adopted by that comparison fall in the ranges adopted in the present work for ($p/d_i$), ($p/d_i$ = 0.7143 to 3.6364) and slightly larger for ($e/d_i$), ($e/d_i$ = 0.0714 to 0.0909), but for comparison, these considered values can be inserted in the proposed equation (5.1), to give fig. 6-2. It reveals good agreement of the present work results with that of Sethumadhavan and Rao and good agreement in being not largely dependent on Reynolds number with that of Zhang et al. Also the present results disagree with the results of Viedma et al. Generally, the results of Zhang et al. and Viedma et al. overpredict the results of the present work while those of Sethumadhavan and Rao, and Inaba et al. underpredict [8].

The large contradiction in the friction factor results obtained by the mentioned works and other works might be, as an interpretation suggested by Rabas [8], resulting from the vibrations of the coil and the tube and the clearance that sometimes exists between the coil and the tube wall, enforcing many authors not to correlate their experimental friction factor results [8]. In the present work, considerable care has been given to the registration of the pressure drop especially at high Reynolds numbers which increase these vibrations and always the average of many readings is considered.

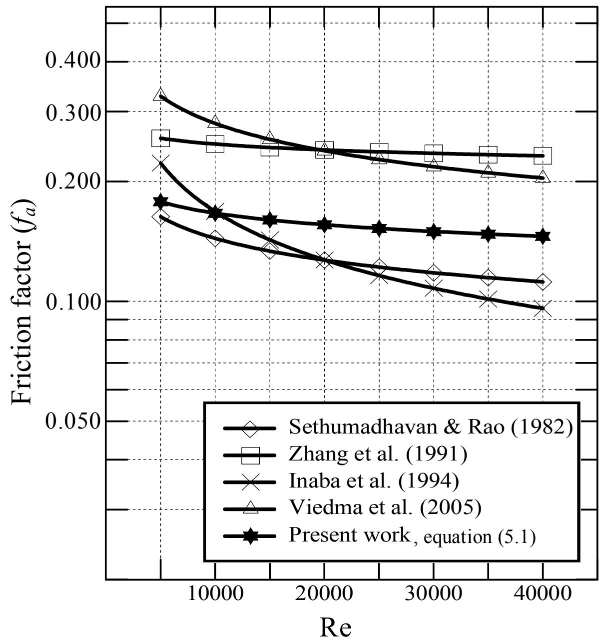



**Figure 6-2:** Comparison of present work friction factor (equation (5.1)) with that of previous works for tube-side heat transfer enhancement by wire coil of $e/d_i = 0.1$ and $p/d_i = 1.2$.

### 6.3.5.2 Friction Factor Augmentation for Annulus-Side Heat Transfer Enhancement by Wire Coil

In case of the annulus-side heat transfer enhancement using wire coil set up on the outer surface of the inner tube, the experimental results collected in the present work are more numerous than those of the first case giving a more comprehensive relationship. Here the friction factor augmentation relationship can be obtained by dividing equation (5.4) by (5.10)

$$\frac{f_a}{f_s} = 26.7406\,\mathrm{Re}^{0.0928}\left(\frac{e}{D_e}\right)^{1.0126}\left(\frac{p}{D_e}\right)^{-0.4870}\left(\frac{D_i}{D_o}\right)^{0.6203} \quad \text{... (6.2)}$$

Using equation (6.2) directly with substituting values of the geometrical parameters to obtain the values of friction factor augmentation as listed in tables C-25 through C-32 which are plotted versus Reynolds number in fig. 6-3 which indicates a huge jump in friction factor augmentation registered for the wire of $e$=2.2 mm and of greater value in case of the annulus of the smallest gap (annulus of $D_i$=15.5 mm), reaching the greatest magnitude of 8.5 as compared to smooth annulus, registered for the wire coil of $e$=2.2 wound around the inner tube of 15.5 mm outer diameter with $p$=10 mm ($e/D_e$=0.176 and $p/D_e$=0.8) at Reynolds number of 10000.

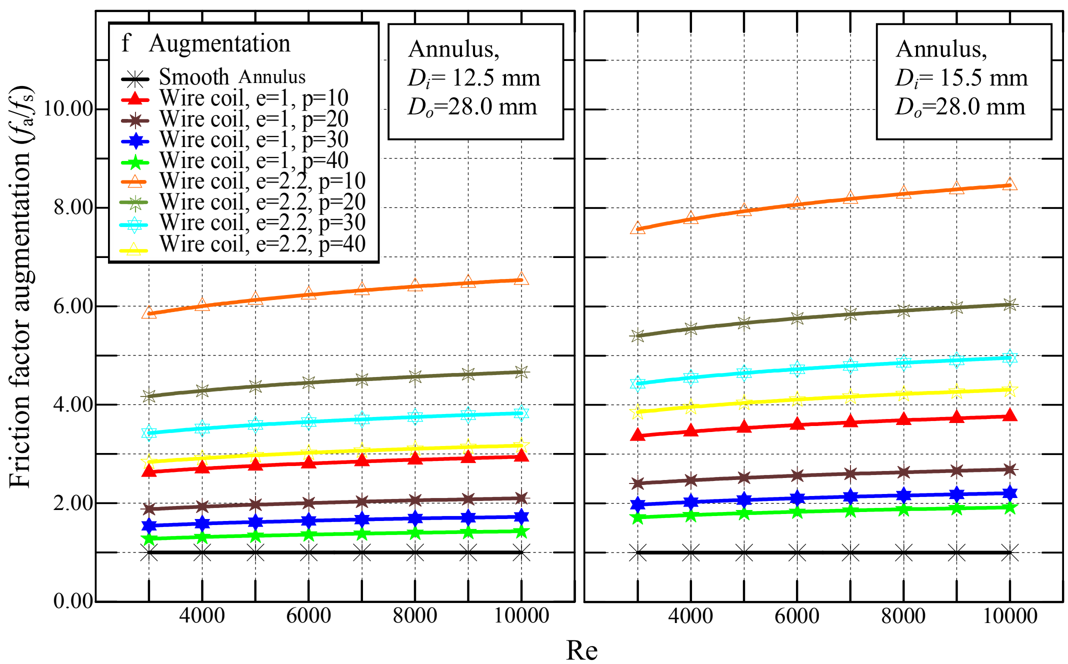



**Figure 6-3:** Friction factor augmentation vs. Reynolds number for annulus-side heat transfer enhancement using two wire coils of 1 and $e$=2.2 mm for two annulus sizes.

That magnitude, when compared to the friction factor augmentation registered for the case of using 1 mm diameter wire with the same coiling pitch ($e/D_e$=0.08 and $p/D_e$=0.80) at the same Reynolds number, reveals a great dependency of friction factor augmentation on wire diameter, as clearly observed by equation (6.2). The wire coil here progressively formulates obstacle not only increases friction factor but also decreases heat transfer as will be seen later giving an imagination that increasing the wire diameter as well as decreasing the coiling pitch might lead to unwanted result at least in the dimensions adopted in the present work. Here, the least friction factor augmentation registered is 1.275 at Reynolds number of 3000 in case of largest annulus with $e$=1 mm wire and $p$=40 mm.

#### 6.3.5.3 Friction Factor Augmentation for Annulus-Side Heat Transfer Enhancement by Circular Ribs

There is no doubt that the results of the friction factor augmentation of annulus-side enhancement by wire coil foretells the magnification of that by circular ribs in similar manner to that in discussing the effect of the type of augmentation device on friction factor, but just to show the effect of changing to circular ribs instead of wire coil, the study continues. Friction factor augmentation of annulus-side heat transfer enhancement by circular ribs is obtained by dividing equation (5.7) by (5.10) as:

$$\frac{f_a}{f_s} = 250.6181 \mathrm{Re}^{0.0729} \left( \frac{e}{D_e} \right)^{2.1579} \left( \frac{p}{D_e} \right)^{-0.4821} \left( \frac{D_i}{D_o} \right)^{-0.0671} \qquad \text{... (6-3)}$$

Equation (6.3), after inserting the required parameters gives the values of friction factor augmentation as listed in tables C-33 through C-36 which are plotted in fig. 6-4. Figure 6-4 reveals a friction factor augmentation of more than one and a half times that for the same dimensions in case of the annulus-side enhancement by wire coil. This supports the previous interpretation of the effect of the swirl in reducing the friction factor. Friction factor augmentation ratio in equation (6-3) is Reynolds number-independent with greatest friction factor augmentation is in case of the least ribbing pitch with the least annular gap.

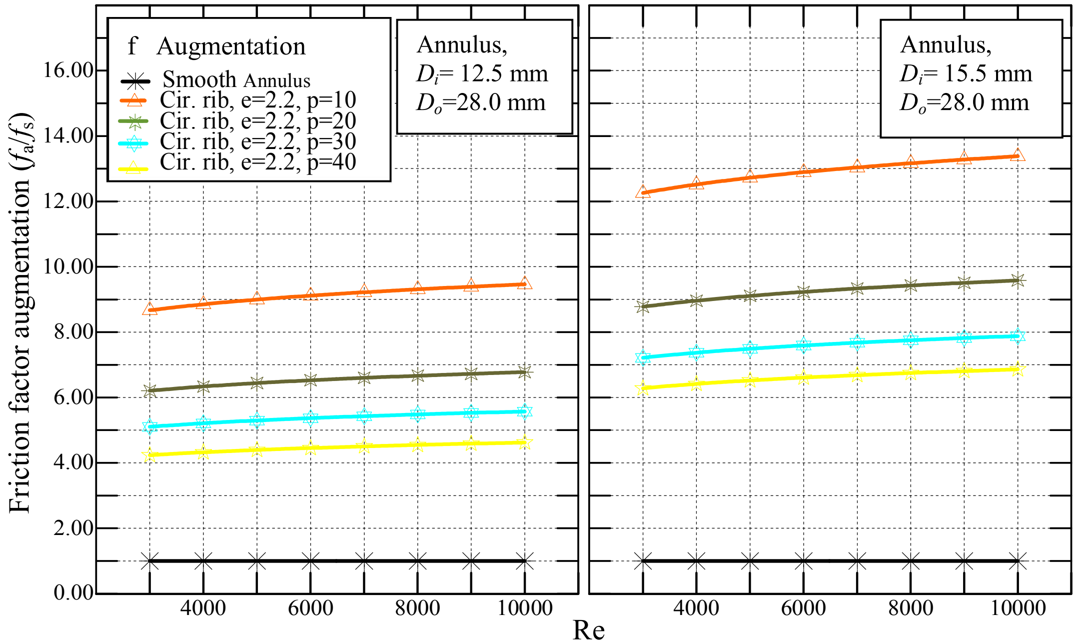



**Figure 6-4:** Friction factor augmentation vs. Reynolds number for annulus-side heat transfer enhancement using circular ribs of $e$ = 2.2 mm for two annulus sizes.

It is important to state that the methods of heat transfer enhancement in the annulus of double pipe heat exchanger (by wire coils, as well as circular ribs), adopted in the present work are completely new, with no similar works to be compared with, for friction factor or Nusselt number, like those for tube-side heat transfer enhancement by wire coils.

## 6.4 Heat Transfer in Enhanced Tubes and Annuli

The enhancement of heat transfer by turbulence promoters has more difficult mechanisms than the manner by which the friction factor increases as a result of adding these turbulators, differing according to their types, their geometrical characteristics and, the position where they are attached to or in the vicinity of installment. In addition, Prandtl number plays an important role in the mechanism of heat transfer when using roughened tubes.

### 6.4.1 The Effect of the Wire or Rib Diameter and Coiling or Ribbing Pitch on Nusselt Number.

The geometrical characteristics of inserts either wire coils or circular ribs affect heat transfer differently as compared to magnifying the friction factor, where the latter increases with increasing the intensity of roughness either by decreasing the coiling or ribbing pitches or by increasing the diameter of wire coils or ribs, while that doesn't occur always in case of heat transfer. In case of tube-side heat transfer enhancement by wire coils, Nusselt number increases with decreasing the coiling pitches or ($p/d_i$) for the same tube size, as shown in fig. 5-17. In addition, the ratio ($e/d_i$) influences Nusselt number, in spite of using one wire size here, but with varying the tube diameter that is possible. The behavior discussed here cannot be generalized for geometrical dimensions outside the range adopted in the present work.

Enhancement of heat transfer by wire coils, inserted inside the inner tube, might be considered to act in two ways, one might overcome the other. The first is as a swirl flow generator, generating a helical flow at the periphery of the flow. This rotating flow is superimposed upon the axially directed central core flow and promotes centrifugal forces that aid convection. The second is as a turbulence promoter increasing the flow turbulence level by a separation and reattachment mechanism. Moreover, when wire coils are in contact with the tube wall, they act as roughness elements disturbing the existing laminar sublayer. Wire coils increase heat transfer rate through one or two of the mechanisms mentioned above, depending on flow conditions and wire geometry. However, it is expected that wire coils will act as random roughness at high Reynolds numbers [8].

When the coiling pitches approach one another reaching a limit which prevents the formation of these reattachment points, as obviously seen in fig. 3-3 where heat transfer will decrease [61]. This does not occur in case of tube-side heat transfer enhancement because the coiling pitch range, adopted in the present work, does not reach this limit. But in case of the annulus-side heat transfer, this is obvious, especially in case of 2.2 mm wire coil. In the annulus-side heat transfer like in tube-side, heat transfer is imposed upon the mechanism of separation and reattachment mechanism, as well as the enhancement of heat transfer by swirl generation. In case of using the wire coil of $e$=1 mm, for the two annulus sizes, Nusselt number was kept increasing with decreasing the coiling pitch as clearly presented in fig. 5-18. Very close values of Nusselt number are observed in case $p$=20 and 10, giving an idea that the coiling pitch plays no more role in enhancing heat transfer.

The last observation might be considered as a critical value to start a reverse relationship as in case of the $e$= 2.2 mm wire as clear in fig. 5-19, where heat transfer keeps increasing with decreasing coiling pitch to a specified value and then the relationship goes reversely when the coils become close to each other preventing the formation of the reattachment regions which increase the local heat transfer coefficient. In fig. 5-19, the maximum Nusselt number values are obtained for $p$=20 mm using the annulus of $D_i$= 12.5 mm, while for the annulus having the smallest annular gap, it is when $p$=30 mm. The last observation confirms the great role of the mechanism of separation and reattachment which needs enough space to form as in fig. 3-2 [59].

Considering the case of 2.2 mm wire coil, the role of swirl appears clearly as a heat transfer inducer in a manner similar to that of Coetzee [34], who used a spiraling tape around the inner tube of the double pipe heat exchanger. The enhanced heat transfer is by swirls tending to increase the effective flow path of the fluid through the tube or annulus. This would increase heat transfer, as well as pressure drop, but this effect decreases or disappears altogether at higher helix angles since fluid flow simply passes axially over coils [57, 68].

What happens in case of annulus-side heat transfer enhancement by circular ribs supports the opinion of giving the swirl flow an importance in heat transfer. In this case, the effect of the swirl flow completely disappears, keeping the only means for enhancing heat transfer being the mechanism of separation and reattachment leading to lower Nusselt number values in addition to increase the friction factor as seen previously. In the last case the majority of experiments have given close values of Nusselt number especially in case of close ribs (the least values of ($p/D_e$)).

The complex situation encountered in case of annulus-side heat transfer enhancement has led to the complex correlations of Nusselt number (equation (5.12) and (5.13)). These correlations have been desired to express all points or curves included in figs. 5-18 through 5-20, but revealing an accurate description as these correlations do not express all these points or curves giving as reasonably accurate relationships as possible to express the majority of them and to surpass the irregular points or curves, as will be seen in the Nusselt number augmentation curves, depicted later.

### 6.4.2 The Effect of the Annulus Diameter Ratio ($D_i/D_o$)

The ($D_i/D_o$) parameter has appeared in Nusselt number correlations for the annulus-side heat transfer enhancement, giving significance to the annular gap size in enhanced annuli as well as smooth ones as in equations (5.12) and

(5.13) and (5.15) respectively. Since the exponent of that parameter in equation (5.15) makes it giving values close to those fixed as deviation values of Nusselt number in smooth annuli used in the present work (table 5-1), it might be valuable to consider it as a correction factor concerned with the smooth annuli used presently.

On the other hand, such parameter seems more effective in equations (5.12) and (5.13) to suppose reasonably that this factor is more than a correction factor in case of the annulus-side heat transfer either by wire coils or circular ribs. No clear explanation is available for such case in the literature, where most valuable description of fluid flow and heat transfer around ribs is cited for a flat plate or circular tube, as in fig. 3-2. The present situation might be different where the local circulation eddies are formed over the ribs and the separation and reattachment zones, undergoing an impedance caused by the outer wall of the annulus, meaning that the impedance is greatly affected by the annular gap size which is represented by the ratio ($D_i/D_o$) [59].

### 6.4.3 The Dependency of Nusselt Number on Reynolds Number

It seems clearly that the dependency of Nusselt number on Reynolds number in case of tube-side enhancement by wire coils as obviously seen in fig. 5-17 and equation (5.11), is very close to that for smooth tubes. On the other hand, the relation for the case of the annulus-side enhancement is different where the dependency is related to the geometrical characteristics of inserts themselves as obvious in equations (5.12) and (5.13). Indeed, the complex exponents of Reynolds number in these equations have come as a result of the complex physics of fluid flow and heat transfer in the annulus. Clearer picture would be formed later in the study of Nusselt number augmentation.

### 6.4.4 The Effect of Prandtl Number on Heat Transfer

Many studies refer to the great role, Prandtl number plays in the enhancement of heat transfer by wire coils or by other disruption shapes. Mathematically, the effect of Prandtl number appears significantly in the exponent of Prandtl number in Nusselt number correlations (e.g., equations (5.11), (5.12) and (5.13)). As a conclusion Webb et al., [61] attained that Prandtl number exponent doesn't differ greatly from the value of about 0.33 depending on Prandtl number itself. The value of this exponent decreases with Prandtl number.

In the present work, Prandtl number exponents are 0.27 for tube-side heat transfer enhancement and 0.3 and 0.29 for annulus-side enhancement by wire coils and circular ribs respectively. No doubt that the narrow range of Prandtl number adopted in the present work (using water as the only working fluid), doesn't anyway permit to have more accurate idea about the dependency of heat transfer in enhanced tubes and annuli.

### 6.4.5 Nusselt Number Augmentation

It is defined by the ratio between the Nusselt numbers of enhanced (augmented) tube or annulus and that of smooth ones at the same Prandtl and Reynolds numbers [8, 35].

#### 6.4.5.1 Nusselt Number Augmentation for Tube-Side Heat Transfer Enhancement

The equation of Nusselt number augmentation for the tube-side heat transfer enhancement is obtained by dividing equation (5.11) by equation (5.14), which represents the actual Nusselt number correlation of smooth tube in the present work, to give the equation

$$\frac{\overline{N}u_a}{\overline{N}u_s} = 5.1385\,\mathrm{Re}^{-0.0392}\,\mathrm{Pr}^{0.0091}\left(\frac{e}{d_i}\right)^{0.2049}\left(\frac{p}{d_i}\right)^{-0.3532} \qquad \text{... (6.4)}$$

Inserting the required values of dimensionless parameters from table C-41 into equation (6.4) gives the values of Nusselt number augmentation for tube-side heat transfer enhancement by wire coils for the two tube sizes and all values of the adopted geometrical characteristics as listed in tables C-20 through 23 and plotted in fig. 6-5. The latter reveals good agreement with fig. 5-17 that shows the Nusselt number-Reynolds number relationship for different conditions. The four experimental conditions have been summarized into two cases only (concerned with the change of the hot fluid inlet temperature), because Prandtl number has insignificant variation for the other two conditions. Also the variation of the inlet temperature of hot fluid with fixing that of cold one leads to variation of the approach temperature difference which would be adopted in the PEC calculations discussed later.

For all values of the characteristic variables in fig. 6-5, the Nusselt number augmentation decreases with Reynolds number leading to suggest that the heat transfer enhancement inside the inner tube by wire coils at low Reynolds numbers is more efficient than that at high Reynolds number especially when knowing that these low values of Reynolds number have given the lowest friction factor augmentation values as stated previously. But in general, Nusselt number augmentation is weakly dependent on Reynolds number especially at high values.

The maximum value of Nusselt number augmentation obtained is 2.43 for the 14 mm diameter tube and 2.34 for the other size, both at Reynolds number of 5000, $e$ = 10 and $p$ =10, corresponding to maxima in friction factor augmentation of 4.75 and 4.88. For the same geometries, for high

Reynolds number (40000), the maxima registered, are 2.24 and 2.16 with corresponding friction factor augmentation values of 6.83 and 7.01 respectively. That means that the maximum heat transfer augmentation is 2.43 for the wire geometries of ($e/d_i$= 0.0714 and $p/d_i$= 0.7143). Close values for the two experimental conditions have been registered.

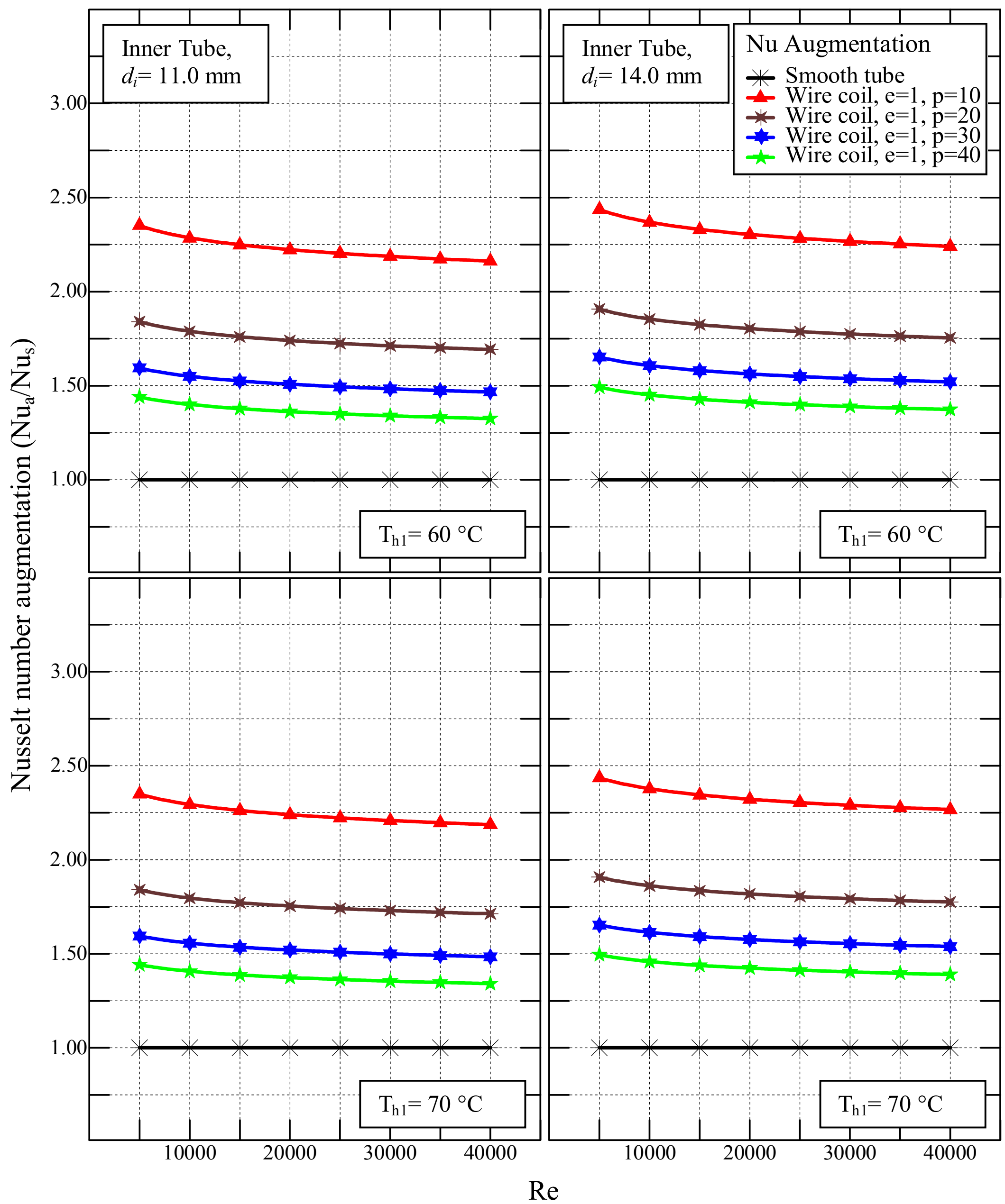



**Figure 6-5:** Nusselt number augmentation vs. Reynolds number for inner tube-side heat transfer enhancement using a wire coil of $e$ = 1 mm for two inner tube sizes.

Similar to the comparison performed for friction factor correlation (equation (5.1)), another comparison must be performed for Nusselt number (equation (5.11)), with results or correlations proposed by other works which were carried out in similar ranges of Reynolds and Prandtl number as well as geometrical characteristics. The work of Sethumadhavan and Rao and Viedma [8], Kumar and Judd [9] and Klaczak [70], are chosen for the comparison. The comparison is for a specified Prandtl number equaling to 3, $e/d_i$=0.1 and $p/d_i$=1.2, as depicted in fig. 6-6. It reveals that the results of the present work are very close to those of Kumar and Judd and in good agreement with the results of Klaczak, and in general, lower than the results of Sethumadhavan and Rao and Viedma. Indeed, the latter has also high friction factor compared to the present work (fig. 6-2). At the same time the work of Klaczak is very appropriate to be compared with, because water was used as the only flowing fluid with similar geometrical characteristics [70].

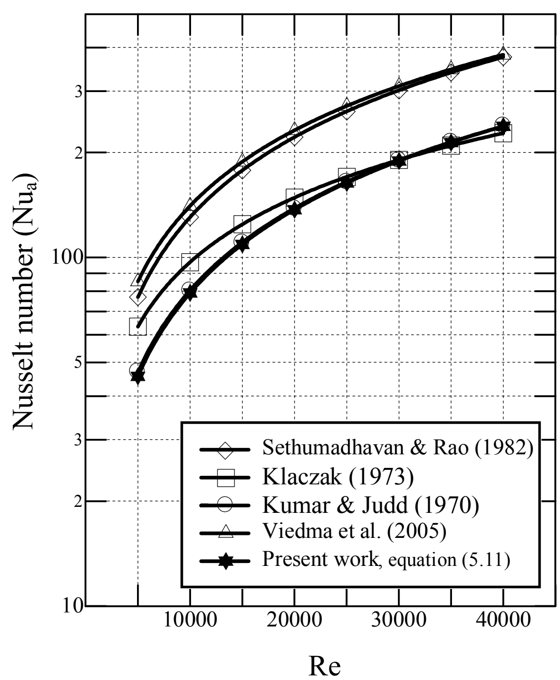



**Figure 6-6:** Comparison of Nusselt number resulted in the present work (equation (5.11)) with that of previous works for tube-side heat transfer enhancement with wire coil of $e/d_i$=0.1 and $p/d_i$=1.2 and Pr=3.0.

### 6.4.5.2 Nusselt Number Augmentation for Annulus-Side Heat Transfer Enhancement by Wire Coil

The Nusselt number augmentation relationship of annulus-side heat transfer enhancement by wire coil is obtained by dividing equation (5.12) by (5.15)

$$\frac{\overline{Nu}_a}{\overline{Nu}_s} = 0.1613\,\mathrm{Re}^{-0.843+1.1462\left(\frac{e}{D_e}\right)^{0.2464}\left(\frac{p}{D_e}\right)^{0.1475}}\mathrm{Pr}^{-0.15}$$

$$\times\left[\frac{\left(\frac{e}{D_e}\right)^{-0.8156}}{\left(\frac{e}{D_e}\right)^{2.5892}+0.01}\right]\left[\frac{\left(\frac{p}{D_e}\right)^{-0.5503}}{\left(\frac{p}{D_e}\right)^{1.515}+3.8717}\right]\left(\frac{D_i}{D_o}\right)^{-0.1431} \qquad \text{... (6.5)}$$

Substituting the required values of geometrical parameters from table C-41 for the two wire sizes produces the values of Nusselt number augmentation as listed in tables C-25 through C-32 and plotted in fig. 6-7 which shows a complex situation for Nusselt number augmentation specified in the range of the geometrical characteristics adopted in the present work. A great role is observed for the ratios ($e/D_e$) and ($p/D_e$) to determine the relationship of the augmentation ratio with Reynolds number. Unlike the tube-side heat transfer enhancement a great dependency of Nusselt number augmentation upon Reynolds number is observed specially for low values of ($e/D_e$). The case of the group of greater ($e/D_e$) ratio ($e$=2.2 mm) reveals low Reynolds number dependency giving close augmentation ratio for the four ($p/D_e$) ratios with reflection in the relationship at the values of $p$= 20 and 30 mm ($e$=2.2 mm) have given values of Nusselt number augmentation larger than $p$= 10 and 40 mm. The maximum value of Nusselt number augmentation for annulus-side enhancement by wire coils is registered at Reynolds number of 3000 for $e$=1 mm and $p$=10 mm for the annulus of $D_i$=12.5 mm ($e/D_e$=0.0645 and $p/D_e$=0.6452) having a value of 3.25. For the other annulus, it is 3.15. These values are corresponding to friction factor augmentation of 2.63 and 3.37 respectively. The largest value for high Reynolds number (10000) is for $e$=2.2 mm and $p$=20 mm having a value of 2.49 and 2.3 with friction factor augmentation of 4.66 and 6.03 for the two annuli respectively. Then, the maximum for 10000 Reynolds number is 2.49 for ($e/D_e$=0.176 and $p/D_e$=1.6).

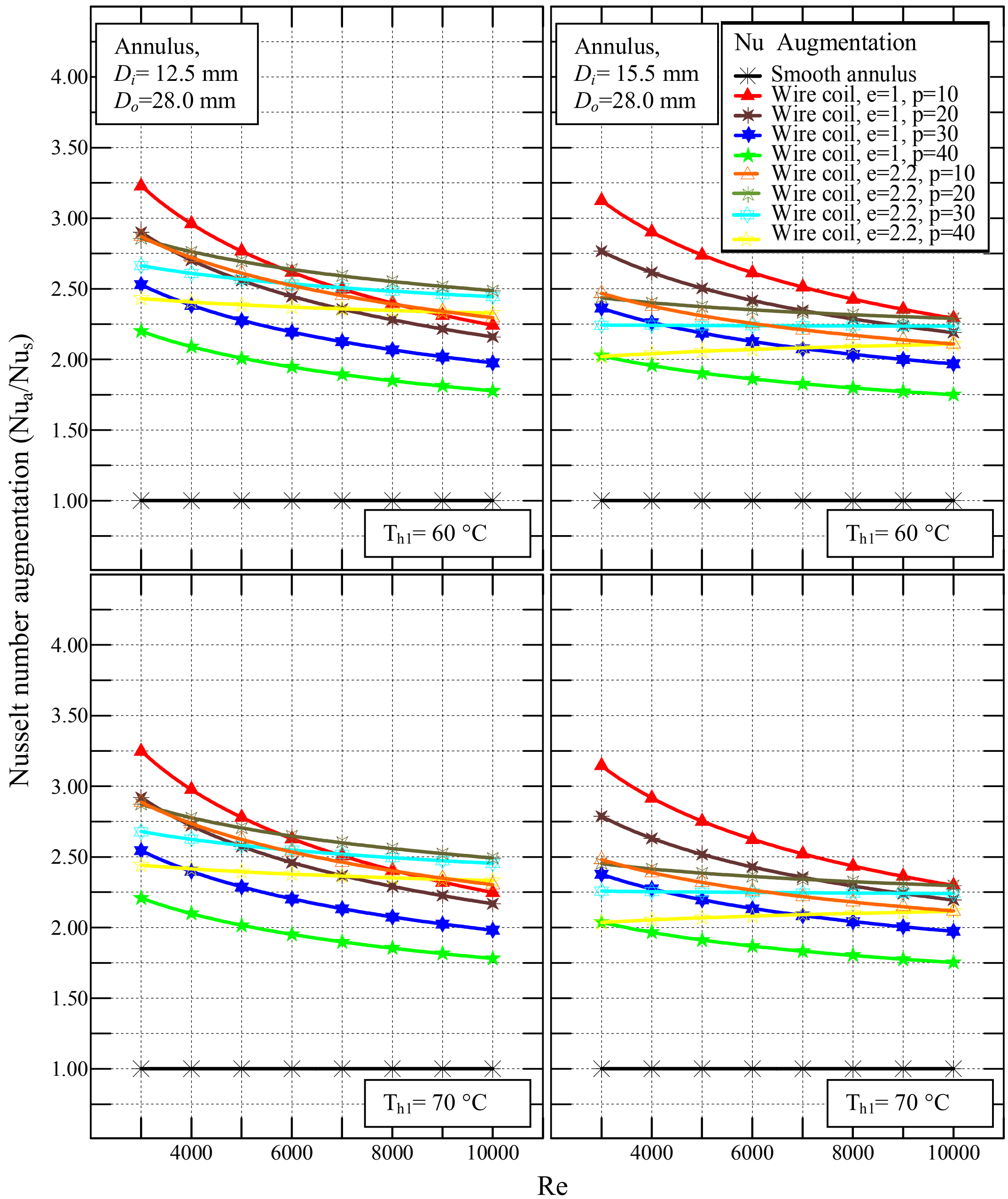



**Figure 6-7:** Nusselt number augmentation vs. Reynolds number for annulus-side heat transfer enhancement using two wire coils of e=1 and 2.2 mm for two annulus sizes.

### 6.4.5.3 Nusselt Number Augmentation for Annulus-Side Heat Transfer Enhancement by Circular Ribs

Nusselt number augmentation relationship of the annulus-side heat transfer enhancement by circular ribs can be obtained by dividing equation (5.13) by (5.15) to be

$$\frac{\overline{Nu}_a}{\overline{Nu}_s} = 8.1129\,\mathrm{Re}^{-0.843+0.3298\left(\frac{e}{D_e}\right)^{-0.4696}\left(\frac{p}{D_e}\right)^{-0.0645}}\,\mathrm{Pr}^{-0.16}$$

$$\times\left[\frac{\left(\frac{e}{D_e}\right)^{0.0527}}{\left(\frac{e}{D_e}\right)^{-2.3452}+0.5044}\right]\left[\frac{\left(\frac{p}{D_e}\right)^{0.51}}{\left(\frac{p}{D_e}\right)^{0.001}-0.983}\right]\left(\frac{D_i}{D_o}\right)^{0.1192} \quad \text{... (6.6)}$$

Substituting values of the geometrical parameters from table C-41 gives fig. 6-8 (values are listed in tables C-33 through C-36) which shows close Nusselt number augmentation regardless of the values of the geometrical parameters of inserts with simple superiority for the coils with the largest coiling pitches especially in case of the annulus of $D_i$=15.5 mm which has the least annular gap. In general all Nusselt number augmentation ratios in case of using circular ribs are less than the corresponding values in case of using wire coils. The high friction factor augmentation ratios registered for this case, as explained previously, gives an impression that the use of circular ribs has less efficiency than the wire coil regardless of the geometrical dimensions.

A comparison between the proposed methods of annulus-side heat transfer enhancement with the method of Coetzee [34] shows that the proposed method has higher efficiency than Coetzee's which had a maximum value of Nusselt number augmentation of 2.06 with friction factor augmentation of 2.03. These are less than the values obtained in the present work that equal to 3.25 with friction factor augmentation of 2.63 in case of wire coil insert as discussed previously.

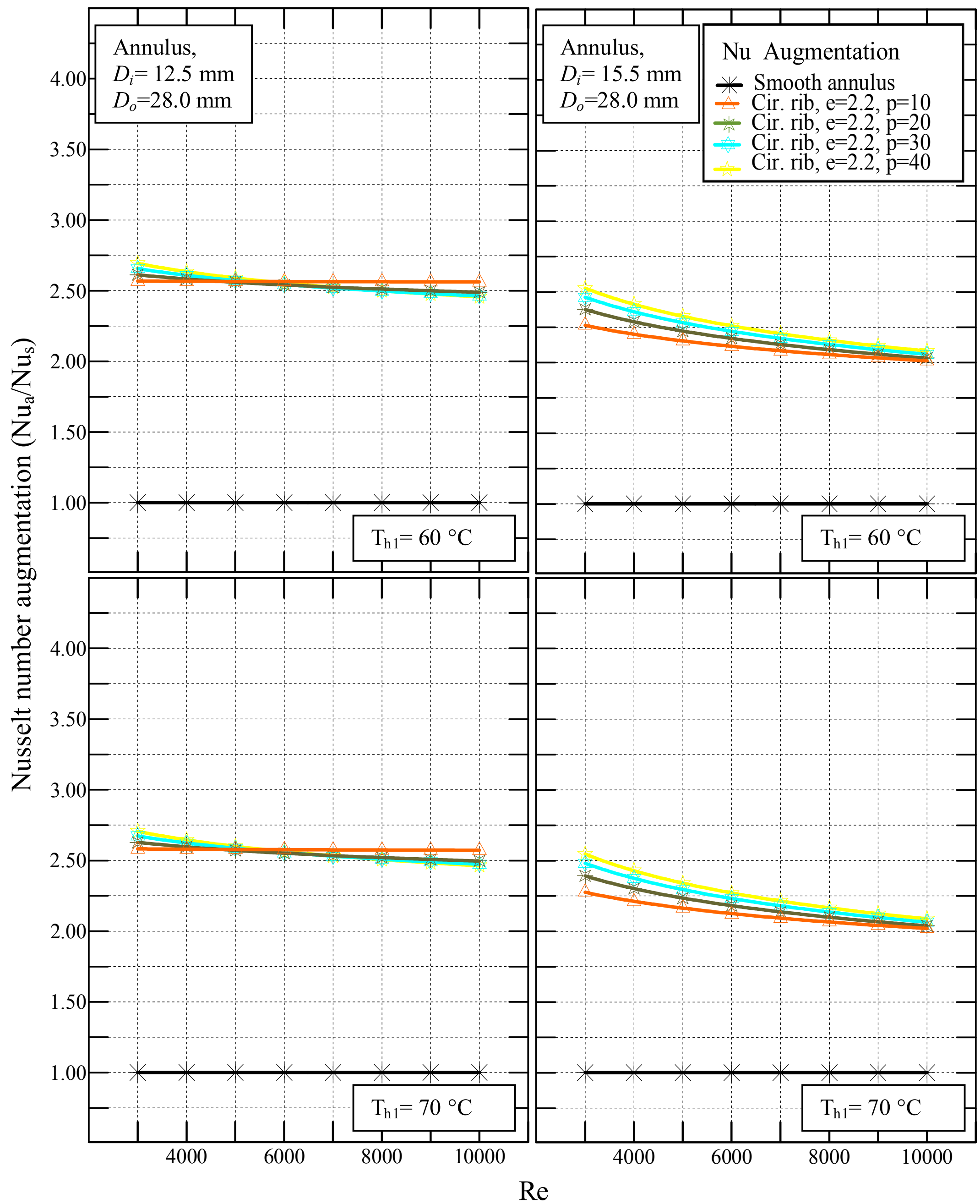



**Figure 6-8:** Nusselt number augmentation vs. Reynolds number for annulus-side heat transfer enhancement using circular ribs of $e$ = 2.2 mm for two annulus sizes (the axis scales, in spite of unclarity, have been taken the same as in fig. 6-7 to enable comparison between the two methods of annulus-side heat transfer enhancement).

## 6.5 Performance Evaluation Criteria (PEC)

One possibility to quantify the performance improvement is to calculate Nusselt number and friction factor augmentation ratios as detailed previously. That has led to the fact that the friction factor of an enhanced surface in single-phase flow is higher than that of the smooth surface, when operated at the same velocity (or Reynolds number). However, this method is not sufficient to describe the most effective enhancement method because it does not define the actual performance improvement, subject to specific operating constraints. If one simply calculated the Nusselt number augmentation ratio, at equal velocities, an unfair comparison may result. This is because the enhanced surface would be allowed to operate at a higher pressure drop. The plain surface would give a higher $h$ value if it were allowed to operate at a higher velocity, giving the same pressure drop as the enhanced surface. Thus, the pressure drop constraint is a very important consideration for calculating the performance benefits of an enhanced surface in single-phase flow [35]. Twelve performance evaluation criteria (PECs) had been set to accommodate different cases that might be encountered in the industrial application as listed in table 3-1.

To apply these criteria to the results of the present work, starting from equation (3.31) derived previously. One of the groupings on the left side becomes the objective function, with the other two set as 1.0 for the corresponding operating constraints, which also provide the mass flux ratio ($G_a/G_s$) that satisfies equation (3.31). This ratio, equaling to the corresponding Reynolds number ratio ($Re_a/Re_s$), is usually for most cases larger than unity. To avoid confusion in defining the "smooth tube" term in equation (3.31) with that used in the previous calculations, a new notation is used "o" to distinguish the smooth tube case at the same Reynolds number from that required to satisfy equation (3.31), leading to write it in the form

$$\frac{h_a A_a / h_o A_o}{(P_a/P_o)^{1/3}(A_a/A_o)^{2/3}} = \frac{j_a/j_o}{(f_a/f_o)^{1/3}} \quad \text{... (6.7)}$$

The application of PECs requires to have fixed tube diameter, so each of the two tubes, used in the present work, would be considered separately. In addition, constant physical properties must be assumed, to qualify the requirements set by Webb and Bergles [35, 58]. Three cases of performance evaluation criteria will be applied to the results of the present work.

### 6.5.1 PEC Application for Tube-Side Heat Transfer Enhancement

In the tube-side heat transfer enhancement case, the four experimental conditions would be briefed into two only, concerning the inlet approach temperature difference ($\Delta T_i$). The two approach temperature differences are 40 and 50 °C. Indeed, this classification is applied due to a difference in the average Prandtl number for each ($\Delta T_i$). Prandtl number values would be fixed to the values of 3.14 and 2.72 and 3.14 and 2.71 for tubes of 11 and 14 mm inner diameter, respectively, as presented in figs. 6-9, 6-10 and 6-11.

**( i ) FG-2a criterion:** the area of flow cross section ($N$ and $d_i$) and tube length $L$ are kept constant. This would typically be applicable for retrofitting the smooth tube of an existing exchanger with enhanced tubes, thereby maintaining the same basic geometry and size ($N$, $d_i$, and $L$). The objective then could be to increase the heat load capacity (q) for the same approach temperature ($\Delta T_i$) and pumping power (P) [1, 35, 58].

To apply this criterion, the ratios ($P_a/P_o$) and ($A_a/A_o$) in equation (6.7) are set to unity. Then equation (6.7) becomes

$$h_a A_a / h_o A_o = \frac{j_a / j_o}{\left(f_a / f_o\right)^{1/3}} \qquad \text{... (6.8)}$$

Returning to the definition of Colburn factor, at fixed physical properties, equation (6.8) becomes

$$h_a A_a / h_o A_o = \frac{\left(Nu_a / Nu_o\right)}{\left(f_a / f_o\right)^{1/3}\left(\mathrm{Re}_a / \mathrm{Re}_o\right)} \qquad \text{... (6.9)}$$

where $Nu_o$ is the Nusselt number for smooth tube calculated at constant pumping power and heat exchange surface area. To satisfy the constrain of constant pumping power, $Nu_o$ is evaluated at $Re_o$ which is obtained by using the ($P_a/P_o$) that has been set to unity. Using equation (3.30) with changing the notation of smooth tube and replacing the mass flux by the Reynolds number (physical properties are constant), then

$$\left(f_o \,\mathrm{Re}_o^3\right) = \left(f_a \,\mathrm{Re}_a^3\right) \qquad \text{... (6.10)}$$

For the tube-side heat transfer enhancement, equations (6.10) and (5.9) for the value of $Re_o$ which would be used to calculate $Nu_o$. In addition, equation (6.10) can be substituted in equation (6.9) to simplify it to be

$$\frac{h_a A_a}{h_o A_o} = \frac{Nu_a}{Nu_o} \qquad \text{... (6.11)}$$

Then the (FG-2a) criterion can be expressed as:

$$\frac{q_a}{q_o} = \left(\frac{Nu_a}{Nu_o}\right)_{L, d_i, \Delta T_i, P} \qquad \text{... (6.12)}$$

Equation (5.11) is used to calculate the values of $Nu_a$, for the range of Reynolds number (5000 to 40000), and with equation (6.12), to obtain the heat transfer ratios (FG-2a) for the tube-side heat transfer enhancement as listed in table C-42, and plotted in fig. 6-10.

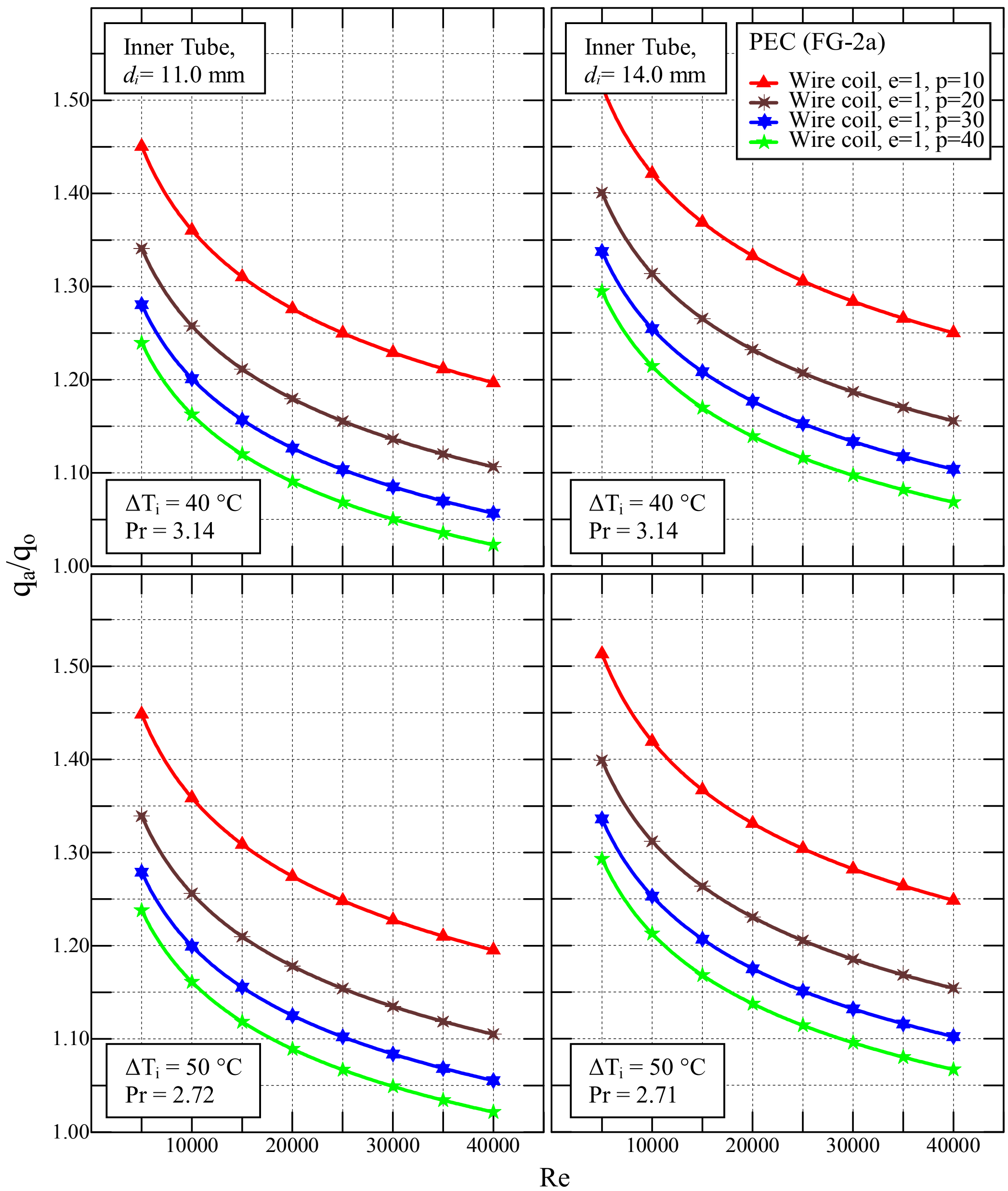



**Figure 6-9:** Application of the performance evaluation criterion (FG-2a) to the tube-side heat transfer enhancement by wire coils for two tube sizes and two experimental conditions.

Indeed the (FG-2a) criterion represents the actual enhancement ratio ($E_h$) defined by equation (3.1) which refers to the most effective method of heat transfer enhancement [35].

In fig. 6-9, the wire coil of 10 mm coiling pitch has the best performance in case of the two tube sizes, having a value of 1.45 for the 11 mm diameter tube and 1.52 for the other size, both at Reynolds number of 5000. The best performance at 40000 Reynolds number is registered for the same geometrical dimensions having the values of 1.2 and 1.25 respectively. That means that the best enhancement ratio is 1.52 for the geometries of $e/d_i$= 0.0714 and $p/d_i$= 0.7143. It is obvious that the arrangement of the four geometries in the heat transfer augmentation depicted in fig. 6-5 has been left unchanged here.

**( ii ) FG-3 criterion:** in this criterion the basic geometry and size ($N, d_i, L$) are also kept constant like the (FG-2a), i.e. constant heat exchange surface area. The objective then could be decreasing the pumping power with keeping the inlet temperature approach and the heat duty constant [1, 35, 58]. So, to apply this criterion the ratios ($A_a/A_o$) and ($h_a A_a/h_o A_o$) in equation (6.7) are set to unity. Then equation (6.7), with substituting the definition of ($j$), becomes

$$\frac{P_a}{P_o} = \left(\frac{f_a}{f_o}\right)\left(\frac{Nu_o}{Nu_a}\right)\left(\frac{\mathrm{Re}_a}{\mathrm{Re}_o}\right)^3 \qquad \text{... (6.13)}$$

To satisfy the constrain of constant heat duty, $f_o$ and $Nu_o$ are evaluated at $\mathrm{Re}_o$ which is obtained by using the ratio $h_a A_a/h_o A_o$=1 to give

$$(Nu_o) = (Nu_a) \qquad \text{... (6.14)}$$

which enables omitting the Nusselt number ratio from equation (6.13) giving

$$\frac{P_a}{P_o} = \left[\left(\frac{f_a}{f_o}\right)\left(\frac{\mathrm{Re}_a}{\mathrm{Re}_o}\right)^3\right]_{L,d_i,\Delta T_i,q} \qquad \text{... (6.15)}$$

By calculating the values of $Nu_a$ (by using equation (5.11)) for equation (6.14), this equation and equation (5.14) are solved directly for $Re_o$. The values of the pumping power ratio ($P_a/P_o$) are fixed in table C-43 and plotted in fig. 6-10.

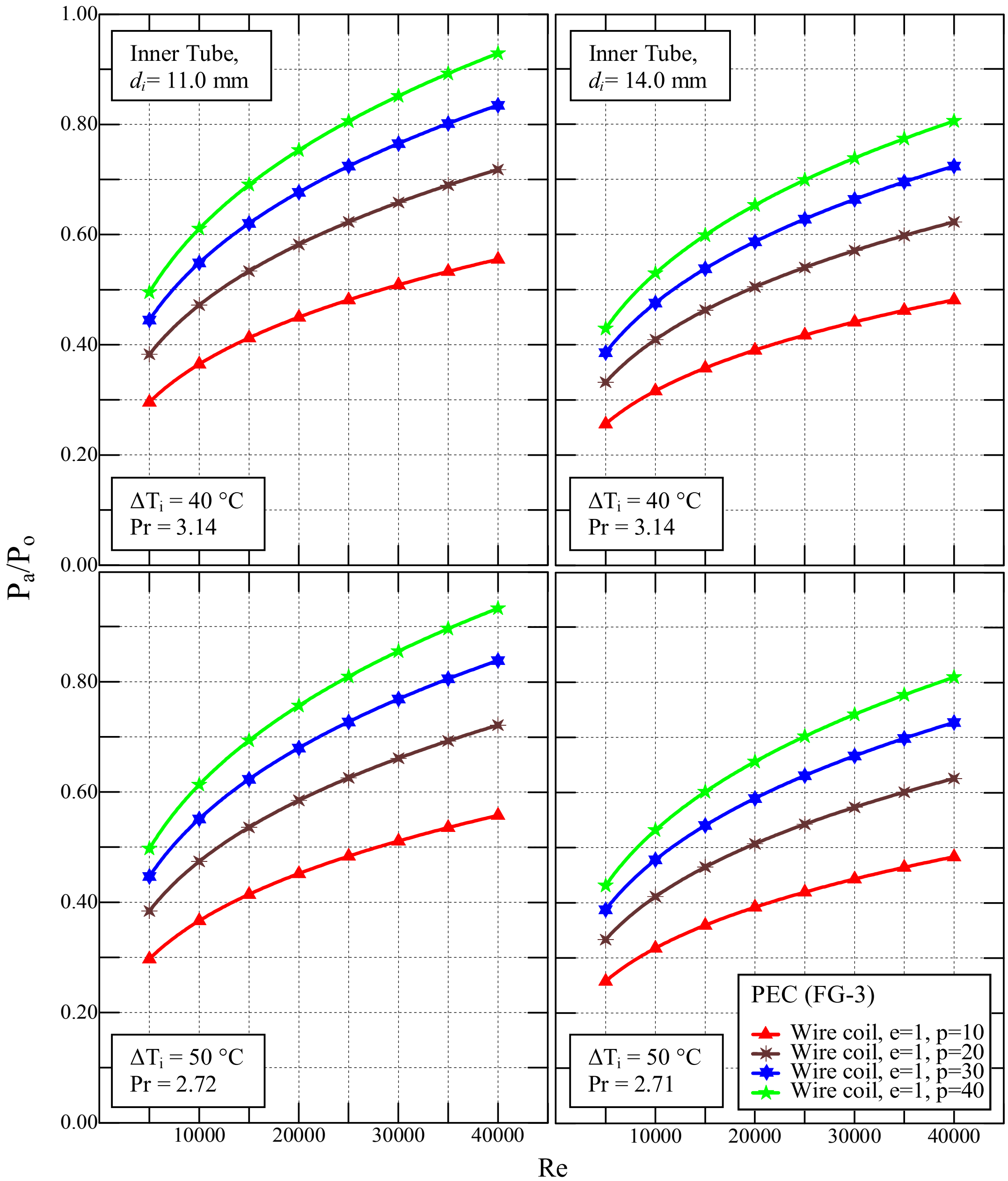



**Figure 6-10:** Application of the performance evaluation criterion (FG-3) to the tube-side heat transfer enhancement by wire coils for two tube sizes and two experimental conditions.

Figure 6-10 reveals that the pumping power, needed with adopting the wire coil of 10 mm coiling pitch is about 30% and 55% that for smooth tube for Re = 5000 and 40000, respectively for the 11 mm diameter tube and for the other tube size the values are 25% and 45% for Re = 5000 and 40000, respectively. The other three geometries have lesser pumping power with the conventional arrangement.

**( iii ) FN-1 criterion:** the flow cross section ($N$ and $d_i$ ) is kept constant, and the heat exchanger length is allowed to vary. Here, the objective is to seek a reduction in heat transfer surface area ($A \rightarrow L$) for a fixed heat load and pumping power [1, 35, 58]. To apply this criterion, the ratios ($h_a A_a/h_o A_o$) and ($P_a/P_o$) in equation (6.7) are set to unity. Then, equation (6.7), with substituting the definition of ($j$), becomes

$$\frac{A_a}{A_o} = \left(\frac{f_a}{f_o}\right)^{1/2} \left(\frac{Nu_o}{Nu_a}\right)^{3/2} \left(\frac{\mathrm{Re}_a}{\mathrm{Re}_o}\right)^{3/2} \qquad \text{... (6.16)}$$

To satisfy the constrain of constant heat duty and pumping power, $f_o$ and $Nu_o$ are evaluated at $Re_o$. The latter is obtained by setting both ($h_a A_a/h_o A_o$) and ($P_a/P_o$) to unity as follows:

$$\frac{h_a A_a}{h_o A_o} = 1 \qquad \text{... (6.17)}$$

$$\left(\frac{Nu_a}{Nu_o}\right)\left(\frac{A_a}{A_o}\right) = 1 \qquad \text{... (6.18)}$$

and

$$\frac{P_a}{P_o} = 1 \qquad \text{... (6.19)}$$

Substituting equation (3.30) in equation (6.19) with replacing the mass flux ratio by the Reynolds number ratio

$$\frac{f_a}{f_o}\frac{A_a}{A_o}\left(\frac{\mathrm{Re}_a}{\mathrm{Re}_o}\right)^3 = 1 \qquad \text{... (6.20)}$$

Dividing equation (6.20) by equation (6.18) leads to the relationship

$$\left(f_o \,\mathrm{Re}_o^3 / Nu_o\right) = \left(f_a \,\mathrm{Re}_a^3 / Nu_a\right) \qquad \text{... (6.21)}$$

Equations (6.21), (5.9) and (5.14) could be solved iteratively for $\mathrm{Re}_o$ until convergence occurs to find the values of $\mathrm{Re}_o$ corresponding to those of $\mathrm{Re}_a$. Furthermore, equation (6.21) can be substituted in equation (6.16) to give the final form of the heat exchange surface area reduction relationship as:

$$\frac{A_a}{A_o} = \left[\left(\frac{f_o}{f_a}\right)\left(\frac{\mathrm{Re}_o}{\mathrm{Re}_a}\right)^3\right]_{d_i,\Delta T_i,q,P} \qquad \text{... (6.22)}$$

Values of heat exchange surface area reduction ratio ($A_a/A_o$) are fixed in table C-44 and plotted in fig. 6-11. It reveals that the best heat exchange surface area reduction is obtained by using the wire coil with the coiling pitch of 10 mm, where the enhanced surface area is about 0.58 and 0.77 of that for smooth tube for Re = 5000 and 40000 respectively using the tube of $d_i$= 11 mm. For the other tube, the ratios are 0.55 and 0.73 for the two Reynolds numbers respectively. Indeed these values, for a constant diameter, represent the reduction of tube lengths. Also, the conventional arrangement of the four geometries for the two tube sizes is kept the same.

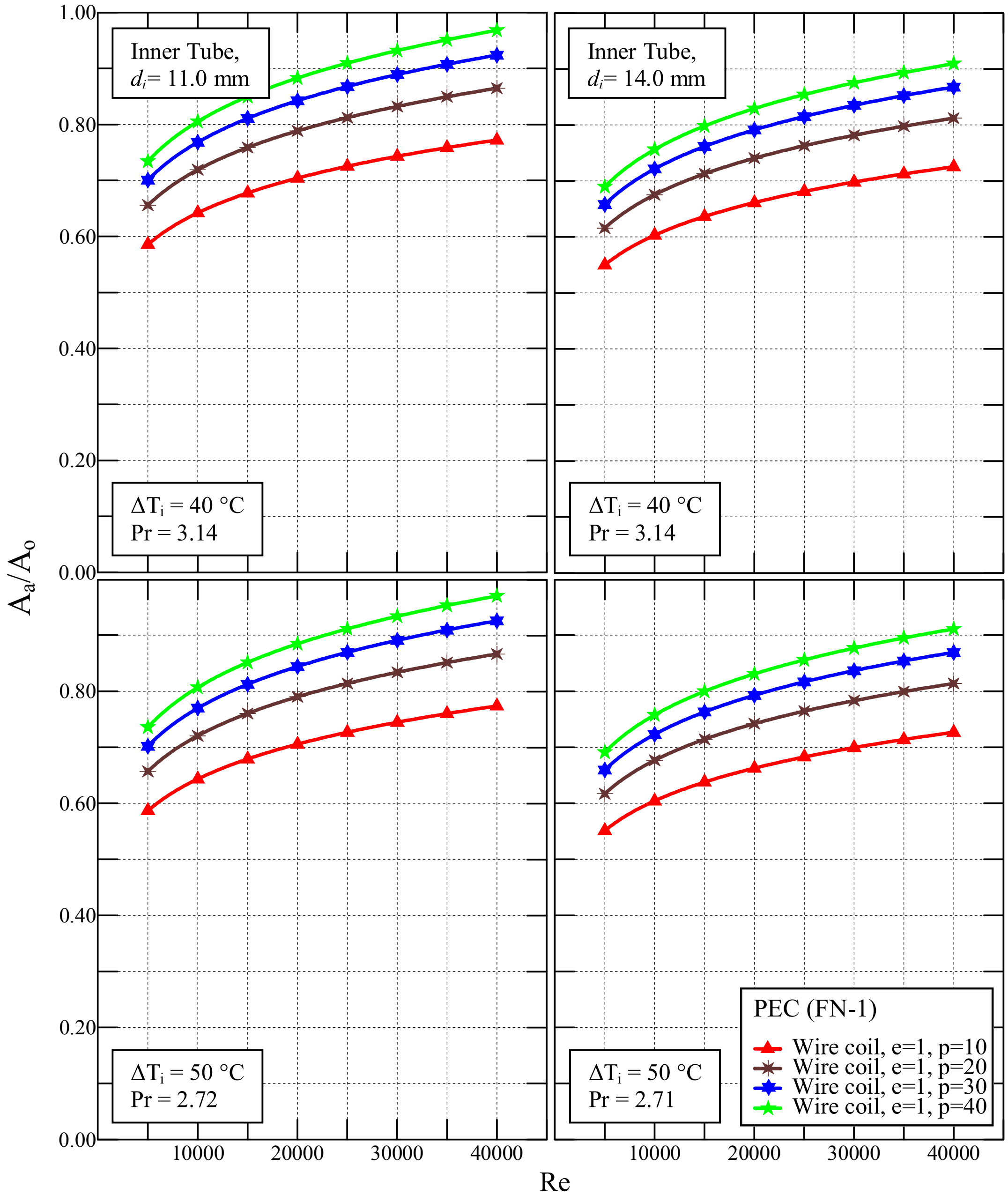



**Figure 6-11:** Application of the performance evaluation criterion (FN-1) to the tube-side heat transfer enhancement by wire coils for two tube sizes and two experimental conditions.

In figs. 6-9 through 6-11, plots have been set to show the ratios ($q_a/q_o$), ($P_a/P_o$) and ($A_a/A_o$) for two concise experimental conditions represented by working with two approach temperature differences. A very slight effect is noticed in the three ratios to the extent that it cannot be read directly in the plots, but by observing the concerned tables (tables C-42 through C-44). Generally, the three ratios are slightly larger in case of working with the 40 °C approach temperature difference. This confirms the exergetic fact that working at lower approach temperature differences is the most efficient. Indeed, the only representation which can be fixed for the approach temperature difference in the mathematics of heat transfer is the changes in physical properties.

### 6.5.2 PEC Application for Annulus-Side Heat Transfer Enhancement

The performance evaluation criteria of Webb and Bergles [35, 58] had been set to accommodate the heat transfer enhancement inside tubes or ducts. To make these criteria suitable for annulus-side heat transfer enhancement, the general equation (6.7) must be checked to suit that use. First, (3.24) is substituted in equation (3.25) with changing the notations for annulus

$$P = f\frac{L}{D_e}\frac{G^3 A_c}{2\rho^2} \qquad \text{... (6.23)}$$

Substituting the cross sectional area and the equivalent diameter of annulus in equation (6.23) leads to:

$$P = fL\frac{G^3}{8\rho^2}\pi\left(D_o + D_i\right) \qquad \text{... (6.24)}$$

Writing equation (6.24) as the ratio, relative to a smooth surface with omitting the property parameters gives:

$$\frac{P_a}{P_o} = \frac{f_a}{f_o}\frac{L_a}{L_o}\left(\frac{G_a}{G_o}\right)^3\left[\frac{\left(D_o + D_i\right)_a}{(D_o + D_i)_o}\right] \qquad \text{... (6.25)}$$

Since the evaluation performance criteria had been set for equal diameter tubes, then equation (6.25) can be simplified for annuli having the same inner and outer diameters. The parenthesis of diameters in equation (6.25) can be omitted safely to give the equation:

$$\frac{P_a}{P_o} = \frac{f_a}{f_o}\frac{L_a}{L_o}\left(\frac{G_a}{G_o}\right)^3 \qquad \text{... (6.26)}$$

But the length ratio is equal to the ratio of the outer surface of the inner tube of the annulus, leading to:

$$\frac{P_a}{P_o} = \frac{f_a}{f_o}\frac{A_a}{A_o}\left(\frac{G_a}{G_o}\right)^3 \qquad \text{... (6.27)}$$

Equation (6.27) is the same as equation (3.30) having the area abbreviation referring to the area of the outer surface of the inner tube of the annulus. On the other hand, equation (3.28) can be used without any change because the area ratio stated there is the heat transfer surface area (outer surface of the inner tube in case of the annulus). Then, equations (3.28) and (6.27) can be used to produce the general equation of the performance evaluation criteria for annulus which is the same as equation (6.7) provided that both the inner and outer diameters of the annulus must be constant, i.e.

$$\left[\frac{h_a A_a / h_o A_o}{(P_a/P_o)^{1/3}(A_a/A_o)^{2/3}} = \frac{j_a/j_o}{(f_a/f_o)^{1/3}}\right]_{D_i, D_o} \qquad \text{... (6.28)}$$

This means that equations of the three ratios, derived for the tube-side enhancement, can be used for the annulus-side enhancement but with considering the specificity of the annulus, as shown later.

It is important to state that the area ratios in both equations (6.7) and (6.28) are the same as the effective length ratio for the double pipe heat exchanger because the only way to change the surface area, with keeping the diameters constant, is by changing the effective length of the exchanger.

In the present work, the PECs are applied for the annulus-side heat transfer enhancement by wire coils and circular ribs together, with using the concerned equations for each type, to make a direct comparison for the two cases. Moreover, the four experimental conditions have been briefed in one only because the differences caused by changing these conditions are very slight and cannot be recognized for comparison. The average values for physical properties of the four conditions have been considered. The application of the three criteria is as follows:

**( i ) FG-2a criterion:** using the modified conditions, the area of flow cross section is constant with keeping the $D_i$ and $D_o$ constant, as well as the tube length $L$ is kept constant. This would typically be applicable for retrofitting the smooth annulus of an existing exchanger with an enhanced one. The objective then could be to increase the heat load capacity (q) for the same approach temperature ($\Delta T_i$) and pumping power (P). The corresponding equation for the annulus-side heat enhancement is:

$$\frac{q_a}{q_o} = \left( \frac{Nu_a}{Nu_o} \right)_{L, D_i, D_o, \Delta T_i, P} \qquad \text{... (6.29)}$$

Likely, equation (6.10) also can be used safely to predict the corresponding Reynolds number $Re_o$ by direct solution with equation (5.10) for smooth annulus. $Nu_a$ is obtained by using equation (5.12) for annulus-side heat transfer enhancement by wire coil and by using equation (5.13) for the enhancement by circular ribs. Results obtained for the ($q_a/q_o$) are fixed in table C-45. The plot of these results is in fig. 6-12.

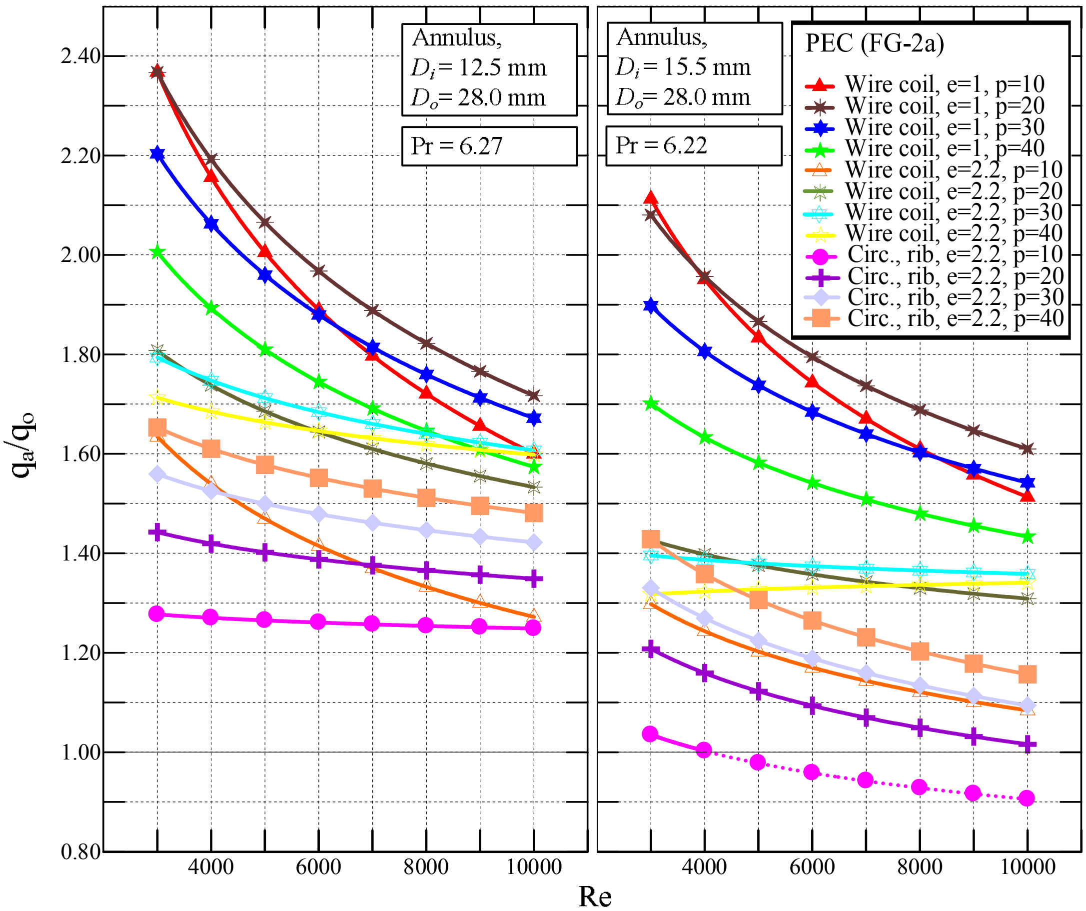



**Figure 6-12:** Application of the performance evaluation criterion (FG-2a) to the annulus-side heat transfer enhancement by wire coils and circular ribs for two annulus sizes and one experimental condition.

Figure 6-12 gives a very important conclusion for the annulus-side heat transfer enhancement study performed in the present work, where the most effective annulus-side insert geometries have become known which is the wire coil insert of geometries $e$=1 mm and $p$= 20 mm (i.e. $e/D_e$= 0.0645 and

$p/D_e$= 1.2903) for the whole Reynolds number range adopted in the present work. The value of the enhancement ratio is 2.367 for Re = 3000 and 1.717 for Re = 10000. These results are for the annulus of $D_i$=12.5 mm, for the $D_i$=15.5 mm annulus the result is something different, where the superiority is registered for the insert of $e$=1 mm and $p$= 20 mm (i.e. $e/D_e$= 0.08 and $p/D_e$= 1.6) for Reynolds number range larger than 4000, but for lower Reynolds numbers, the best is the insert of $e$= 1 mm and $p$= 10 mm ($e/D_e$= 0.08 and $p/D_e$= 0.8).

A general view of fig. 6-12 gives an imagination that the wire of 1 mm diameter has given the best thermal performance for all coiling pitches adopted, to the extent that even that of $p$ = 40 has a thermal performance better than that of the insert of $e$ = 2.2 mm for all coiling pitches. Moreover the circular ribs give the least performance to the extent that the circular ribs of 10 mm coiling pitches, in case of the annulus of $D_i$=15.5 mm, have a performance lower than smooth annulus.

**( ii ) FG-3 criterion:** to apply this criterion the basic geometry and size ($D_i$, $D_o$ and $L$) kept constant, i.e. constant heat exchange surface area. The objective then could be decreasing the pumping power with keeping the inlet temperature approach and the heat duty constant. Corresponding to equation (6.15), the equation of pumping power ratio for the annulus-side heat transfer enhancement is:

$$\frac{P_a}{P_o} = \left[\left(\frac{f_a}{f_o}\right)\left(\frac{\text{Re}_a}{\text{Re}_o}\right)^3\right]_{L,D_i,D_o,\Delta T_i,q} \quad \text{... (6.30)}$$

Equation (6.14) can be used for the annulus-side enhancement to evaluate the $\text{Re}_o$ required for calculating $f_o$ by equation (5.10) in a manner similar to that used for the tube-side heat transfer enhancement but with using the concerned equations of friction factor and heat transfer for the annulus-side heat transfer by wire coil and circular ribs which are equations (5.4) and (5.6) and (5.12) and (5.13) respectively. The predicted results of the ($P_a/P_o$) are listed in table C-46. Figure 6-13 shows these results.

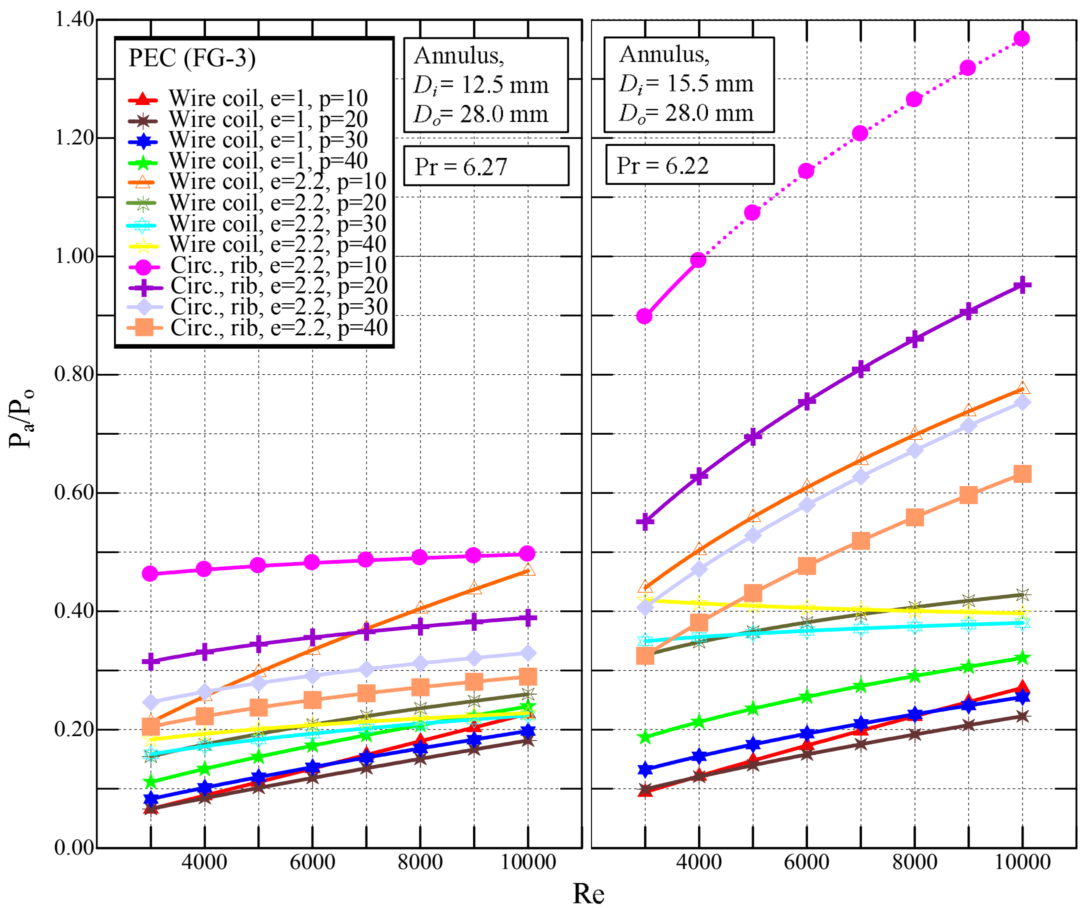



**Figure 6-13:** Application of the performance evaluation criterion (FG-3) to the annulus-side heat transfer enhancement by wire coils and circular ribs for two annulus sizes and one experimental condition.

In fig. 6-13 the best pumping power ratio, performed, is by the wire coil insert of geometries $e$=1 mm and $p$= 20 mm ($e/D_e$= 0.0645 and $p/D_e$= 1.2903) for the annulus of $D_i$=12.5 mm having the value of 0.066 at Re = 3000 and

0.094 performed by the wire coil of $e$=1 mm and $p$= 10 mm for the annulus of $D_i$=15.5 mm. And the best values for Re = 10000 is 0.182 and 0.223 for the two annuli respectively, both for the wire coil having $e$=1 mm and $p$= 20 mm. Close results for the inserts of $e$= 1 mm are observed. Furthermore, the circular ribs have the worst pumping power ratio in an arrangement similar to that observed in case of ($q_a/q_o$) ratio.

**( iii ) FN-1 criterion:** in this criterion the flow cross section is kept constant ($D_i$ and $D_o$ must be constant), and the heat exchanger length is allowed to vary. Here the objective is to seek a reduction in heat transfer surface area for a fixed heat load and pumping power. The equation corresponding to equation (6.22) for the heat exchange area or length reduction of annulus-side heat transfer enhancement is:

$$\frac{A_a}{A_o} = \left[\left(\frac{f_o}{f_a}\right)\left(\frac{\mathrm{Re}_o}{\mathrm{Re}_a}\right)^3\right]_{D_i, D_o, \Delta T_i, q, P} \qquad \text{... (6.31)}$$

The iterative solution of equation (6.21), (5.15) and (5.12) or (5.13) (the latter is for wire coil and circular ribs respectively) is followed to predict the requirements of equation (6.31) as explained previously. The predicted results are fixed in table C-47. These results are plotted in fig. 6-14 which shows that the best value of heat exchange surface area or length reduction in the double pipe heat exchanger is that performed by the wire coil of $e$=1 mm and $p$= 20 mm equaling 0.283 for the annulus of $D_i$=12.5 mm at Re = 3000. For the other annulus size the best value is 0.335 for the wire coil of $e$=1 mm and $p$=10 at Re = 3000, and the best values for Re = 10000 are 0.453 and 0.498 for the two annuli respectively, both performed by the wire coil of $e$=1 mm and $p$ = 20 mm. The circular ribs also give the worst surface area reduction and the wire coil of 2.2 mm is in between.

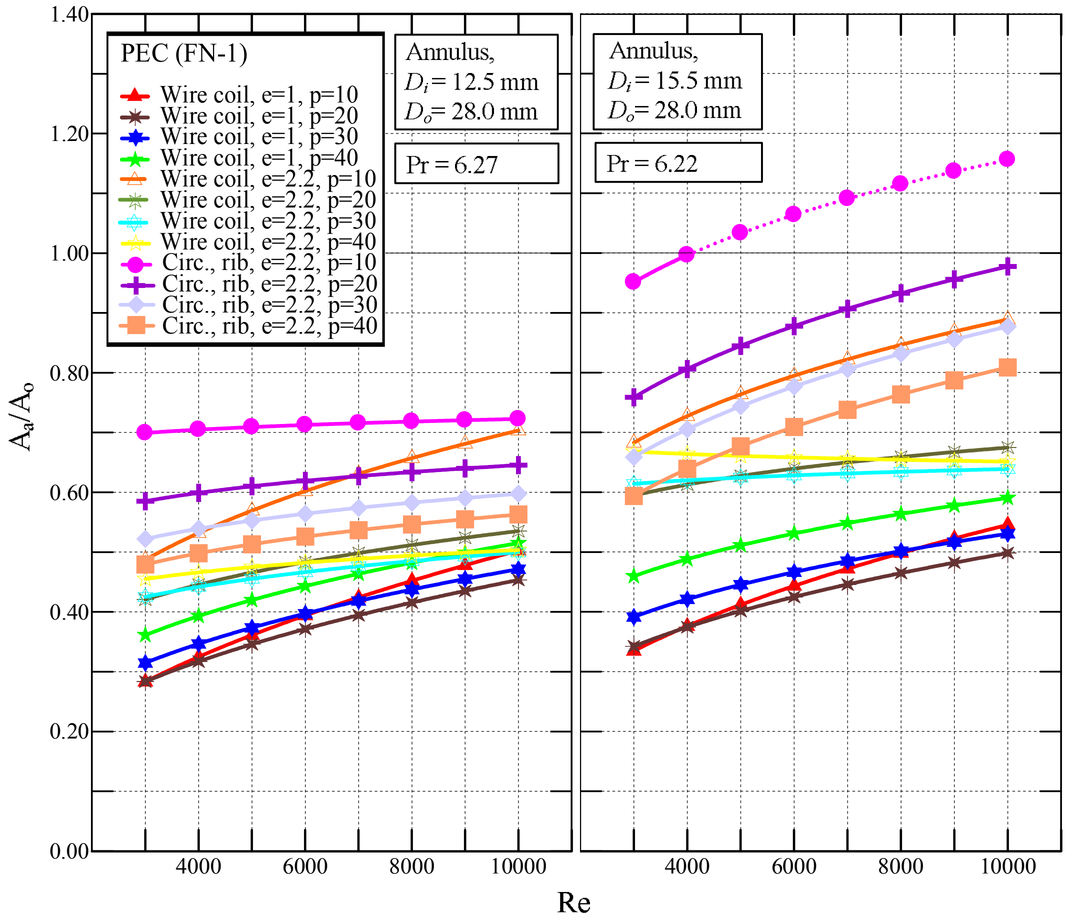



**Figure 6-14:** Application of the performance evaluation criterion (FN-1) to the annulus-side heat transfer enhancement by wire coils and circular ribs for two annulus sizes and one experimental condition.

In general, the wire coil of geometries $e$ = 1 mm and $p$ = 20 can be considered as the best heat transfer enhancer in the annulus for the three PECs studied in the present work for the ranges of geometries and sizes and Reynolds number adopted.

# CHAPTER SEVEN

# Conclusions and Recommendations

## 7.1 Conclusions

In the present work, the following can be concluded:

1- According to high performance results, the proposed method of annulus-side heat transfer enhancement by wire coils can be considered as a promising method of promoting heat transfer in the annulus of the double pipe heat exchanger.

2- For both tube and annulus side heat transfer enhancement, Nusselt number and friction factor are more dependent on Reynolds number at low values than high ones.

3- In the annulus-side enhancement, swirl flow is greatly important for enhancing heat transfer especially when the mechanism of separation and reattachment becomes weak when coils become relatively close with relatively low pressure drop as compared to inserts that forbid the generation of swirls (like circular ribs).

4- Friction factor and heat transfer in enhanced annuli are affected by the annular gap size.

5- In annulus-side enhancement, the performance of wire coils is better than circular ribs in all calculations and PECs.

6- Heat transfer, as well as friction factor increases with decreasing the coiling pitch in the tube-side heat transfer enhancement by wire coils giving a maximum heat transfer augmentation ratio of 2.43 compared to smooth tube at Re = 5000 with 4.75 augmentation of friction factor. That is obtained with wire coil of $e/d_i$= 0.0714 and $p/d_i$= 0.7143. The maximum values at Re = 40000 is given by the same wire coil. They are 2.24 and 6.83 respectively.

7- Heat transfer as well as friction factor increases with decreasing the coiling pitch in the annulus-side heat transfer enhancement by wire coil to a specified limit, then the relationship reflects giving a maximum heat transfer augmentation ratio of 3.25 compared to smooth annulus at Re = 3000 with 2.63 friction factor augmentation. That is obtained with wire coil of ($e/D_e$=0.0645 and $p/D_e$=0.6452). The maximum value at Re = 10000 is given by the wire coil of ($e/D_e$=0.176 and $p/D_e$=1.6). It is 2.49 with 4.66 friction factor augmentation.

8- The PEC calculations have determined that the best wire coil insert used in the tube-side enhancement in the ranges adopted is that having $e/d_i$= 0.0909 and $p/d_i$= 0.9091. In the annulus-side enhancement, the best insert is the wire coil of $e/D_e$= 0.0645 and $p/D_e$= 1.2903.

## 7.2 Recommendations

1- Using chemical additives with water or using other fluids, in addition to water, enables attaining a wider range of Prandtl number, either in tube-side or annulus-side heat transfer enhancement.

2- Using additional tube sizes for the tube-side heat transfer enhancement in order to increase the number of points to make correlations obtained more comprehensive.

3- In case of the annulus-side heat transfer enhancement by wire coil, using a wire coil of diameter in between 1 and 2.2 mm might lead to a better maximum of heat transfer enhancement.

4- Using circular ribs of diameter less than 2.2 to check if the circular ribs carry out a better performance.

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# Appendix A: Physical Properties of Liquid Water

Physical properties of water needed in the calculations of the present work are listed in table A-1 and plotted versus temperature in fig. A-1.

**Table A-1:** Physical Properties of Liquid Water [71, 72].

| T °C | $\rho$ ($kg/m^3$) | $\mu$ ($10^{-3}$) (Pa.s) | k (W/m.°C) |
|---|---|---|---|
| **12** | **999.5** | **1.2341** | **0.5856** |
| **14** | **999.2** | **1.1684** | **0.5892** |
| **16** | **998.9** | **1.1081** | **0.5927** |
| **18** | **998.6** | **1.0527** | **0.5961** |
| **20** | **998.2** | **1.0016** | **0.5995** |
| **22** | **997.8** | **0.9544** | **0.6027** |
| **24** | **997.3** | **0.9107** | **0.6059** |
| **26** | **996.8** | **0.8701** | **0.6090** |
| **28** | **996.2** | **0.8324** | **0.6120** |
| **30** | **995.6** | **0.7972** | **0.6150** |
| **32** | **995.0** | **0.7644** | **0.6178** |
| **34** | **994.4** | **0.7337** | **0.6206** |
| **36** | **993.7** | **0.7050** | **0.6233** |
| **38** | **993.0** | **0.6780** | **0.6260** |
| **40** | **992.2** | **0.6527** | **0.6286** |
| **42** | **991.4** | **0.6289** | **0.6311** |
| **44** | **990.6** | **0.6065** | **0.6335** |
| **46** | **989.8** | **0.5853** | **0.6359** |
| **48** | **988.9** | **0.5654** | **0.6382** |
| **50** | **988.0** | **0.5465** | **0.6405** |
| **52** | **987.1** | **0.5286** | **0.6426** |
| **54** | **986.2** | **0.5117** | **0.6448** |
| **56** | **985.2** | **0.4957** | **0.6468** |
| **58** | **984.2** | **0.4805** | **0.6488** |
| **60** | **983.2** | **0.4660** | **0.6508** |
| **62** | **982.2** | **0.4523** | **0.6526** |
| **64** | **981.1** | **0.4392** | **0.6545** |
| **66** | **980.0** | **0.4267** | **0.6562** |
| **68** | **978.9** | **0.4149** | **0.6579** |
| **70** | **977.8** | **0.4035** | **0.6596** |
| **72** | **976.6** | **0.3927** | **0.6612** |
| **74** | **975.4** | **0.3824** | **0.6627** |

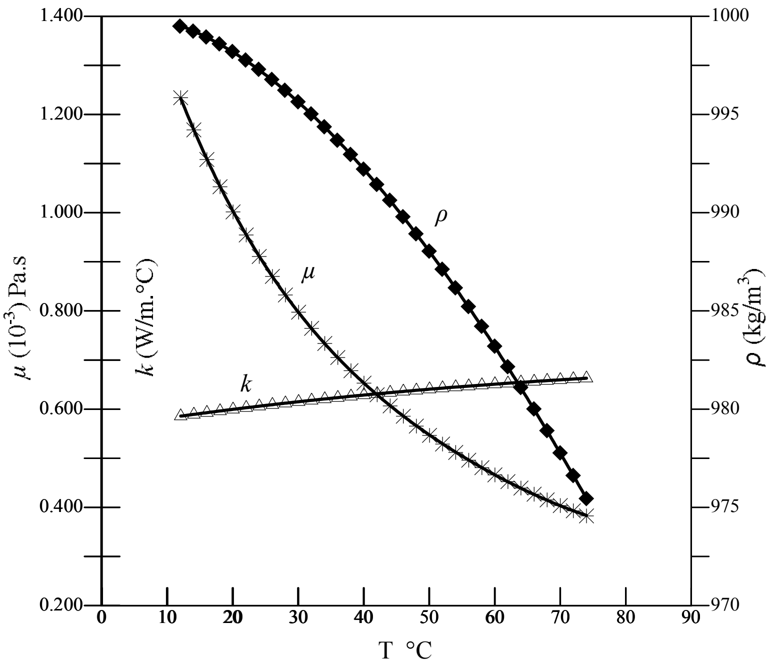


**Figure A-1:** Physical properties of liquid water.

These properties are correlated in three polynomials (as functions of temperature) to make them easy to be used in computer programs as below:

$$\rho = 1000.1 + 0.02215T - 0.00627T^2 + 0.00002T^3 \quad \text{... (A-1)}$$

$$\mu = \left(1777.2 - 58.616T + 1.3358T^2 - 0.02068T^3 + 0.00019T^4\right)\times 10^{-6} \quad \text{... (A-2)}$$

$$k = 0.56837 + 0.00211T - 1.11452\times 10^{-5}T^2 + 1.9724\times 10^{-8}T^3 \quad \text{... (A-3)}$$

where T in degree centigrade. In addition, the heat capacity, Cp is fixed at a value of 4.184 kJ/kg.K and 4.182 kJ/kg.K for hot and cold water, respectively, because the change in the heat capacity values is very slight through the range of temperatures, adopted.

# Appendix B: Calibration of Measurement Instrumentations

## B.1 Calibration of Thermocouples and Temperature Reader

The four thermocouples together with the temperature reader device are calibrated by using a mercury thermometer. Calibration results are fixed in table B-1

**Table B-1:** Calibration of Thermocouples.

| $T_{real}$ °C | $T_{h1}$ °C | $T_{h2}$ °C | $T_{c1}$ °C | $T_{c2}$ °C |
|---|---|---|---|---|
| 17.5 | 16.77 | 16.85 | 16.70 | 16.63 |
| 19.0 | 18.23 | 18.39 | 18.52 | 18.44 |
| 21.0 | 20.36 | 20.65 | 20.57 | 20.45 |
| 22.5 | 21.80 | 21.99 | 22.08 | 21.56 |
| 24.0 | 23.45 | 23.53 | 23.64 | 23.47 |
| 25.0 | 24.40 | 24.25 | 24.66 | 24.48 |
| 27.0 | 26.49 | 26.61 | 26.50 | 26.79 |
| 29.5 | 29.04 | 29.17 | 29.47 | 29.01 |
| 31.0 | 30.50 | 30.91 | 30.97 | 30.52 |
| 33.0 | 32.69 | 32.77 | 32.85 | 32.53 |
| 34.5 | 34.10 | 34.31 | 34.38 | 34.15 |
| 35.5 | 35.23 | 35.04 | 35.01 | 35.05 |
| 37.0 | 36.70 | 36.88 | 36.94 | 36.56 |
| 39.0 | 38.82 | 38.93 | 38.99 | 38.58 |
| 41.0 | 40.80 | 40.78 | 41.33 | 40.59 |
| 43.0 | 42.91 | 43.04 | 43.08 | 42.44 |
| 45.0 | 44.80 | 45.49 | 45.20 | 44.62 |
| 47.5 | 47.59 | 47.66 | 47.68 | 47.14 |
| 49.0 | 49.23 | 49.21 | 49.22 | 48.65 |
| 51.0 | 51.09 | 51.05 | 51.06 | 50.21 |
| 53.0 | 53.14 | 53.30 | 53.31 | 52.67 |
| 55.0 | 55.19 | 55.36 | 55.36 | 54.69 |
| 57.5 | 57.71 | 58.00 | 57.41 | 57.21 |
| 59.0 | 59.51 | 59.46 | 59.45 | 58.70 |
| 60.5 | 60.90 | 61.01 | 60.98 | 60.23 |
| 63.0 | 63.46 | 63.30 | 63.52 | 62.75 |
| 65.0 | 65.31 | 65.63 | 65.59 | 65.00 |
| 66.5 | 66.99 | 67.17 | 67.32 | 66.27 |
| 68.0 | 68.53 | 69.11 | 68.89 | 67.78 |
| 70.0 | 70.70 | 70.76 | 70.70 | 69.49 |
| 72.0 | 72.60 | 72.52 | 72.35 | 71.81 |
| 75.0 | 75.71 | 75.89 | 75.60 | 74.83 |

Values of the four thermocouples are so close that they cannot be distinguished if plotted. Correlating the values above gives calibration curves (straight lines)

$$T_{h1} = 0.9744 T_{h1,real} + 1.2018 \quad \text{... (B.1)}$$

$$T_{h2} = 0.9740 T_{h2,real} + 1.0910 \quad \text{... (B.2)}$$

$$T_{c1} = 0.9779 T_{c1,real} + 0.9035 \quad \text{... (B.3)}$$

$$T_{c2} = 0.9924 T_{c2,real} + 0.7511 \quad \text{... (B-4)}$$

## B.2 Calibration of Rotameter

The rotameter is calibrated manually by using a graduated container of 100 liter volume and a stop watch at four temperatures (20, 40, 60 and 70 °C). The results of the calibration process are fixed in table B-2 and plotted in fig. B-1.

**Table B-2**: Calibration of the Rotameter at 20, 40, 60 and 70 °C.

| $Q_{meas.}$ ($m^3$/hr) | $Q_{obs.}$ ($m^3$/hr) | | | |
|---|---|---|---|---|
| | 20 °C | 40 °C | 60 °C | 70 °C |
| 0.20 | 0.169 | 0.196 | 0.209 | 0.211 |
| 0.30 | 0.264 | 0.291 | 0.307 | 0.308 |
| 0.40 | 0.359 | 0.394 | 0.413 | 0.411 |
| 0.50 | 0.451 | 0.489 | 0.513 | 0.511 |
| 0.60 | 0.551 | 0.593 | 0.608 | 0.617 |
| 0.70 | 0.642 | 0.691 | 0.725 | 0.724 |
| 0.80 | 0.762 | 0.802 | 0.837 | 0.842 |
| 0.90 | 0.846 | 0.884 | 0.932 | 0.936 |
| 1.00 | 0.944 | 0.991 | 1.039 | 1.041 |
| 1.10 | 1.046 | 1.095 | 1.146 | 1.146 |
| 1.20 | 1.139 | 1.185 | 1.240 | 1.255 |
| 1.30 | 1.231 | 1.291 | 1.347 | 1.350 |

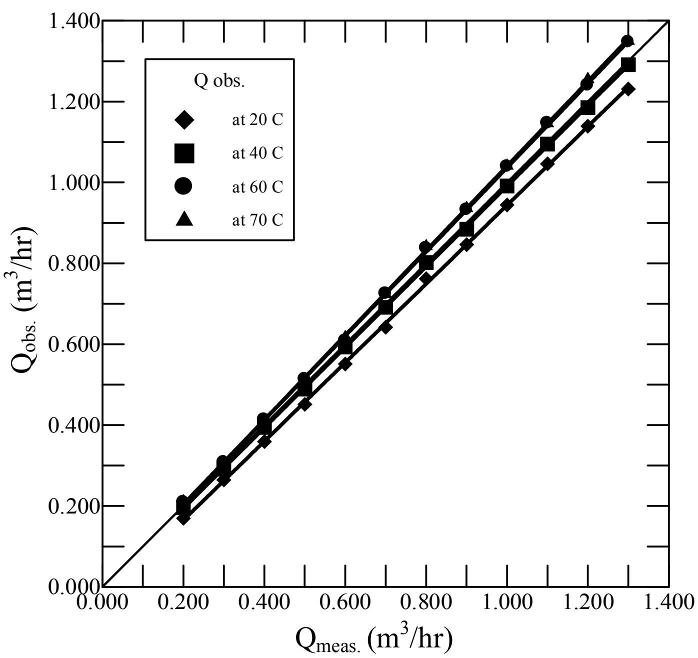


**Figure B-1**: Calibration of the rotameter at 20, 40, 60 and 70 °C.

The calibration curves of the rotameter at the four temperatures which are plotted above are

$$Q_{obs.,20C} = 0.9739 Q_{meas.} - 0.0301 \quad \text{... (B.5)}$$

$$Q_{obs.,40C} = 0.9960 Q_{meas.} - 0.0053 \quad \text{... (B.6)}$$

$$Q_{obs.,60C} = 1.0411 Q_{meas.} - 0.0045 \quad \text{... (B.7)}$$

$$Q_{obs.,70C} = 1.0468 Q_{meas.} - 0.0057 \quad \text{... (B.8)}$$

where Q is in $m^3$/hr. Equations above are used to correct the values of the volumetric flowrates taken from the rotameter.

### B.3 Design and Calibration of the Orifice Plate

An orifice plate is designed as in fig. B-2. The inner diameter of the connecting pipe ($D_1$) is 16 mm and the plate perforation ($D_0$) is 6 mm diameter. To avoid manufacture defaults, actual values of volumetric flowrates are intended to be considered in graduating the mercury manometer and finding an equation for the water manometer to be used in the computer program, so values of an actual calibration are used to produce these equations (volumetric flowrate as a function of pressure drop in mmHg and mm$H_2O$ respectively). The calibration values at 60 and 70 °C are listed in table B-3 and plotted in fig. B-3. The equations produced via curve fitting are

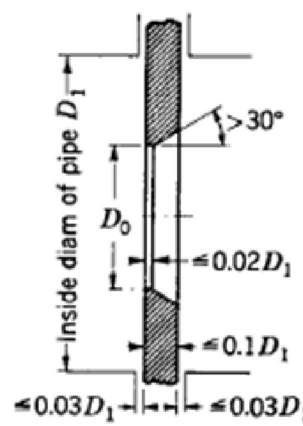


**Figure B-2:** An orifice plate design [37].

$$Q_{obs.,60C} = 0.0233 / \left(\Delta p_{H_2O}\right)^{0.4801} \quad \text{... (B.9)}$$

$$Q_{obs.,60C} = 0.0764 / \left(\Delta p_{Hg}\right)^{0.4996} \quad \text{... (B.10)}$$

$$Q_{obs.,70C} = 0.0206 / \left(\Delta p_{H_2O}\right)^{0.5062} \quad \text{... (B.11)}$$

$$Q_{obs.,70C} = 0.0720/(\Delta p_{Hg})^{0.5093} \quad \text{... (B.12)}$$

Equations (B.10) and (B.12) are used to graduate the mercury manometer, while equations (B.9) and (B.11) are used to determine the flowrate by using the computer program.

**Table B-3**: Calibration of the Orifice Plate at 60 and 70 °C.

| 60 °C | | | 70 °C | | |
|---|---|---|---|---|---|
| $Q_{obs.}$ ($m^3$/hr) | Δp ($mmH_2O$) | Δp (mmHg) | $Q_{obs.}$ ($m^3$/hr) | Δp ($mmH_2O$) | Δp (mmHg) |
| 0.11 | 26 | 1.9 | 0.0833 | 16 | 1.25 |
| 0.14 | 37 | 3 | 0.1134 | 29 | 2.50 |
| 0.165 | 63 | 5 | 0.1325 | 39 | 3.25 |
| 0.186 | 83 | 6.3 | 0.1600 | 57 | 5.00 |
| 0.226 | 120 | 10 | 0.2037 | 92 | 8.25 |
| 0.272 | 163 | 13.5 | 0.3084 | 210 | 17.5 |
| 0.308 | 203 | 16.5 | 0.4130 | 375 | 31.0 |
| 0.412 | --- | 28.5 | 0.5177 | --- | 46.5 |
| 0.516 | --- | 44 | 0.6224 | --- | 67.5 |
| 0.62 | --- | 62 | 0.7270 | --- | 93.0 |
| 0.724 | --- | 87.5 | 0.8318 | --- | 123.5 |
| 0.828 | --- | 119 | --- | --- | --- |

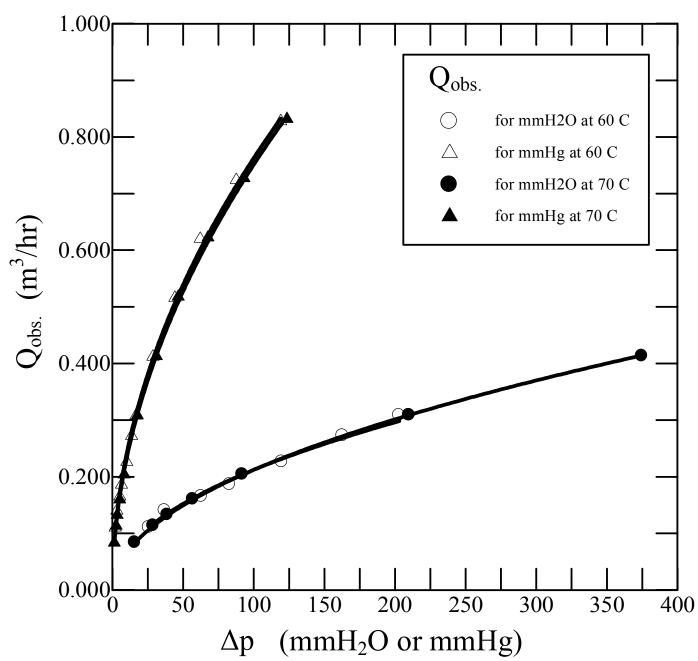


**Figure B-3**: Calibration of the orifice at 60 and 70 °C.

# Appendix C: Experimental and Predicted Results.

This part includes the experimental and predicted results, either plotted or used to complete calculations. To recognize the plotted values, they are written in *Italic*.

For place saving, only some of the tables (C-1, C-2, C-19, C-20, C-37, C-41and C-42) are presented in printed matter. The others are included in a CD-ROM on the back cover of the thesis.

**Table C-1:** Experimental Results of Tube-Side Heat Transfer Enhancement for Two Sizes of Inner Tube (Enhancement Status: Smooth Tube).

| Re Inner tube | $Q_h$ $10^{-4}$ ($m^3/s$) | Temperatures and Temperature Difference (°C) $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | Pressure Drop: Inner tube $mmH_2O$ | Inner tube $N/m^2$ | Annulus $mmH_2O$ | Annulus $N/m^2$ | Heat Transfer Rate (W) $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m | | | | | | | | | | | | | | |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s | | | | | | | | | | | | | | |
| 5000 | 0.2192 | 60.23 | 50.76 | 22.17 | 20.12 | 34.22 | 12.5 | *122.2* | 8 | 78.34 | 855.732 | 857.31 | *856.521* | 0.18 |
| 10000 | 0.4286 | 60.18 | 53.76 | 22.70 | 20.04 | 35.57 | 41.7 | *407.9* | 8 | 78.34 | 1133.75 | 1112.41 | *1123.08* | 1.90 |
| 15000 | 0.6356 | 60.24 | 55.23 | 22.95 | 19.90 | 36.30 | 78.7 | *770.5* | 7.5 | 73.44 | 1311.47 | 1275.51 | *1293.49* | 2.78 |
| 20000 | 0.8383 | 60.36 | 56.57 | 23.47 | 20.40 | 36.53 | 126 | *1233* | 7 | 68.55 | 1308.02 | 1283.87 | *1295.95* | 1.86 |
| 25000 | 1.0476 | 60.07 | 56.90 | 23.27 | 19.95 | 36.87 | 176 | *1722* | 7 | 68.55 | 1367.13 | 1388.42 | *1377.78* | 1.55 |
| 30000 | 1.2477 | 60.48 | 57.50 | 23.79 | 20.30 | 36.94 | 254 | *2484* | 7.5 | 73.44 | 1530.33 | 1459.52 | *1494.92* | 4.74 |
| 35000 | 1.4536 | 60.31 | 57.86 | 23.66 | 20.14 | 37.18 | 322 | *3154* | 7 | 68.55 | 1465.72 | 1472.06 | *1468.89* | 0.43 |
| 40000 | 1.6594 | 60.32 | 58.00 | 23.81 | 20.18 | 37.16 | 410 | *4015* | 7.5 | 73.44 | 1584.41 | 1518.07 | *1551.24* | 4.28 |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s | | | | | | | | | | | | | | |
| 5000 | 0.2252 | 60.32 | 47.14 | 22.05 | 20.17 | 32.29 | 13 | *126.9* | 17.5 | 171.40 | 1224.92 | 1179.32 | *1202.12* | 3.79 |
| 10000 | 0.4355 | 60.23 | 51.60 | 22.55 | 20.10 | 34.5 | 40.7 | *398.8* | 17 | 166.50 | 1549.37 | 1536.89 | *1543.13* | 0.81 |
| 15000 | 0.6437 | 60.35 | 53.43 | 23.30 | 20.44 | 34.98 | 80.5 | *788.6* | 17 | 166.50 | 1835.35 | 1794.08 | *1814.72* | 2.27 |
| 20000 | 0.8526 | 60.25 | 54.41 | 23.49 | 20.37 | 35.38 | 131 | *1278* | 17 | 166.50 | 2051.14 | 1957.18 | *2004.16* | 4.69 |
| 25000 | 1.0585 | 60.25 | 55.32 | 23.40 | 20.00 | 36.08 | 193 | *1894* | 17 | 166.50 | 2149.22 | 2132.82 | *2141.02* | 0.77 |
| 30000 | 1.2610 | 60.43 | 56.12 | 24.00 | 20.50 | 36.02 | 256 | *2511* | 17 | 166.50 | 2237.75 | 2195.55 | *2216.65* | 1.90 |
| 35000 | 1.4663 | 60.42 | 56.58 | 24.13 | 20.40 | 36.23 | 330 | *3227* | 17 | 166.50 | 2317.98 | 2339.83 | *2328.91* | 0.94 |
| 40000 | 1.6710 | 60.40 | 56.98 | 24.35 | 20.48 | 36.27 | 413 | *4043* | 17 | 166.50 | 2352.5 | 2427.65 | *2390.08* | 3.14 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s | | | | | | | | | | | | | | |
| 5000 | 0.1971 | 69.80 | 55.52 | 22.77 | 20.14 | 40.93 | 9.72 | *95.18* | 8 | 78.34 | 1156.07 | 1099.87 | *1127.97* | 4.98 |
| 10000 | 0.3793 | 69.85 | 60.76 | 23.85 | 20.3 | 43.17 | 31.5 | *308.2* | 8 | 78.34 | 1414.22 | 1484.61 | *1449.42* | 4.86 |
| 15000 | 0.5603 | 69.78 | 62.92 | 24.03 | 20.1 | 44.27 | 63.9 | *625.4* | 8 | 78.34 | 1575.67 | 1643.53 | *1609.6* | 4.22 |
| 20000 | 0.7392 | 69.96 | 64.17 | 24.47 | 20.32 | 44.66 | 98.1 | *960.8* | 8 | 78.34 | 1753.86 | 1735.53 | *1744.7* | 1.05 |
| 25000 | 0.9125 | 70.20 | 65.60 | 24.21 | 20.00 | 45.79 | 141 | *1378* | 7 | 68.55 | 1719.39 | 1760.62 | *1740* | 2.37 |
| 30000 | 1.0910 | 70.12 | 66.17 | 24.41 | 20.00 | 45.94 | 193 | *1885* | 7 | 68.55 | 1764.96 | 1844.26 | *1804.61* | 4.39 |
| 35000 | 1.2645 | 70.32 | 66.84 | 24.88 | 20.38 | 45.95 | 247 | *2420* | 7 | 68.55 | 1801.78 | 1881.9 | *1841.84* | 4.35 |
| 40000 | 1.4454 | 70.16 | 66.98 | 24.71 | 20.30 | 46.06 | 313 | *3064* | 7 | 68.55 | 1881.96 | 1844.26 | *1863.11* | 2.02 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s | | | | | | | | | | | | | | |
| 5000 | 0.2027 | 69.77 | 51.70 | 22.19 | 19.90 | 39.16 | 10.2 | *99.71* | 18 | 176.3 | 1506.05 | 1436.52 | *1471.28* | 4.73 |
| 10000 | 0.3881 | 69.77 | 57.68 | 22.95 | 20.02 | 42.07 | 33.3 | *326.3* | 17 | 166.5 | 1926.39 | 1837.99 | *1882.19* | 4.70 |
| 15000 | 0.5701 | 70.00 | 60.32 | 23.50 | 20.00 | 43.34 | 62 | *607.3* | 17 | 166.5 | 2263.99 | 2195.55 | *2229.77* | 3.07 |
| 20000 | 0.7480 | 70.30 | 62.22 | 23.91 | 20.12 | 44.21 | 101 | *988* | 17 | 166.5 | 2477.92 | 2377.47 | *2427.69* | 4.14 |
| 25000 | 0.9299 | 70.14 | 63.12 | 24.45 | 20.33 | 44.22 | 145 | *1423* | 17 | 166.5 | 2675.87 | 2584.48 | *2630.17* | 3.47 |
| 30000 | 1.1057 | 70.30 | 64.20 | 24.42 | 20.00 | 45.03 | 196 | *1922* | 17 | 166.5 | 2763.76 | 2772.67 | *2768.21* | 0.32 |
| 35000 | 1.2858 | 70.14 | 64.80 | 24.86 | 20.19 | 44.94 | 255 | *2493* | 17 | 166.5 | 2813.08 | 2929.49 | *2871.29* | 4.05 |
| 40000 | 1.4621 | 70.34 | 65.27 | 24.85 | 20.15 | 45.30 | 323 | *3163* | 17 | 166.5 | 3036.59 | 2948.31 | *2992.45* | 2.95 |
| Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m | | | | | | | | | | | | | | |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s | | | | | | | | | | | | | | |
| 5000 | 0.2788 | 59.87 | 51.20 | 22.55 | 20.12 | 34.10 | 6.2 | *60.870* | 16 | 156.68 | 996.479 | 1016.23 | *1006.35* | 1.96 |
| 10000 | 0.5470 | 59.97 | 53.62 | 23.66 | 20.07 | 34.91 | 18.5 | *181.29* | 16 | 156.68 | 1431.11 | 1501.34 | *1466.23* | 4.79 |
| 15000 | 0.8098 | 60.10 | 55.23 | 24.22 | 20.17 | 35.47 | 38.9 | *380.70* | 16 | 156.68 | 1624.26 | 1693.71 | *1658.98* | 4.19 |
| 20000 | 1.0723 | 60.22 | 56.03 | 24.81 | 20.37 | 35.53 | 62.9 | *616.37* | 15 | 146.89 | 1850.10 | 1856.81 | *1853.45* | 0.36 |
| 25000 | 1.3295 | 60.50 | 56.85 | 25.00 | 20.41 | 35.97 | 91.6 | *897.37* | 15 | 146.89 | 1997.62 | 1919.54 | *1958.58* | 3.99 |
| 30000 | 1.5968 | 60.13 | 57.10 | 25.04 | 20.45 | 35.86 | 126 | *1232.7* | 14 | 137.09 | 1991.79 | 1919.54 | *1955.66* | 3.69 |
| 35000 | 1.8507 | 60.42 | 57.70 | 25.22 | 20.32 | 36.28 | 158 | *1550.0* | 14 | 137.09 | 2071.83 | 2049.18 | *2060.51* | 1.10 |
| 40000 | 2.1142 | 60.30 | 57.88 | 25.32 | 20.38 | 36.23 | 205 | *2003.2* | 14 | 137.09 | 2105.69 | 2065.91 | *2085.80* | 1.91 |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s | | | | | | | | | | | | | | |
| 5000 | 0.2816 | 59.86 | 49.91 | 21.64 | 19.78 | 34.01 | 6.48 | *63.450* | 29 | 283.98 | 1155.42 | 1166.78 | *1161.10* | 0.98 |
| 10000 | 0.5534 | 59.84 | 52.20 | 22.82 | 19.97 | 34.57 | 18.5 | *181.29* | 29 | 283.98 | 1742.84 | 1787.81 | *1765.32* | 2.55 |
| 15000 | 0.8177 | 60.37 | 53.66 | 23.65 | 20.22 | 35.05 | 40.7 | *398.83* | 29 | 283.98 | 2260.62 | 2151.64 | *2206.13* | 4.94 |
| 20000 | 1.0806 | 60.42 | 54.80 | 24.12 | 20.30 | 35.39 | 63.9 | *625.44* | 29 | 283.98 | 2501.33 | 2396.29 | *2448.81* | 4.29 |
| 25000 | 1.3461 | 60.26 | 55.42 | 24.10 | 20.02 | 35.78 | 87.9 | *861.11* | 29 | 283.98 | 2683.16 | 2559.38 | *2621.27* | 4.72 |
| 30000 | 1.6125 | 60.06 | 55.86 | 24.40 | 20.16 | 35.68 | 129 | *1259.9* | 28 | 274.19 | 2788.86 | 2659.75 | *2724.31* | 4.74 |
| 35000 | 1.8653 | 60.40 | 56.66 | 24.88 | 20.27 | 35.95 | 160 | *1568.1* | 28 | 274.19 | 2872.01 | 2891.85 | *2881.93* | 0.69 |
| 40000 | 2.1300 | 60.30 | 56.87 | 24.95 | 20.37 | 35.92 | 206 | *2021.3* | 27 | 264.39 | 3007.69 | 2873.03 | *2940.36* | 4.58 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s | | | | | | | | | | | | | | |
| 5000 | 0.2469 | 69.95 | 57.53 | 22.93 | 19.97 | 42.11 | 5.09 | *49.854* | 16 | 156.68 | 1259.06 | 1237.87 | *1248.47* | 1.70 |
| 10000 | 0.4801 | 70.14 | 61.22 | 24.32 | 20.00 | 43.48 | 13.9 | *135.96* | 15 | 146.89 | 1756.23 | 1806.62 | *1781.43* | 2.83 |
| 15000 | 0.7107 | 70.21 | 62.95 | 25.00 | 20.11 | 44.01 | 28.7 | *280.99* | 15 | 146.89 | 2114.87 | 2045.00 | *2079.94* | 3.36 |
| 20000 | 0.9369 | 70.34 | 64.34 | 25.67 | 20.22 | 44.39 | 50.9 | *498.54* | 15 | 146.89 | 2303.37 | 2279.19 | *2291.28* | 1.06 |
| 25000 | 1.1673 | 70.14 | 64.98 | 26.00 | 20.33 | 44.39 | 68.5 | *670.76* | 15 | 146.89 | 2467.71 | 2371.19 | *2419.45* | 3.99 |
| 30000 | 1.3875 | 70.43 | 65.96 | 26.53 | 20.26 | 44.79 | 93.5 | *915.5* | 15 | 146.89 | 2540.05 | 2622.11 | *2581.08* | 3.18 |
| 35000 | 1.6149 | 70.35 | 66.36 | 26.14 | 20.11 | 45.22 | 119 | *1169.3* | 14 | 137.09 | 2638.55 | 2521.75 | *2580.15* | 4.53 |
| 40000 | 1.8403 | 70.35 | 66.74 | 26.48 | 20.17 | 45.21 | 147 | *1441.2* | 14 | 137.09 | 2720.17 | 2638.84 | *2679.51* | 3.04 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s | | | | | | | | | | | | | | |
| 5000 | 0.2498 | 69.85 | 56.04 | 22.51 | 20.14 | 41.36 | 5.09 | *49.854* | 28 | 274.19 | 1416.84 | 1486.7 | *1451.77* | 4.81 |
| 10000 | 0.4889 | 69.77 | 59.10 | 23.37 | 20.12 | 42.58 | 15.7 | *154.09* | 28 | 274.19 | 2140.76 | 2038.73 | *2089.74* | 4.88 |
| 15000 | 0.7239 | 69.88 | 60.76 | 24.21 | 20.00 | 43.17 | 30.5 | *299.12* | 28 | 274.19 | 2708.17 | 2640.93 | *2674.55* | 2.51 |
| 20000 | 0.9528 | 70.00 | 62.41 | 24.97 | 20.23 | 43.59 | 49.1 | *480.41* | 28 | 274.19 | 2964.95 | 2973.4 | *2969.18* | 0.28 |
| 25000 | 1.1802 | 70.23 | 63.41 | 25.28 | 20.22 | 44.06 | 65.7 | *643.57* | 27 | 264.39 | 3299.00 | 3174.14 | *3236.57* | 3.86 |
| 30000 | 1.4085 | 70.13 | 64.25 | 25.58 | 20.38 | 44.21 | 91.6 | *897.37* | 27 | 264.39 | 3393.79 | 3261.96 | *3327.88* | 3.96 |
| 35000 | 1.6328 | 70.24 | 65.00 | 26.00 | 20.27 | 44.48 | 123 | *1205.6* | 27 | 264.39 | 3505.09 | 3594.43 | *3549.76* | 2.52 |
| 40000 | 1.8562 | 70.32 | 65.63 | 26.11 | 20.15 | 44.84 | 156 | *1522.8* | 26 | 254.6 | 3565.64 | 3738.71 | *3652.17* | 4.74 |

**Table C-2:** Experimental Results of Tube-Side Heat Transfer Enhancement for Two Sizes of Inner Tube (Enhancement Status: Wire coil, e= 1 mm, p= 10 mm).

| Re | $Q_h$ $10^{-4}$ | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| Inner tube | ($m^3$/s) | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | N/$m^2$ | $mmH_2O$ | N/$m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| 5000 | 0.2265 | 59.87 | 46.87 | 23.20 | 20.34 | 31.33 | 65.11 | *637.58* | 9.5 | 93.03 | 1215.22 | 1196.05 | *1205.64* | 1.59 |
| 10000 | 0.4336 | 60.50 | 51.92 | 23.90 | 20.34 | 34.03 | 226.4 | *2216.9* | 9 | 88.13 | 1533.28 | 1488.79 | *1511.04* | 2.94 |
| 15000 | 0.6432 | 60.05 | 53.84 | 23.99 | 20.34 | 34.76 | 483.1 | *4730.5* | 9 | 88.13 | 1645.63 | 1526.43 | *1586.03* | 7.52 |
| 20000 | 0.8503 | 60.13 | 54.90 | 24.37 | 20.18 | 35.24 | 826 | *8088.5* | 9.5 | 93.03 | 1831.64 | 1752.26 | *1791.95* | 4.43 |
| 25000 | 1.0512 | 60.32 | 56.18 | 24.29 | 20.19 | 36.01 | 1241 | *12156* | 9 | 88.13 | 1791.93 | 1714.62 | *1753.27* | 4.41 |
| 30000 | 1.2526 | 60.50 | 56.95 | 24.33 | 20.16 | 36.48 | 1738 | *17023* | 9 | 88.13 | 1830.46 | 1743.89 | *1787.18* | 4.84 |
| 35000 | 1.4580 | 60.43 | 57.33 | 24.65 | 20.35 | 36.38 | 2315 | *22670* | 9 | 88.13 | 1860.41 | 1798.26 | *1829.34* | 3.4 |
| 40000 | 1.6619 | 60.46 | 57.66 | 24.54 | 20.14 | 36.71 | 3004 | *29414* | 9 | 88.13 | 1915.14 | 1840.08 | *1877.61* | 4.00 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| 5000 | 0.2310 | 60.23 | 44.00 | 22.60 | 20.11 | 30.24 | 66.65 | *652.63* | 18 | 176.3 | 1548.41 | 1561.98 | *1555.19* | 0.87 |
| 10000 | 0.4437 | 60.27 | 49.12 | 23.30 | 20.19 | 32.79 | 245.3 | *2402* | 18 | 176.3 | 2040.79 | 1950.90 | *1995.84* | 4.50 |
| 15000 | 0.6526 | 60.25 | 51.72 | 23.80 | 20.15 | 33.95 | 493.4 | *4831.3* | 18 | 176.3 | 2294.61 | 2289.65 | *2292.13* | 0.22 |
| 20000 | 0.8599 | 60.18 | 53.35 | 24.15 | 20.21 | 34.56 | 840.5 | *8230.4* | 18 | 176.3 | 2420.02 | 2471.56 | *2445.79* | 2.11 |
| 25000 | 1.0655 | 60.25 | 54.45 | 24.20 | 20.29 | 35.10 | 1267 | *12409* | 17.5 | 171.4 | 2545.58 | 2452.74 | *2499.16* | 3.71 |
| 30000 | 1.2705 | 60.24 | 55.31 | 24.40 | 20.19 | 35.48 | 1786 | *17485* | 17.5 | 171.4 | 2577.45 | 2640.93 | *2609.19* | 2.43 |
| 35000 | 1.4736 | 60.33 | 56.00 | 24.70 | 20.50 | 35.56 | 2374 | *23250* | 17 | 166.5 | 2627.27 | 2634.66 | *2630.96* | 0.28 |
| 40000 | 1.6820 | 60.25 | 56.25 | 24.60 | 20.23 | 35.83 | 3063 | *29994* | 17.5 | 171.4 | 2769.75 | 2741.30 | *2755.52* | 1.03 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| 5000 | 0.2022 | 70.00 | 51.79 | 23.80 | 20.32 | 38.36 | 52.76 | *516.67* | 9 | 88.13 | 1514.04 | 1455.34 | *1484.69* | 3.95 |
| 10000 | 0.3845 | 70.13 | 58.61 | 24.97 | 20.50 | 41.54 | 183.3 | *1794.7* | 9 | 88.13 | 1817.80 | 1869.35 | *1843.58* | 2.80 |
| 15000 | 0.5637 | 70.42 | 61.45 | 25.00 | 20.41 | 43.19 | 367.5 | *3598.5* | 9 | 88.13 | 2073.39 | 1919.54 | *1996.46* | 7.71 |
| 20000 | 0.7401 | 70.44 | 63.53 | 25.26 | 20.38 | 44.16 | 626.7 | *6136.5* | 8.5 | 83.24 | 2095.70 | 2040.82 | *2068.26* | 2.65 |
| 25000 | 0.9190 | 70.50 | 64.35 | 25.50 | 20.23 | 44.56 | 948.8 | *9290.9* | 9 | 88.13 | 2315.75 | 2203.91 | *2259.83* | 4.95 |
| 30000 | 1.0989 | 70.18 | 65.15 | 25.69 | 20.37 | 44.64 | 1340 | *13125* | 9 | 88.13 | 2264.39 | 2225.66 | *2245.02* | 1.73 |
| 35000 | 1.2744 | 70.23 | 65.90 | 25.65 | 20.40 | 45.04 | 1782 | *17449* | 8.5 | 83.24 | 2260.04 | 2195.55 | *2227.79* | 2.89 |
| 40000 | 1.4488 | 70.33 | 66.50 | 25.75 | 20.37 | 45.35 | 2283 | *22353* | 8.5 | 83.24 | 2272.16 | 2248.84 | *2260.50* | 1.03 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| 5000 | 0.2079 | 70.23 | 47.81 | 22.88 | 19.95 | 36.75 | 56.46 | *552.92* | 17 | 166.5 | 1918.02 | 1837.99 | *1878.01* | 4.26 |
| 10000 | 0.3943 | 70.33 | 54.95 | 24.05 | 20.23 | 40.22 | 187.9 | *1840.1* | 18 | 176.3 | 2491.00 | 2396.29 | *2443.64* | 3.88 |
| 15000 | 0.5775 | 70.30 | 58.25 | 24.55 | 20.00 | 41.89 | 381.4 | *3734.5* | 18 | 176.3 | 2856.24 | 2854.22 | *2855.23* | 0.07 |
| 20000 | 0.7597 | 70.16 | 60.25 | 24.75 | 19.97 | 42.79 | 659.1 | *6453.8* | 18 | 176.3 | 3088.27 | 2998.49 | *3043.38* | 2.95 |
| 25000 | 0.9384 | 70.41 | 61.62 | 25.48 | 20.24 | 43.13 | 982.1 | *9617.2* | 17.5 | 171.4 | 3382.18 | 3287.05 | *3334.62* | 2.85 |
| 30000 | 1.1163 | 70.10 | 63.11 | 25.14 | 19.90 | 44.08 | 1375 | *13461* | 17.5 | 171.4 | 3198.55 | 3287.05 | *3242.80* | 2.73 |
| 35000 | 1.2919 | 70.30 | 64.00 | 25.45 | 20.22 | 44.31 | 1834 | *17956* | 17 | 166.5 | 3335.24 | 3280.78 | *3308.01* | 1.65 |
| 40000 | 1.4693 | 70.24 | 64.72 | 25.65 | 20.31 | 44.50 | 2337 | *22887* | 17 | 166.5 | 3322.81 | 3349.78 | *3336.30* | 0.81 |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| 5000 | 0.2881 | 59.70 | 47.11 | 23.34 | 19.90 | 31.56 | 29.6 | *289.9* | 14 | 137.1 | 1497.02 | 1438.61 | *1467.81* | 3.98 |
| 10000 | 0.5519 | 60.14 | 52.26 | 23.96 | 19.73 | 34.32 | 97.2 | *951.8* | 14 | 137.1 | 1792.52 | 1768.99 | *1780.75* | 1.32 |
| 15000 | 0.8170 | 60.00 | 54.14 | 24.45 | 19.73 | 34.98 | 215 | *2103* | 14 | 137.1 | 1972.56 | 1973.9 | *1973.23* | 0.07 |
| 20000 | 1.0765 | 60.25 | 55.48 | 24.94 | 20.00 | 35.39 | 367 | *3589* | 14 | 137.1 | 2114.66 | 2065.91 | *2090.29* | 2.33 |
| 25000 | 1.3382 | 60.21 | 56.26 | 24.92 | 19.82 | 35.86 | 562 | *5502* | 13.5 | 132.2 | 2176.47 | 2132.82 | *2154.65* | 2.03 |
| 30000 | 1.6005 | 60.17 | 56.75 | 25.61 | 20.32 | 35.49 | 782 | *7659* | 14 | 137.1 | 2253.51 | 2212.28 | *2232.9* | 1.85 |
| 35000 | 1.8509 | 60.5 | 57.61 | 25.61 | 20.3 | 36.09 | 1038 | *10161* | 13 | 127.3 | 2201.49 | 2220.64 | *2211.07* | 0.87 |
| 40000 | 2.1171 | 60.27 | 57.72 | 25.63 | 20.24 | 36.04 | 1342 | *13143* | 13 | 127.3 | 2222.03 | 2254.1 | *2238.06* | 1.43 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| 5000 | 0.2923 | 59.85 | 45.10 | 22.77 | 19.95 | 30.73 | 29.6 | *290.1* | 27 | 264.4 | 1780.50 | 1768.99 | *1774.74* | 0.65 |
| 10000 | 0.5608 | 60.21 | 50.10 | 23.80 | 19.90 | 33.21 | 103 | *1006* | 27 | 264.4 | 2337.97 | 2446.47 | *2392.22* | 4.54 |
| 15000 | 0.8282 | 60.12 | 52.22 | 24.32 | 19.95 | 34.00 | 222 | *2175* | 27 | 264.4 | 2696.88 | 2741.3 | *2719.09* | 1.63 |
| 20000 | 1.0901 | 60.25 | 53.81 | 24.67 | 19.95 | 34.71 | 373 | *3653* | 26.5 | 259.5 | 2892.19 | 2960.86 | *2926.53* | 2.35 |
| 25000 | 1.3528 | 60.25 | 54.77 | 25.10 | 20.00 | 34.96 | 569 | *5575* | 26 | 254.6 | 3053.50 | 3199.23 | *3126.36* | 4.66 |
| 30000 | 1.6091 | 60.45 | 55.75 | 25.42 | 20.37 | 35.20 | 787 | *7705* | 25 | 244.8 | 3114.14 | 3167.87 | *3141.00* | 1.71 |
| 35000 | 1.8717 | 60.31 | 56.29 | 25.64 | 20.45 | 35.25 | 1060 | *10379* | 25 | 244.8 | 3097.96 | 3255.69 | *3176.82* | 4.96 |
| 40000 | 2.1345 | 60.34 | 56.55 | 25.41 | 20.24 | 35.62 | 1375 | *13461* | 25 | 244.8 | 3330.52 | 3243.14 | *3286.83* | 2.66 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| 5000 | 0.2555 | 69.85 | 52.95 | 23.96 | 19.90 | 39.12 | 23.1 | *226.6* | 14 | 137.1 | 1774.74 | 1697.89 | *1736.31* | 4.43 |
| 10000 | 0.4903 | 69.75 | 58.73 | 24.95 | 19.87 | 41.76 | 78.7 | *770.5* | 14 | 137.1 | 2217.50 | 2124.46 | *2170.98* | 4.29 |
| 15000 | 0.7192 | 69.98 | 61.55 | 25.80 | 19.87 | 42.92 | 167 | *1632* | 14 | 137.1 | 2486.42 | 2479.93 | *2483.17* | 0.26 |
| 20000 | 0.9429 | 70.32 | 63.51 | 26.43 | 20.12 | 43.64 | 282 | *2765* | 14 | 137.1 | 2631.49 | 2638.84 | *2635.17* | 0.28 |
| 25000 | 1.1673 | 70.50 | 64.62 | 26.45 | 19.96 | 44.35 | 424 | *4151* | 14 | 137.1 | 2812.04 | 2714.12 | *2763.08* | 3.54 |
| 30000 | 1.3962 | 70.21 | 65.35 | 26.27 | 19.90 | 44.69 | 592 | *5801* | 13 | 127.3 | 2779.58 | 2663.93 | *2721.76* | 4.25 |
| 35000 | 1.6219 | 70.13 | 66.00 | 26.84 | 20.13 | 44.57 | 794 | *7777* | 13 | 127.3 | 2743.55 | 2806.12 | *2774.84* | 2.26 |
| 40000 | 1.8474 | 70.13 | 66.45 | 27.15 | 20.19 | 44.60 | 1019 | *9980* | 13 | 127.3 | 2784.04 | 2910.67 | *2847.36* | 4.45 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| 5000 | 0.2608 | 69.95 | 50.03 | 23.68 | 20.10 | 37.51 | 24.1 | *235.7* | 27 | 264.4 | 2137.06 | 2245.73 | *2191.40* | 4.96 |
| 10000 | 0.4992 | 70.12 | 55.87 | 24.83 | 20.32 | 40.22 | 83.3 | *815.8* | 27 | 264.4 | 2921.77 | 2829.12 | *2875.44* | 3.22 |
| 15000 | 0.7319 | 70.25 | 58.88 | 25.21 | 19.87 | 41.95 | 172 | *1686* | 26 | 254.6 | 3415.09 | 3349.78 | *3382.44* | 1.93 |
| 20000 | 0.9613 | 70.22 | 60.98 | 25.90 | 20.00 | 42.63 | 292 | *2855* | 26 | 254.6 | 3642.89 | 3701.07 | *3671.98* | 1.58 |
| 25000 | 1.1878 | 70.34 | 62.43 | 26.31 | 20.21 | 43.12 | 438 | *4287* | 27 | 264.4 | 3851.84 | 3826.53 | *3839.19* | 0.66 |
| 30000 | 1.4141 | 70.34 | 63.51 | 26.33 | 20.32 | 43.6 | 611 | *5982* | 25 | 244.8 | 3958.22 | 3770.07 | *3864.15* | 4.87 |
| 35000 | 1.6400 | 70.45 | 64.20 | 26.63 | 20.22 | 43.9 | 812 | *7949* | 25 | 244.8 | 4199.82 | 4020.99 | *4110.40* | 4.35 |
| 40000 | 1.8655 | 70.35 | 64.93 | 27.00 | 20.48 | 43.9 | 1038 | *10161* | 25 | 244.8 | 4142.14 | 4090.00 | *4116.07* | 1.27 |

**Table C-3:** Experimental Results of Tube-Side Heat Transfer Enhancement for Two Sizes of Inner Tube (Enhancement Status: Wire Coil, e= 1 mm, p= 20 mm).

| Re | $Q_h$ $10^{-4}$ | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| Inner tube | ($m^3/s$) | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | $N/m^2$ | $mmH_2O$ | $N/m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Err. % |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2258 | 60.00 | 47.11 | 22.74 | 19.97 | 31.93 | 39.09 | *382.78* | 9 | 88.13 | 1201.35 | 1158.41 | *1179.88* | 3.64 |
| **10000** | 0.4349 | 60.06 | 51.97 | 23.70 | 20.32 | 33.95 | 129.6 | *1269* | 9 | 88.13 | 1450.15 | 1413.52 | *1431.83* | 2.56 |
| **15000** | 0.6394 | 60.11 | 54.56 | 23.69 | 20.33 | 35.31 | 278.6 | *2728.4* | 8.5 | 83.24 | 1461.85 | 1405.15 | *1433.50* | 3.96 |
| **20000** | 0.8480 | 60.07 | 55.31 | 24.05 | 20.22 | 35.55 | 473.9 | *4640.9* | 9 | 88.13 | 1662.53 | 1601.71 | *1632.12* | 3.73 |
| **25000** | 1.0500 | 60.28 | 56.38 | 24.12 | 19.90 | 36.32 | 710.9 | *6961.4* | 9 | 88.13 | 1685.97 | 1764.80 | *1725.39* | 4.57 |
| **30000** | 1.2577 | 60.16 | 56.74 | 24.29 | 20.05 | 36.28 | 985.8 | *9653.5* | 9 | 88.13 | 1770.89 | 1773.17 | *1772.03* | 0.13 |
| **35000** | 1.4576 | 60.39 | 57.41 | 24.44 | 20.31 | 36.52 | 1321 | *12935* | 8.5 | 83.24 | 1787.85 | 1727.17 | *1757.51* | 3.45 |
| **40000** | 1.6689 | 60.08 | 57.47 | 24.21 | 20.11 | 36.61 | 1707 | *16715* | 8.5 | 83.24 | 1792.99 | 1714.62 | *1753.81* | 4.47 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2296 | 60.50 | 44.51 | 22.54 | 20.00 | 30.75 | 41.65 | *407.89* | 18 | 176.3 | 1515.83 | 1593.34 | *1554.59* | 4.99 |
| **10000** | 0.4420 | 60.34 | 49.55 | 23.22 | 20.05 | 33.16 | 138.8 | *1359.6* | 17.5 | 171.4 | 1967.07 | 1988.54 | *1977.80* | 1.09 |
| **15000** | 0.6476 | 60.24 | 52.75 | 23.47 | 20.14 | 34.65 | 291.6 | *2855.3* | 17 | 166.5 | 1998.81 | 2088.91 | *2043.86* | 4.41 |
| **20000** | 0.8553 | 60.42 | 53.82 | 23.85 | 19.96 | 35.20 | 488.7 | *4786* | 18 | 176.3 | 2325.64 | 2440.20 | *2382.92* | 4.81 |
| **25000** | 1.0610 | 60.43 | 54.83 | 24.10 | 20.03 | 35.56 | 732.2 | *7169.9* | 17.5 | 171.4 | 2447.16 | 2553.11 | *2500.14* | 4.24 |
| **30000** | 1.2698 | 60.20 | 55.42 | 23.87 | 19.85 | 35.95 | 1009 | *9880.1* | 17.5 | 171.4 | 2499.63 | 2521.75 | *2510.69* | 0.88 |
| **35000** | 1.4708 | 60.47 | 56.11 | 24.20 | 20.00 | 36.19 | 1351 | *13234* | 17.5 | 171.4 | 2640.39 | 2634.66 | *2637.52* | 0.22 |
| **40000** | 1.6735 | 60.50 | 56.68 | 24.29 | 19.90 | 36.49 | 1732 | *16959* | 17.5 | 171.4 | 2631.68 | 2753.85 | *2692.77* | 4.54 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2006 | 70.22 | 52.64 | 23.72 | 20.41 | 38.93 | 29.62 | *290.06* | 8.5 | 83.24 | 1449.89 | 1384.24 | *1417.06* | 4.63 |
| **10000** | 0.3838 | 70.07 | 58.92 | 24.31 | 20.20 | 42.14 | 103.7 | *1015.2* | 9 | 88.13 | 1756.10 | 1718.80 | *1737.45* | 2.15 |
| **15000** | 0.5620 | 70.30 | 61.98 | 24.51 | 20.05 | 43.83 | 218.5 | *2139.2* | 8.5 | 83.24 | 1917.15 | 1865.17 | *1891.16* | 2.75 |
| **20000** | 0.7398 | 70.40 | 63.62 | 25.04 | 19.95 | 44.51 | 359.2 | *3517* | 9 | 88.13 | 2055.49 | 2128.64 | *2092.06* | 3.50 |
| **25000** | 0.9173 | 70.38 | 64.72 | 25.33 | 20.23 | 44.77 | 539.7 | *5284.5* | 9 | 88.13 | 2127.12 | 2132.82 | *2129.97* | 0.27 |
| **30000** | 1.0959 | 70.19 | 65.51 | 25.42 | 20.31 | 44.98 | 749.8 | *7342.1* | 8.5 | 83.24 | 2100.78 | 2137.00 | *2118.89* | 1.71 |
| **35000** | 1.2737 | 70.20 | 66.00 | 25.51 | 20.33 | 45.18 | 1004 | *9834.8* | 8.5 | 83.24 | 2190.99 | 2166.28 | *2178.63* | 1.13 |
| **40000** | 1.4472 | 70.31 | 66.66 | 25.63 | 20.10 | 45.61 | 1279 | *12527* | 8.5 | 83.24 | 2163.00 | 2312.65 | *2237.82* | 6.69 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2069 | 70.23 | 48.46 | 22.81 | 20.00 | 37.14 | 33.32 | *326.32* | 17 | 166.5 | 1853.19 | 1762.71 | *1807.95* | 5.00 |
| **10000** | 0.3932 | 70.22 | 55.44 | 23.89 | 20.13 | 40.57 | 111.1 | *1087.7* | 18 | 176.3 | 2386.98 | 2358.65 | *2372.82* | 1.19 |
| **15000** | 0.5755 | 70.23 | 58.81 | 24.21 | 20.05 | 42.29 | 226.8 | *2220.8* | 17.5 | 171.4 | 2696.92 | 2609.57 | *2653.24* | 3.29 |
| **20000** | 0.7587 | 70.10 | 60.49 | 24.61 | 20.07 | 42.91 | 376.7 | *3689.2* | 18 | 176.3 | 2990.70 | 2847.94 | *2919.32* | 4.89 |
| **25000** | 0.9333 | 70.23 | 62.54 | 25.02 | 20.11 | 43.81 | 557.2 | *5456.7* | 17 | 166.5 | 2942.27 | 3080.04 | *3011.16* | 4.58 |
| **30000** | 1.1141 | 70.15 | 63.33 | 24.95 | 20.04 | 44.24 | 785 | *7686.5* | 17 | 166.5 | 3114.31 | 3080.04 | *3097.18* | 1.11 |
| **35000** | 1.2900 | 70.20 | 64.30 | 25.32 | 20.11 | 44.53 | 1032 | *10107* | 17 | 166.5 | 3118.67 | 3268.23 | *3193.45* | 4.68 |
| **40000** | 1.4621 | 70.50 | 65.11 | 25.50 | 20.19 | 44.96 | 1324 | *12962* | 17 | 166.5 | 3228.24 | 3330.96 | *3279.60* | 3.13 |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2859 | 59.87 | 47.93 | 23.10 | 19.83 | 32.24 | 19.55 | *191.45* | 14 | 137.1 | 1408.47 | 1367.51 | *1387.99* | 2.95 |
| **10000** | 0.5529 | 59.87 | 52.30 | 23.90 | 19.75 | 34.23 | 65.72 | *643.57* | 14 | 137.1 | 1725.11 | 1735.53 | *1730.32* | 0.60 |
| **15000** | 0.8151 | 60.13 | 54.32 | 24.50 | 20.05 | 34.95 | 141.6 | *1386.8* | 14.5 | 142 | 1951.03 | 1860.99 | *1906.01* | 4.72 |
| **20000** | 1.0760 | 60.21 | 55.58 | 24.81 | 20.14 | 35.42 | 238.8 | *2338.6* | 14 | 137.1 | 2051.65 | 1952.99 | *2002.32* | 4.93 |
| **25000** | 1.3359 | 60.31 | 56.39 | 25.22 | 20.22 | 35.63 | 360.1 | *3526* | 14 | 137.1 | 2156.12 | 2091.00 | *2123.56* | 3.07 |
| **30000** | 1.5981 | 60.14 | 56.98 | 25.31 | 20.22 | 35.79 | 505.4 | *4949.1* | 13 | 127.3 | 2079.00 | 2128.64 | *2103.82* | 2.36 |
| **35000** | 1.8537 | 60.35 | 57.55 | 25.55 | 20.43 | 35.95 | 669.2 | *6553.5* | 13 | 127.3 | 2136.36 | 2141.18 | *2138.77* | 0.23 |
| **40000** | 2.1136 | 60.36 | 57.86 | 25.56 | 20.38 | 36.12 | 865.5 | *8475.1* | 13 | 127.3 | 2174.63 | 2166.28 | *2170.45* | 0.38 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2922 | 59.75 | 45.25 | 22.60 | 19.67 | 31.01 | 20.36 | *199.42* | 28 | 274.2 | 1749.61 | 1837.99 | *1793.80* | 4.93 |
| **10000** | 0.5581 | 60.50 | 50.44 | 23.91 | 20.12 | 33.36 | 68.5 | *670.76* | 28 | 274.2 | 2314.85 | 2377.47 | *2346.16* | 2.67 |
| **15000** | 0.8265 | 60.24 | 52.38 | 24.21 | 19.97 | 34.19 | 148.1 | *1450.3* | 28 | 274.2 | 2677.34 | 2659.75 | *2668.55* | 0.66 |
| **20000** | 1.0921 | 60.15 | 53.66 | 24.60 | 20.03 | 34.58 | 245.3 | *2402* | 27 | 264.4 | 2920.32 | 2866.76 | *2893.54* | 1.85 |
| **25000** | 1.3515 | 60.20 | 54.95 | 24.86 | 20.38 | 34.95 | 367.5 | *3598.5* | 26 | 254.6 | 2922.40 | 2810.30 | *2866.35* | 3.91 |
| **30000** | 1.6090 | 60.34 | 55.87 | 25.12 | 20.20 | 35.44 | 506.3 | *4958.2* | 26 | 254.6 | 2961.52 | 3086.32 | *3023.92* | 4.13 |
| **35000** | 1.8720 | 60.27 | 56.31 | 25.51 | 20.41 | 35.33 | 682.2 | *6680.4* | 26 | 254.6 | 3052.19 | 3199.23 | *3125.71* | 4.70 |
| **40000** | 2.1334 | 60.29 | 56.67 | 25.22 | 20.13 | 35.80 | 873.8 | *8556.7* | 25 | 244.8 | 3179.42 | 3192.96 | *3186.19* | 0.42 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2538 | 69.71 | 53.98 | 23.97 | 20.13 | 39.50 | 13.88 | *135.96* | 14 | 137.1 | 1640.81 | 1605.89 | *1623.35* | 2.15 |
| **10000** | 0.4889 | 69.85 | 59.00 | 25.18 | 20.22 | 41.66 | 50.91 | *498.54* | 14 | 137.1 | 2177.20 | 2074.27 | *2125.74* | 4.84 |
| **15000** | 0.7181 | 70.00 | 61.74 | 25.53 | 19.95 | 43.12 | 105.5 | *1033.3* | 14 | 137.1 | 2432.39 | 2333.56 | *2382.97* | 4.15 |
| **20000** | 0.9422 | 70.24 | 63.69 | 26.10 | 20.34 | 43.74 | 179.6 | *1758.5* | 13 | 127.3 | 2529.08 | 2408.83 | *2468.96* | 4.87 |
| **25000** | 1.1682 | 70.31 | 64.71 | 26.41 | 20.26 | 44.17 | 272.1 | *2664.9* | 13.5 | 132.2 | 2680.21 | 2571.93 | *2626.07* | 4.12 |
| **30000** | 1.3935 | 70.20 | 65.62 | 26.65 | 20.31 | 44.42 | 381.4 | *3734.5* | 13 | 127.3 | 2614.15 | 2651.39 | *2632.77* | 1.41 |
| **35000** | 1.6155 | 70.34 | 66.32 | 26.71 | 20.17 | 44.88 | 504.5 | *4940.1* | 13 | 127.3 | 2659.43 | 2735.03 | *2697.23* | 2.80 |
| **40000** | 1.8400 | 70.43 | 66.68 | 26.85 | 20.26 | 44.99 | 648 | *6345* | 13 | 127.3 | 2825.22 | 2755.94 | *2790.58* | 2.48 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2602 | 69.75 | 50.55 | 22.98 | 19.75 | 38.23 | 15.74 | *154.09* | 27 | 264.4 | 2054.81 | 2026.18 | *2040.50* | 1.40 |
| **10000** | 0.4985 | 70.23 | 55.95 | 24.31 | 19.85 | 40.81 | 53.69 | *525.73* | 27 | 264.4 | 2923.73 | 2797.76 | *2860.74* | 4.40 |
| **15000** | 0.7317 | 69.88 | 59.30 | 25.04 | 19.85 | 42.09 | 112 | *1096.8* | 27 | 264.4 | 3176.61 | 3255.69 | *3216.15* | 2.46 |
| **20000** | 0.9573 | 70.34 | 61.43 | 25.47 | 20.11 | 43.07 | 187 | *1831* | 26 | 254.6 | 3497.61 | 3362.33 | *3429.97* | 3.94 |
| **25000** | 1.1846 | 70.40 | 62.74 | 26.02 | 20.34 | 43.38 | 278.6 | *2728.4* | 26 | 254.6 | 3719.56 | 3563.06 | *3641.31* | 4.30 |
| **30000** | 1.4159 | 70.14 | 63.54 | 26.29 | 20.16 | 43.61 | 393.4 | *3852.3* | 26 | 254.6 | 3829.92 | 3845.35 | *3837.64* | 0.40 |
| **35000** | 1.6385 | 70.36 | 64.41 | 26.52 | 20.15 | 44.05 | 519.3 | *5085.1* | 26 | 254.6 | 3994.52 | 3995.90 | *3995.21* | 0.03 |
| **40000** | 1.8649 | 70.27 | 65.05 | 26.87 | 20.31 | 44.07 | 665.5 | *6517.2* | 25 | 244.8 | 3988.06 | 4115.09 | *4051.57* | 3.14 |

**Table C-4:** Experimental Results of Tube-Side Heat Transfer Enhancement for Two Sizes of Inner Tube (Enhancement Status: Wire Coil, e= 1 mm, p= 30 mm).

| Re | $Q_h$ $10^{-4}$ | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| Inner tube | ($m^3/s$) | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | $N/m^2$ | $mmH_2O$ | $N/m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2229 | 60.10 | 48.70 | 22.31 | 19.82 | 33.14 | 26.8 | *262.4* | 8 | 78.34 | 1048.19 | 1041.32 | *1044.75* | 0.66 |
| **10000** | 0.4313 | 60.11 | 53.00 | 23.11 | 19.95 | 34.99 | 86.09 | *842.98* | 8 | 78.34 | 1263.75 | 1321.51 | *1292.63* | 4.47 |
| **15000** | 0.6416 | 60.00 | 54.22 | 23.58 | 19.75 | 35.44 | 186.1 | *1821.9* | 8.5 | 83.24 | 1527.76 | 1601.71 | *1564.73* | 4.73 |
| **20000** | 0.8446 | 60.12 | 55.80 | 23.50 | 19.90 | 36.26 | 309.2 | *3027.5* | 8 | 78.34 | 1502.57 | 1505.52 | *1504.04* | 0.20 |
| **25000** | 1.0499 | 60.17 | 56.50 | 23.80 | 20.15 | 36.36 | 461.9 | *4523.1* | 8 | 78.34 | 1586.42 | 1526.43 | *1556.43* | 3.85 |
| **30000** | 1.2572 | 60.05 | 56.91 | 24.05 | 20.12 | 36.39 | 637.8 | *6245.3* | 8.5 | 83.24 | 1625.16 | 1643.53 | *1634.34* | 1.12 |
| **35000** | 1.4582 | 60.21 | 57.53 | 24.21 | 20.21 | 36.66 | 845.1 | *8275.7* | 8 | 78.34 | 1608.60 | 1672.80 | *1640.70* | 3.91 |
| **40000** | 1.6724 | 59.84 | 57.43 | 24.02 | 20.04 | 36.60 | 1089 | *10660* | 8 | 78.34 | 1659.16 | 1664.44 | *1661.80* | 0.32 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2281 | 60.41 | 45.40 | 22.49 | 20.32 | 31.06 | 29.62 | *290.06* | 18 | 176.3 | 1413.71 | 1361.24 | *1387.47* | 3.78 |
| **10000** | 0.4396 | 60.32 | 50.30 | 23.01 | 20.25 | 33.55 | 94.42 | *924.56* | 18 | 176.3 | 1816.16 | 1731.35 | *1773.75* | 4.78 |
| **15000** | 0.6473 | 60.31 | 52.74 | 23.45 | 20.17 | 34.67 | 190.7 | *1867.3* | 18 | 176.3 | 2019.21 | 2057.54 | *2038.38* | 1.88 |
| **20000** | 0.8567 | 60.31 | 53.71 | 23.76 | 20.22 | 35.00 | 319.3 | *3127.2* | 17 | 166.5 | 2329.62 | 2220.64 | *2275.13* | 4.79 |
| **25000** | 1.0600 | 60.43 | 54.96 | 24.00 | 20.21 | 35.58 | 476.7 | *4668.1* | 17.5 | 171.4 | 2387.95 | 2377.47 | *2382.71* | 0.44 |
| **30000** | 1.2708 | 59.90 | 55.61 | 23.86 | 20.10 | 35.77 | 659.1 | *6453.8* | 17 | 166.5 | 2245.30 | 2358.65 | *2301.97* | 4.92 |
| **35000** | 1.4699 | 60.34 | 56.33 | 24.42 | 20.36 | 35.94 | 860.9 | *8429.8* | 17 | 166.5 | 2426.75 | 2546.84 | *2486.79* | 4.83 |
| **40000** | 1.6761 | 60.30 | 56.67 | 24.39 | 20.23 | 36.17 | 1096 | *10732* | 17 | 166.5 | 2504.83 | 2609.57 | *2557.20* | 4.10 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.1997 | 70.10 | 53.42 | 23.13 | 19.77 | 39.94 | 20.36 | *199.42* | 9 | 88.13 | 1368.82 | 1405.15 | *1386.99* | 2.62 |
| **10000** | 0.3809 | 70.34 | 59.68 | 24.06 | 20.27 | 42.75 | 68.5 | *670.76* | 8 | 78.34 | 1665.91 | 1584.98 | *1625.44* | 4.98 |
| **15000** | 0.5605 | 70.38 | 62.26 | 24.38 | 20.13 | 44.04 | 140.7 | *1377.8* | 8.5 | 83.24 | 1865.93 | 1777.35 | *1821.64* | 4.86 |
| **20000** | 0.7390 | 70.24 | 63.93 | 24.95 | 20.19 | 44.51 | 235.1 | *2302.3* | 8.5 | 83.24 | 1910.79 | 1990.63 | *1950.71* | 4.09 |
| **25000** | 0.9157 | 70.34 | 65.00 | 24.76 | 19.95 | 45.31 | 349.9 | *3426.3* | 8 | 78.34 | 2003.13 | 2011.54 | *2007.34* | 0.42 |
| **30000** | 1.0907 | 70.50 | 65.83 | 25.21 | 20.38 | 45.37 | 482.3 | *4722.5* | 8 | 78.34 | 2086.02 | 2019.91 | *2052.97* | 3.22 |
| **35000** | 1.2694 | 70.34 | 66.31 | 25.43 | 20.19 | 45.51 | 638.7 | *6254.4* | 8.5 | 83.24 | 2094.92 | 2191.37 | *2143.14* | 4.50 |
| **40000** | 1.4489 | 70.22 | 66.60 | 25.12 | 20.13 | 45.78 | 823.8 | *8067.2* | 8 | 78.34 | 2147.75 | 2086.82 | *2117.28* | 2.88 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2058 | 69.95 | 49.44 | 22.52 | 19.66 | 37.92 | 22.22 | *217.54* | 18 | 176.3 | 1736.63 | 1794.08 | *1765.36* | 3.25 |
| **10000** | 0.3925 | 69.90 | 56.00 | 23.47 | 20.04 | 40.97 | 74.98 | *734.21* | 17 | 166.5 | 2240.81 | 2151.64 | *2196.22* | 4.06 |
| **15000** | 0.5744 | 69.98 | 59.31 | 23.86 | 20.04 | 42.60 | 148.1 | *1450.3* | 17 | 166.5 | 2515.05 | 2396.29 | *2455.67* | 4.84 |
| **20000** | 0.7552 | 70.23 | 60.98 | 24.48 | 19.92 | 43.36 | 249.9 | *2447.4* | 18 | 176.3 | 2865.15 | 2860.49 | *2862.82* | 0.16 |
| **25000** | 0.9321 | 70.22 | 62.73 | 24.96 | 20.25 | 43.86 | 361.9 | *3544.2* | 17 | 166.5 | 2861.81 | 2954.58 | *2908.20* | 3.19 |
| **30000** | 1.1116 | 70.12 | 63.66 | 24.73 | 19.88 | 44.58 | 505.4 | *4949.1* | 17 | 166.5 | 2943.13 | 3042.41 | *2992.77* | 3.32 |
| **35000** | 1.2904 | 70.12 | 64.34 | 25.10 | 20.19 | 44.58 | 659.1 | *6453.8* | 17 | 166.5 | 3056.18 | 3080.04 | *3068.11* | 0.78 |
| **40000** | 1.4631 | 70.42 | 65.10 | 25.54 | 20.34 | 44.82 | 846 | *8284.8* | 17 | 166.5 | 3188.55 | 3261.96 | *3225.25* | 2.28 |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2855 | 59.78 | 48.19 | 23.00 | 19.86 | 32.37 | 14.02 | *137.3* | 15 | 146.9 | 1365.32 | 1313.15 | *1339.24* | 3.90 |
| **10000** | 0.5519 | 59.95 | 52.44 | 23.82 | 19.93 | 34.29 | 47.21 | *462.3* | 14.5 | 142 | 1708.49 | 1626.8 | *1667.64* | 4.90 |
| **15000** | 0.8158 | 59.93 | 54.41 | 24.40 | 19.95 | 34.99 | 101.8 | *997.1* | 14.5 | 142 | 1855.23 | 1860.99 | *1858.11* | 0.31 |
| **20000** | 1.0785 | 59.87 | 55.61 | 24.83 | 20.1 | 35.27 | 164.8 | *1613* | 14 | 137.1 | 1892.22 | 1978.09 | *1935.15* | 4.44 |
| **25000** | 1.3363 | 60.22 | 56.44 | 25.00 | 20.14 | 35.76 | 242.5 | *2375* | 14 | 137.1 | 2079.76 | 2032.45 | *2056.11* | 2.30 |
| **30000** | 1.6000 | 60.10 | 56.86 | 24.40 | 19.18 | 36.68 | 344.3 | *3372* | 14 | 137.1 | 2134.25 | 2183.00 | *2158.63* | 2.26 |
| **35000** | 1.8588 | 60.11 | 57.42 | 25.42 | 20.31 | 35.89 | 454.5 | *4451* | 13 | 127.3 | 2058.26 | 2137.00 | *2097.63* | 3.75 |
| **40000** | 2.1200 | 60.11 | 57.70 | 25.42 | 20.15 | 36.10 | 580.4 | *5683* | 13 | 127.3 | 2102.93 | 2203.91 | *2153.42* | 4.69 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2903 | 59.96 | 45.88 | 22.53 | 19.80 | 31.41 | 14.81 | *145* | 29.5 | 288.9 | 1687.37 | 1712.53 | *1699.95* | 1.48 |
| **10000** | 0.5571 | 60.31 | 50.85 | 23.34 | 19.82 | 33.91 | 49.99 | *489.5* | 29 | 284 | 2173.01 | 2208.10 | *2190.55* | 1.60 |
| **15000** | 0.8230 | 60.38 | 52.80 | 24.00 | 19.92 | 34.60 | 99.97 | *978.9* | 28 | 274.2 | 2570.69 | 2559.38 | *2565.04* | 0.44 |
| **20000** | 1.0860 | 60.36 | 54.20 | 24.31 | 19.83 | 35.20 | 167.5 | *1641* | 28 | 274.2 | 2755.73 | 2810.30 | *2783.01* | 1.96 |
| **25000** | 1.3508 | 60.24 | 54.98 | 24.78 | 20.22 | 35.11 | 250.9 | *2456* | 27 | 264.4 | 2926.38 | 2860.49 | *2893.43* | 2.28 |
| **30000** | 1.6089 | 60.32 | 55.90 | 25.00 | 20.10 | 35.56 | 344.3 | *3372* | 27 | 264.4 | 2928.16 | 3073.77 | *3000.97* | 4.85 |
| **35000** | 1.8686 | 60.45 | 56.37 | 25.42 | 20.33 | 35.53 | 458.2 | *4487* | 27 | 264.4 | 3138.88 | 3192.96 | *3165.92* | 1.71 |
| **40000** | 2.1283 | 60.50 | 56.78 | 25.38 | 20.42 | 35.74 | 586.9 | *5747* | 26 | 254.6 | 3259.23 | 3111.41 | *3185.32* | 4.64 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2536 | 69.80 | 54.03 | 23.81 | 19.74 | 39.85 | 12.03 | *117.8* | 15 | 146.9 | 1643.24 | 1702.07 | *1672.66* | 3.52 |
| **10000** | 0.4874 | 69.82 | 59.46 | 24.73 | 19.96 | 42.23 | 37.03 | *362.6* | 15 | 146.9 | 2072.14 | 1994.81 | *2033.48* | 3.80 |
| **15000** | 0.7147 | 70.12 | 62.26 | 25.32 | 19.96 | 43.54 | 75.9 | *743.3* | 14 | 137.1 | 2303.34 | 2241.55 | *2272.45* | 2.72 |
| **20000** | 0.9400 | 70.31 | 63.93 | 26.12 | 20.23 | 43.94 | 125.9 | *1233* | 14 | 137.1 | 2457.57 | 2463.20 | *2460.38* | 0.23 |
| **25000** | 1.1665 | 70.36 | 64.86 | 26.45 | 20.11 | 44.33 | 187.9 | *1840* | 14 | 137.1 | 2628.27 | 2651.39 | *2639.83* | 0.88 |
| **30000** | 1.3933 | 70.26 | 65.58 | 26.73 | 20.11 | 44.49 | 261 | *2556* | 14 | 137.1 | 2670.81 | 2768.48 | *2719.65* | 3.59 |
| **35000** | 1.6184 | 70.30 | 66.12 | 26.93 | 20.19 | 44.64 | 341.6 | *3345* | 14 | 137.1 | 2770.48 | 2818.67 | *2794.58* | 1.72 |
| **40000** | 1.8394 | 70.47 | 66.68 | 27.18 | 20.36 | 44.79 | 438.8 | *4296* | 14 | 137.1 | 2854.46 | 2852.12 | *2853.29* | 0.08 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2600 | 69.95 | 50.46 | 23.15 | 19.66 | 38.24 | 12.03 | *117.8* | 28 | 274.2 | 2084.11 | 2189.28 | *2136.69* | 4.92 |
| **10000** | 0.4930 | 70.34 | 57.38 | 24.32 | 20.00 | 41.55 | 35.17 | *344.4* | 28 | 274.2 | 2622.86 | 2709.94 | *2666.40* | 3.27 |
| **15000** | 0.7244 | 70.39 | 60.15 | 24.94 | 19.85 | 42.82 | 78.68 | *770.5* | 28 | 274.2 | 3043.06 | 3192.96 | *3118.01* | 4.81 |
| **20000** | 0.9551 | 70.47 | 61.61 | 25.81 | 20.12 | 43.06 | 128.7 | *1260* | 27 | 264.4 | 3469.78 | 3569.34 | *3519.56* | 2.83 |
| **25000** | 1.1849 | 70.24 | 62.86 | 25.92 | 20.07 | 43.55 | 195.3 | *1913* | 28 | 274.2 | 3584.69 | 3669.71 | *3627.20* | 2.34 |
| **30000** | 1.4092 | 70.45 | 63.87 | 26.11 | 20.32 | 43.94 | 271.2 | *2656* | 27 | 264.4 | 3799.57 | 3632.07 | *3715.82* | 4.51 |
| **35000** | 1.6352 | 70.42 | 64.62 | 26.55 | 20.16 | 44.16 | 354.5 | *3472* | 27 | 264.4 | 3885.70 | 4008.45 | *3947.07* | 3.11 |
| **40000** | 1.8595 | 70.46 | 65.25 | 26.54 | 20.06 | 44.55 | 448.9 | *4396* | 26 | 254.6 | 3968.38 | 4064.90 | *4016.64* | 2.40 |

**Table C-5:** Experimental Results of Tube-Side Heat Transfer Enhancement for Two Sizes of Inner Tube (Enhancement Status: Wire Coil, e= 1 mm, p= 40 mm).

| **Re** | **$Q_h$ $10^{-4}$** | **Temperatures and Temperature Difference (°C)** | | | | | **Pressure Drop** | | | | **Heat Transfer Rate (W)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | **Inner tube** | | **Annulus** | | | | | |
| **Inner tube** | **($m^3/s$)** | **$T_{h1}$** | **$T_{h2}$** | **$T_{c1}$** | **$T_{c2}$** | **LMTD** | $mmH_2O$ | **$N/m^2$** | $mmH_2O$ | **$N/m^2$** | $q_h$ | $q_c$ | $q_{avg.}$ | **Dev. %** |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2234 | 59.72 | 48.76 | 22.58 | 20.12 | 32.71 | 21.48 | *210.31* | 8 | 78.34 | 1010.31 | 1028.77 | *1019.54* | 1.81 |
| **10000** | 0.4307 | 60.50 | 52.80 | 22.93 | 19.65 | 35.31 | 69.42 | *679.82* | 8 | 78.34 | 1366.59 | 1371.70 | *1369.14* | 0.37 |
| **15000** | 0.6355 | 60.42 | 55.08 | 23.41 | 20.14 | 35.97 | 139.8 | *1368.7* | 8 | 78.34 | 1397.53 | 1367.51 | *1382.52* | 2.17 |
| **20000** | 0.8409 | 60.47 | 56.04 | 23.62 | 20.10 | 36.39 | 222.2 | *2175.4* | 8.5 | 83.24 | 1533.84 | 1472.06 | *1502.95* | 4.11 |
| **25000** | 1.0503 | 60.10 | 56.52 | 23.70 | 19.85 | 36.53 | 342.5 | *3353.8* | 8 | 78.34 | 1548.11 | 1610.07 | *1579.09* | 3.92 |
| **30000** | 1.2491 | 60.50 | 57.33 | 24.32 | 20.24 | 36.63 | 467.5 | *4577.5* | 8.5 | 83.24 | 1629.77 | 1706.26 | *1668.01* | 4.59 |
| **35000** | 1.4524 | 60.43 | 57.85 | 24.00 | 20.14 | 37.07 | 611.9 | *5991.5* | 7.5 | 73.44 | 1542.19 | 1614.25 | *1578.22* | 4.57 |
| **40000** | 1.6643 | 60.10 | 57.82 | 24.02 | 20.13 | 36.88 | 775.7 | *7595.9* | 7.5 | 73.44 | 1561.86 | 1626.80 | *1594.33* | 4.07 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2272 | 60.43 | 45.91 | 22.33 | 20.08 | 31.57 | 21.29 | *208.48* | 17.5 | 171.4 | 1361.70 | 1411.43 | *1386.56* | 3.59 |
| **10000** | 0.4389 | 60.50 | 50.32 | 23.11 | 20.04 | 33.71 | 71.28 | *697.95* | 18 | 176.3 | 1842.25 | 1925.81 | *1884.03* | 4.44 |
| **15000** | 0.6454 | 60.50 | 52.94 | 23.43 | 20.17 | 34.88 | 142.6 | *1395.9* | 18 | 176.3 | 2010.42 | 2045.00 | *2027.71* | 1.71 |
| **20000** | 0.8529 | 60.35 | 54.26 | 23.56 | 20.28 | 35.37 | 240.7 | *2356.7* | 17 | 166.5 | 2139.78 | 2057.54 | *2098.66* | 3.92 |
| **25000** | 1.0591 | 60.50 | 55.00 | 23.95 | 20.17 | 35.68 | 348 | *3408.2* | 18 | 176.3 | 2399.01 | 2371.19 | *2385.10* | 1.17 |
| **30000** | 1.2694 | 60.13 | 55.53 | 24.00 | 20.34 | 35.66 | 481.3 | *4713.4* | 17 | 166.5 | 2404.76 | 2295.92 | *2350.34* | 4.63 |
| **35000** | 1.4693 | 60.42 | 56.30 | 24.06 | 20.18 | 36.24 | 626.7 | *6136.5* | 17 | 166.5 | 2492.36 | 2433.92 | *2463.14* | 2.37 |
| **40000** | 1.6800 | 60.14 | 56.52 | 24.10 | 20.10 | 36.23 | 794.2 | *7777.2* | 17 | 166.5 | 2503.88 | 2509.2 | *2506.54* | 0.21 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.1984 | 69.86 | 54.54 | 22.90 | 20.00 | 40.43 | 17.59 | *172.22* | 8 | 78.34 | 1248.90 | 1212.78 | *1230.84* | 2.93 |
| **10000** | 0.3808 | 70.12 | 59.94 | 24.00 | 20.37 | 42.76 | 54.61 | *534.8* | 8 | 78.34 | 1590.41 | 1518.07 | *1554.24* | 4.65 |
| **15000** | 0.5580 | 70.41 | 62.85 | 24.21 | 20.00 | 44.50 | 108.3 | *1060.5* | 8 | 78.34 | 1729.03 | 1760.62 | *1744.82* | 1.81 |
| **20000** | 0.7369 | 70.39 | 64.15 | 24.45 | 20.04 | 45.02 | 177.7 | *1740.4* | 8 | 78.34 | 1884.21 | 1844.26 | *1864.24* | 2.14 |
| **25000** | 0.9177 | 70.14 | 64.90 | 24.98 | 20.45 | 44.80 | 262 | *2565.2* | 8 | 78.34 | 1970.19 | 1894.45 | *1932.32* | 3.92 |
| **30000** | 1.0911 | 70.33 | 65.95 | 25.20 | 20.36 | 45.36 | 359.2 | *3517* | 8 | 78.34 | 1957.25 | 2024.09 | *1990.67* | 3.36 |
| **35000** | 1.2659 | 70.50 | 66.52 | 25.42 | 20.25 | 45.67 | 461.9 | *4523.1* | 8 | 78.34 | 2062.93 | 2162.09 | *2112.51* | 4.69 |
| **40000** | 1.4565 | 69.82 | 66.30 | 25.00 | 20.21 | 45.45 | 597 | *5846.5* | 8 | 78.34 | 2099.89 | 2003.18 | *2051.53* | 4.71 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2034 | 69.80 | 51.22 | 22.52 | 19.93 | 38.74 | 16.66 | *163.16* | 17 | 166.5 | 1553.85 | 1624.71 | *1589.28* | 4.46 |
| **10000** | 0.3903 | 69.85 | 56.82 | 23.56 | 20.11 | 41.32 | 57.39 | *561.99* | 17 | 166.5 | 2088.41 | 2164.19 | *2126.30* | 3.56 |
| **15000** | 0.5730 | 70.33 | 59.30 | 24.15 | 20.15 | 42.57 | 112 | *1096.8* | 17 | 166.5 | 2593.23 | 2509.20 | *2551.22* | 3.29 |
| **20000** | 0.7496 | 70.44 | 61.80 | 24.72 | 20.31 | 43.57 | 184.2 | *1803.8* | 18 | 176.3 | 2655.32 | 2766.39 | *2710.86* | 4.10 |
| **25000** | 0.9295 | 70.41 | 62.92 | 24.94 | 19.87 | 44.25 | 266.6 | *2610.5* | 18 | 176.3 | 2853.50 | 3180.41 | *3016.95* | 10.8 |
| **30000** | 1.1063 | 70.48 | 63.95 | 24.91 | 20.12 | 44.69 | 368.4 | *3607.6* | 17 | 166.5 | 2960.18 | 3004.77 | *2982.47* | 1.49 |
| **35000** | 1.2820 | 70.48 | 64.85 | 25.34 | 20.39 | 44.80 | 474.9 | *4650* | 17 | 166.5 | 2956.91 | 3105.14 | *3031.02* | 4.89 |
| **40000** | 1.4645 | 70.34 | 65.05 | 25.59 | 20.45 | 44.67 | 616.5 | *6036.8* | 17 | 166.5 | 3173.77 | 3224.32 | *3199.05* | 1.58 |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2808 | 60.14 | 50.00 | 23.14 | 20.23 | 33.25 | 11.18 | *109.46* | 15 | 146.9 | 1174.03 | 1216.96 | *1195.50* | 3.59 |
| **10000** | 0.5507 | 60.06 | 52.62 | 24.31 | 20.33 | 33.99 | 39.8 | *389.77* | 16 | 156.7 | 1688.73 | 1664.44 | *1676.58* | 1.45 |
| **15000** | 0.8130 | 60.16 | 54.64 | 24.43 | 20.12 | 35.12 | 75.9 | *743.27* | 15 | 146.9 | 1848.62 | 1802.44 | *1825.53* | 2.53 |
| **20000** | 1.0763 | 60.12 | 55.64 | 25.03 | 20.31 | 35.21 | 125 | *1223.7* | 15 | 146.9 | 1985.64 | 1973.9 | *1979.77* | 0.59 |
| **25000** | 1.3317 | 60.41 | 56.72 | 25.14 | 20.22 | 35.88 | 188.8 | *1849.1* | 14 | 137.1 | 2022.92 | 2057.54 | *2040.23* | 1.70 |
| **30000** | 1.5987 | 60.11 | 56.96 | 25.43 | 20.43 | 35.60 | 262.9 | *2574.3* | 14 | 137.1 | 2073.22 | 2091.00 | *2082.11* | 0.85 |
| **35000** | 1.8576 | 60.21 | 57.41 | 25.63 | 20.36 | 35.80 | 346.2 | *3390.1* | 14 | 137.1 | 2140.95 | 2203.91 | *2172.43* | 2.90 |
| **40000** | 2.1139 | 60.32 | 57.88 | 25.52 | 20.45 | 36.10 | 437.8 | *4287.4* | 13 | 127.3 | 2122.76 | 2120.27 | *2121.52* | 0.12 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2850 | 60.22 | 47.96 | 22.42 | 20.11 | 32.57 | 11.11 | *108.77* | 29 | 284 | 1441.82 | 1449.06 | *1445.44* | 0.50 |
| **10000** | 0.5565 | 60.10 | 51.20 | 23.52 | 20.21 | 33.71 | 41.65 | *407.89* | 29 | 284 | 2042.12 | 2076.36 | *2059.24* | 1.66 |
| **15000** | 0.8229 | 60.17 | 53.02 | 23.85 | 20.05 | 34.62 | 78.68 | *770.47* | 29 | 284 | 2424.67 | 2383.74 | *2404.20* | 1.70 |
| **20000** | 1.0881 | 60.20 | 54.10 | 24.52 | 20.32 | 34.72 | 128.7 | *1259.9* | 29 | 284 | 2734.40 | 2634.66 | *2684.53* | 3.72 |
| **25000** | 1.3508 | 60.20 | 55.02 | 24.71 | 19.92 | 35.29 | 194.4 | *1903.5* | 28 | 274.2 | 2881.87 | 3004.77 | *2943.32* | 4.18 |
| **30000** | 1.6162 | 60.06 | 55.55 | 24.93 | 20.12 | 35.28 | 270.3 | *2646.8* | 28 | 274.2 | 3001.88 | 3017.31 | *3009.60* | 0.51 |
| **35000** | 1.8679 | 60.41 | 56.46 | 25.13 | 20.22 | 35.76 | 352.7 | *3453.5* | 27 | 264.4 | 3037.70 | 3080.04 | *3058.87* | 1.38 |
| **40000** | 2.1286 | 60.41 | 56.85 | 25.28 | 20.12 | 35.92 | 447.1 | *4378.1* | 27 | 264.4 | 3119.53 | 3236.87 | *3178.20* | 3.69 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2512 | 69.75 | 55.34 | 23.42 | 19.81 | 40.69 | 8.331 | *81.579* | 15 | 146.9 | 1487.34 | 1509.7 | *1498.52* | 1.49 |
| **10000** | 0.4837 | 70.34 | 59.98 | 24.9 | 20.22 | 42.54 | 30.55 | *299.12* | 15 | 146.9 | 2055.90 | 1957.18 | *2006.54* | 4.92 |
| **15000** | 0.7153 | 70.14 | 62.14 | 25.57 | 20.22 | 43.23 | 59.24 | *580.12* | 15 | 146.9 | 2346.16 | 2237.37 | *2291.76* | 4.75 |
| **20000** | 0.9393 | 70.46 | 63.88 | 26.12 | 20.27 | 43.97 | 99.04 | *969.88* | 15 | 146.9 | 2532.66 | 2446.47 | *2489.56* | 3.46 |
| **25000** | 1.1668 | 70.25 | 64.93 | 26.23 | 20.23 | 44.36 | 143.5 | *1405* | 14 | 137.1 | 2543.04 | 2509.2 | *2526.12* | 1.34 |
| **30000** | 1.3940 | 70.17 | 65.60 | 26.53 | 20.07 | 44.58 | 202.7 | *1985.1* | 14 | 137.1 | 2609.46 | 2701.57 | *2655.51* | 3.47 |
| **35000** | 1.6213 | 70.11 | 66.07 | 26.3 | 19.85 | 45.00 | 263.8 | *2583.3* | 14 | 137.1 | 2682.72 | 2697.39 | *2690.05* | 0.55 |
| **40000** | 1.8456 | 70.20 | 66.51 | 26.8 | 20.12 | 44.88 | 337.9 | *3308.5* | 14 | 137.1 | 2788.76 | 2793.58 | *2791.17* | 0.17 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | | | |
| **5000** | 0.2537 | 70.50 | 53.24 | 23.11 | 20.24 | 39.76 | 9.257 | *90.643* | 28 | 274.2 | 1799.72 | 1800.35 | *1800.04* | 0.03 |
| **10000** | 0.4948 | 70.22 | 57.00 | 24.33 | 20.05 | 41.26 | 29.62 | *290.06* | 28 | 274.2 | 2685.58 | 2684.84 | *2685.21* | 0.03 |
| **15000** | 0.7285 | 70.13 | 59.65 | 25.13 | 20.35 | 42.09 | 62.94 | *616.37* | 28 | 274.2 | 3132.35 | 2998.49 | *3065.42* | 4.37 |
| **20000** | 0.9550 | 70.44 | 61.65 | 25.54 | 20.13 | 43.19 | 100.9 | *988.01* | 28 | 274.2 | 3442.10 | 3393.69 | *3417.90* | 1.42 |
| **25000** | 1.1863 | 70.00 | 62.95 | 25.73 | 20.07 | 43.57 | 149 | *1459.4* | 28 | 274.2 | 3428.34 | 3550.52 | *3489.43* | 3.50 |
| **30000** | 1.4086 | 70.40 | 63.97 | 26.08 | 20.13 | 44.08 | 206.4 | *2021.3* | 27 | 264.4 | 3711.53 | 3732.44 | *3721.98* | 0.56 |
| **35000** | 1.6328 | 70.41 | 64.83 | 26.3 | 20.12 | 44.41 | 267.5 | *2619.6* | 27 | 264.4 | 3732.52 | 3876.71 | *3804.62* | 3.79 |
| **40000** | 1.8589 | 70.50 | 65.25 | 26.54 | 20.21 | 44.50 | 342.5 | *3353.8* | 26 | 254.6 | 3997.60 | 3970.81 | *3984.21* | 0.67 |

**Table C-6:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Smooth Annulus).

| Re Annul -us | $Q_c$ $10^{-4}$ ($m^3/s$) | Temperatures and Temperature Difference (°C) $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | Pressure Drop Inner tube $mmH_2O$ | Inner tube $N/m^2$ | Annulus $mmH_2O$ | Annulus $N/m^2$ | Heat Transfer Rate (W) $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | | | | | | | |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8948 | 60.50 | 56.70 | 25.30 | 20.43 | 35.73 | 203.6 | 1994.2 | 7 | *68.547* | 1788.66 | 1817.86 | *1803.26* | 1.62 |
| 4000 | 1.1996 | 60.18 | 55.63 | 24.80 | 20.46 | 35.27 | 203.6 | 1994.2 | 11 | *107.72* | 2141.69 | 2172.01 | *2156.85* | 1.41 |
| 5000 | 1.5045 | 60.46 | 55.03 | 24.50 | 20.47 | 35.26 | 203.6 | 1994.2 | 16 | *156.68* | 2555.90 | 2529.72 | *2542.81* | 1.03 |
| 6000 | 1.8289 | 59.93 | 54.04 | 23.80 | 20.07 | 35.04 | 204.6 | 2003.2 | 22 | *215.43* | 2772.42 | 2846.59 | *2809.51* | 2.64 |
| 7000 | 2.1305 | 59.91 | 53.32 | 23.72 | 20.28 | 34.59 | 205.5 | 2012.3 | 30 | *293.77* | 3101.91 | 3058.08 | *3080.00* | 1.42 |
| 8000 | 2.4282 | 60.00 | 52.87 | 23.72 | 20.51 | 34.28 | 206.4 | 2021.3 | 38 | *372.11* | 3356.09 | 3252.37 | *3304.23* | 3.14 |
| 9000 | 2.757 | 60.13 | 52.66 | 23.30 | 20.15 | 34.63 | 206.4 | 2021.3 | 49 | *479.83* | 3516.13 | 3624.04 | *3570.09* | 3.02 |
| 10000 | 3.0504 | 60.11 | 52.35 | 23.41 | 20.40 | 34.27 | 207.3 | 2030.4 | 61 | *597.34* | 3652.63 | 3831.26 | *3741.94* | 4.77 |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.9024 | 60.06 | 57.83 | 25.00 | 20.00 | 36.43 | 571.1 | 5592.7 | 6.5 | *63.65* | 1866.06 | 1882.50 | *1874.28* | 0.88 |
| 4000 | 1.1977 | 60.31 | 57.62 | 25.02 | 20.37 | 36.26 | 571.1 | 5592.7 | 10.5 | *102.82* | 2250.99 | 2323.59 | *2287.29* | 3.17 |
| 5000 | 1.5042 | 60.30 | 57.00 | 24.62 | 20.37 | 36.15 | 572.1 | 5601.8 | 15 | *146.89* | 2761.44 | 2667.19 | *2714.32* | 3.47 |
| 6000 | 1.8052 | 60.46 | 56.60 | 24.51 | 20.47 | 36.04 | 572.1 | 5601.8 | 23 | *225.22* | 3230.05 | 3042.84 | *3136.44* | 5.97 |
| 7000 | 2.1101 | 60.31 | 56.20 | 24.36 | 20.46 | 35.84 | 572.1 | 5601.8 | 29.5 | *288.88* | 3439.25 | 3433.45 | *3436.35* | 0.17 |
| 8000 | 2.4137 | 60.24 | 55.74 | 24.26 | 20.48 | 35.62 | 572.1 | 5601.8 | 41 | *401.49* | 3765.60 | 3806.81 | *3786.20* | 1.09 |
| 9000 | 2.7151 | 60.00 | 55.10 | 24.25 | 20.50 | 35.17 | 573 | 5610.8 | 47 | *460.24* | 4100.32 | 4248.17 | *4174.24* | 3.54 |
| 10000 | 3.0343 | 60.26 | 55.02 | 23.88 | 20.38 | 35.50 | 573 | 5610.8 | 59 | *577.75* | 4386.51 | 4433.05 | *4409.78* | 1.06 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8877 | 70.06 | 65.00 | 26.30 | 20.11 | 44.32 | 201.8 | 1976 | 7 | *68.547* | 2381.74 | 2292.25 | *2336.99* | 3.83 |
| 4000 | 1.1861 | 70.31 | 64.50 | 25.90 | 20.33 | 44.29 | 201.8 | 1976 | 10 | *97.924* | 2734.77 | 2756.00 | *2745.38* | 0.77 |
| 5000 | 1.4987 | 69.99 | 63.35 | 25.19 | 20.11 | 44.02 | 202.7 | 1985.1 | 15 | *146.89* | 3125.45 | 3176.44 | *3150.94* | 1.62 |
| 6000 | 1.8178 | 69.78 | 62.29 | 24.50 | 19.89 | 43.82 | 201.8 | 1976 | 21 | *205.64* | 3525.54 | 3496.49 | *3511.02* | 0.83 |
| 7000 | 2.0973 | 70.10 | 62.00 | 24.90 | 20.44 | 43.35 | 202.7 | 1985.1 | 27 | *264.39* | 3812.67 | 3902.43 | *3857.55* | 2.33 |
| 8000 | 2.3994 | 70.40 | 61.74 | 24.75 | 20.50 | 43.41 | 202.7 | 1985.1 | 38 | *372.11* | 4076.26 | 4254.44 | *4165.35* | 4.28 |
| 9000 | 2.7327 | 70.20 | 60.57 | 24.00 | 20.20 | 43.22 | 202.7 | 1985.1 | 46 | *450.45* | 4532.84 | 4332.97 | *4432.91* | 4.51 |
| 10000 | 3.0355 | 70.12 | 60.30 | 24.00 | 20.23 | 43.03 | 202.7 | 1985.1 | 56 | *548.37* | 4622.27 | 4780.37 | *4701.32* | 3.36 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8807 | 70.10 | 67.00 | 26.98 | 20.12 | 44.97 | 569.3 | 5574.6 | 7 | *68.547* | 2594.08 | 2520.00 | *2557.04* | 2.90 |
| 4000 | 1.1836 | 70.10 | 66.41 | 26.30 | 20.11 | 45.04 | 569.3 | 5574.6 | 10 | *97.924* | 3087.79 | 3056.33 | *3072.06* | 1.02 |
| 5000 | 1.4775 | 70.30 | 66.00 | 26.20 | 20.33 | 44.88 | 569.3 | 5574.6 | 14.5 | *141.99* | 3598.24 | 3617.84 | *3608.04* | 0.54 |
| 6000 | 1.7796 | 70.00 | 65.27 | 25.80 | 20.41 | 44.53 | 570.2 | 5583.6 | 20 | *195.85* | 3958.06 | 4001.34 | *3979.70* | 1.09 |
| 7000 | 2.0875 | 70.22 | 65.00 | 25.40 | 20.34 | 44.74 | 570.2 | 5583.6 | 27 | *264.39* | 4368.10 | 4406.64 | *4387.37* | 0.88 |
| 8000 | 2.3863 | 70.20 | 64.44 | 25.26 | 20.46 | 44.46 | 571.1 | 5592.7 | 36 | *352.53* | 4819.97 | 4778.51 | *4799.24* | 0.86 |
| 9000 | 2.6883 | 70.28 | 64.20 | 25.08 | 20.52 | 44.44 | 571.1 | 5592.7 | 45 | *440.66* | 5087.74 | 5114.24 | *5100.99* | 0.52 |
| 10000 | 3.0071 | 70.17 | 63.60 | 24.70 | 20.33 | 44.36 | 572.1 | 5601.8 | 55 | *538.58* | 5498.97 | 5486.18 | *5492.58* | 0.23 |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | | | | | | | |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.9533 | 60.39 | 55.68 | 25.97 | 20.46 | 34.82 | 67.57 | 661.7 | 13 | *127.3* | 2217.00 | 2191.06 | *2204.03* | 1.18 |
| 4000 | 1.2781 | 60.30 | 54.85 | 25.46 | 20.49 | 34.60 | 67.57 | 661.7 | 22 | *215.43* | 2565.32 | 2649.96 | *2607.64* | 3.25 |
| 5000 | 1.6013 | 60.41 | 54.11 | 25.25 | 20.50 | 34.38 | 67.57 | 661.7 | 32 | *313.36* | 2965.41 | 3173.26 | *3069.34* | 6.77 |
| 6000 | 1.9328 | 60.38 | 53.35 | 24.80 | 20.45 | 34.22 | 67.57 | 661.7 | 43 | *421.07* | 3309.02 | 3507.82 | *3408.42* | 5.83 |
| 7000 | 2.2677 | 60.50 | 52.84 | 24.35 | 20.42 | 34.25 | 68.04 | 666.23 | 55 | *538.58* | 3605.56 | 3718.35 | *3661.95* | 3.08 |
| 8000 | 2.5971 | 60.50 | 52.28 | 24.18 | 20.41 | 34.05 | 68.5 | 670.76 | 66 | *646.3* | 3869.15 | 4085.22 | *3977.19* | 5.43 |
| 9000 | 2.9310 | 60.50 | 51.38 | 23.94 | 20.38 | 33.70 | 69.42 | 679.82 | 81.5 | *798.08* | 4292.78 | 4353.79 | *4323.29* | 1.41 |
| 10000 | 3.2642 | 60.43 | 51.04 | 23.68 | 20.44 | 33.58 | 69.89 | 684.36 | 97 | *949.86* | 4417.86 | 4407.12 | *4412.49* | 0.24 |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.9437 | 60.49 | 57.37 | 26.95 | 20.35 | 35.25 | 181 | 1772.1 | 13 | *127.3* | 2610.82 | 2598.04 | *2604.43* | 0.49 |
| 4000 | 1.2710 | 60.50 | 56.84 | 25.97 | 20.46 | 35.45 | 180.5 | 1767.5 | 22 | *215.43* | 3062.69 | 2921.42 | *2992.05* | 4.72 |
| 5000 | 1.5897 | 60.30 | 56.02 | 25.89 | 20.49 | 34.97 | 180.5 | 1767.5 | 31 | *303.56* | 3581.50 | 3580.96 | *3581.23* | 0.02 |
| 6000 | 1.9121 | 60.41 | 55.70 | 25.68 | 20.50 | 34.96 | 181.4 | 1776.6 | 43.5 | *425.97* | 3941.33 | 4131.74 | *4036.54* | 4.72 |
| 7000 | 2.2419 | 60.33 | 55.09 | 25.27 | 20.48 | 34.83 | 182.4 | 1785.7 | 54 | *528.79* | 4384.83 | 4479.98 | *4432.40* | 2.15 |
| 8000 | 2.6005 | 60.50 | 54.62 | 24.52 | 19.96 | 35.32 | 182.8 | 1790.2 | 64 | *626.71* | 4920.38 | 4947.72 | *4934.05* | 0.55 |
| 9000 | 2.8952 | 60.35 | 54.00 | 24.87 | 20.50 | 34.48 | 183.3 | 1794.7 | 78 | *763.81* | 5313.68 | 5278.46 | *5296.07* | 0.67 |
| 10000 | 3.2376 | 60.41 | 53.90 | 24.43 | 20.39 | 34.73 | 183.3 | 1794.7 | 93 | *910.69* | 5448.76 | 5455.35 | *5452.06* | 0.12 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.9337 | 70.50 | 64.41 | 27.80 | 20.43 | 43.34 | 65.72 | 643.57 | 13 | *127.3* | 2866.56 | 2870.09 | *2868.33* | 0.12 |
| 4000 | 1.2588 | 70.50 | 63.57 | 26.83 | 20.44 | 43.40 | 66.18 | 648.1 | 23 | *225.22* | 3261.95 | 3355.00 | *3308.48* | 2.81 |
| 5000 | 1.5813 | 70.35 | 62.36 | 26.34 | 20.50 | 42.93 | 65.72 | 643.57 | 32 | *313.36* | 3760.89 | 3852.01 | *3806.45* | 2.39 |
| 6000 | 1.9083 | 70.10 | 61.33 | 25.88 | 20.47 | 42.52 | 67.11 | 657.16 | 40.5 | *396.59* | 4128.04 | 4306.62 | *4217.33* | 4.23 |
| 7000 | 2.2367 | 70.37 | 60.81 | 25.46 | 20.49 | 42.57 | 66.65 | 652.63 | 53 | *519* | 4499.89 | 4637.43 | *4568.66* | 3.01 |
| 8000 | 2.5687 | 70.38 | 59.88 | 25.10 | 20.43 | 42.30 | 67.57 | 661.7 | 63 | *616.92* | 4942.35 | 5004.63 | *4973.49* | 1.25 |
| 9000 | 2.8915 | 70.44 | 59.20 | 25.01 | 20.47 | 41.99 | 67.57 | 661.7 | 77 | *754.01* | 5290.67 | 5476.70 | *5383.69* | 3.46 |
| 10000 | 3.2210 | 70.38 | 58.76 | 24.80 | 20.46 | 41.83 | 67.57 | 661.7 | 90 | *881.31* | 5468.19 | 5830.23 | *5649.21* | 6.41 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.9236 | 70.50 | 66.63 | 28.77 | 20.42 | 43.93 | 179.6 | 1758.5 | 12 | *117.51* | 3238.42 | 3216.04 | *3227.23* | 0.69 |
| 4000 | 1.2439 | 70.23 | 65.73 | 27.84 | 20.47 | 43.81 | 179.6 | 1758.5 | 21 | *205.64* | 3765.60 | 3823.25 | *3794.43* | 1.52 |
| 5000 | 1.5550 | 70.24 | 64.39 | 27.80 | 20.50 | 43.16 | 180.5 | 1767.5 | 31 | *303.56* | 4895.28 | 4734.22 | *4814.75* | 3.35 |
| 6000 | 1.8868 | 70.13 | 64.27 | 26.83 | 20.50 | 43.53 | 181 | 1772.1 | 45 | *440.66* | 4903.65 | 4981.78 | *4942.71* | 1.58 |
| 7000 | 2.2051 | 70.12 | 63.52 | 26.68 | 20.50 | 43.23 | 181 | 1772.1 | 51 | *499.41* | 5522.88 | 5684.24 | *5603.56* | 2.88 |
| 8000 | 2.5315 | 70.41 | 63.13 | 26.33 | 20.46 | 43.37 | 181.4 | 1776.6 | 64 | *626.71* | 6091.90 | 6198.49 | *6145.2* | 1.73 |
| 9000 | 2.8552 | 70.00 | 62.16 | 26.10 | 20.47 | 42.79 | 182.4 | 1785.7 | 76 | *744.22* | 6560.51 | 6705.37 | *6632.94* | 2.18 |
| 10000 | 3.1895 | 70.23 | 62.00 | 25.63 | 20.47 | 43.05 | 182.4 | 1785.7 | 88 | *861.73* | 6889.25 | 6860.03 | *6874.64* | 0.43 |

**Table C-7:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e=1 mm, p= 10 mm).

| **Re** Annul -us | $Q_c$ $10^{-4}$ ($m^3$/s) | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| | | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | N/$m^2$ | $mmH_2O$ | N/$m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| **3000** | 0.8577 | 60.21 | 53.22 | 29.53 | 19.89 | 31.99 | 211 | 2066.7 | 19 | *186.06* | 3290.19 | 3447.74 | *3368.97* | 4.68 |
| **4000** | 1.1467 | 60.36 | 52.31 | 28.68 | 20.50 | 31.74 | 211 | 2066.7 | 30 | *293.77* | 3789.14 | 3911.50 | *3850.32* | 3.18 |
| **5000** | 1.4531 | 60.47 | 51.57 | 27.61 | 20.37 | 32.02 | 212.9 | 2084.8 | 44 | *430.86* | 4189.23 | 4387.67 | *4288.45* | 4.63 |
| **6000** | 1.7597 | 59.85 | 50.40 | 26.75 | 20.43 | 31.51 | 212.9 | 2084.8 | 57.5 | *563.06* | 4448.12 | 4638.96 | *4543.54* | 4.20 |
| **7000** | 2.0728 | 60.50 | 50.27 | 26.07 | 20.28 | 32.16 | 214.8 | 2102.9 | 74 | *724.64* | 4815.26 | 5006.46 | *4910.86* | 3.89 |
| **8000** | 2.3772 | 60.00 | 49.30 | 25.6 | 20.45 | 31.54 | 214.8 | 2102.9 | 91 | *891.11* | 5036.49 | 5107.13 | *5071.81* | 1.39 |
| **9000** | 2.7174 | 60.50 | 48.97 | 24.81 | 19.87 | 32.28 | 215.7 | 2112 | 117 | *1145.7* | 5427.17 | 5600.89 | *5514.03* | 3.15 |
| **10000** | 3.0096 | 60.27 | 48.41 | 24.70 | 20.26 | 31.72 | 215.7 | 2112 | 143 | *1400.3* | 5582.50 | 5580.50 | *5581.50* | 0.04 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| **3000** | 0.8473 | 59.98 | 55.44 | 30.63 | 19.87 | 32.36 | 581.3 | 5692.4 | 18 | *176.26* | 3799.07 | 3801.25 | *3800.16* | 0.06 |
| **4000** | 1.1402 | 60.05 | 54.72 | 29.73 | 19.95 | 32.49 | 581.3 | 5692.4 | 29 | *283.98* | 4460.14 | 4649.92 | *4555.03* | 4.17 |
| **5000** | 1.4347 | 60.28 | 54.29 | 28.92 | 20.18 | 32.72 | 583.2 | 5710.5 | 43 | *421.07* | 5012.43 | 5228.89 | *5120.66* | 4.23 |
| **6000** | 1.7421 | 60.28 | 53.74 | 27.88 | 20.18 | 32.98 | 583.2 | 5710.5 | 59 | *577.75* | 5472.67 | 5594.56 | *5533.62* | 2.20 |
| **7000** | 2.0376 | 60.28 | 53.30 | 27.42 | 20.42 | 32.87 | 585 | 5728.7 | 78 | *763.81* | 5840.86 | 5948.73 | *5894.80* | 1.83 |
| **8000** | 2.3393 | 60.28 | 52.98 | 26.96 | 20.48 | 32.91 | 585 | 5728.7 | 94 | *920.48* | 6108.64 | 6322.75 | *6215.69* | 3.44 |
| **9000** | 2.6595 | 60.50 | 52.65 | 26.27 | 20.26 | 33.30 | 585 | 5728.7 | 114 | *1116.3* | 6568.88 | 6667.42 | *6618.15* | 1.49 |
| **10000** | 2.9574 | 60.49 | 52.44 | 26.07 | 20.39 | 33.22 | 585.9 | 5737.7 | 144 | *1410.1* | 6736.24 | 7007.19 | *6871.72* | 3.94 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| **3000** | 0.8333 | 70.26 | 61.46 | 32.07 | 19.92 | 39.84 | 210.1 | 2057.6 | 18 | *176.26* | 4142.16 | 4220.71 | *4181.44* | 1.88 |
| **4000** | 1.1143 | 70.42 | 60.19 | 31.23 | 20.50 | 39.44 | 211.5 | 2071.2 | 27 | *264.39* | 4815.26 | 4984.45 | *4899.86* | 3.45 |
| **5000** | 1.4160 | 69.82 | 58.70 | 29.78 | 20.48 | 39.12 | 212 | 2075.7 | 40 | *391.7* | 5234.18 | 5490.73 | *5362.46* | 4.78 |
| **6000** | 1.7292 | 70.46 | 58.10 | 28.56 | 20.15 | 39.89 | 212.9 | 2084.8 | 53 | *519* | 5817.85 | 6064.84 | *5941.34* | 4.16 |
| **7000** | 2.0357 | 70.46 | 57.40 | 27.76 | 20.16 | 39.91 | 212.9 | 2084.8 | 76 | *744.22* | 6147.34 | 6452.65 | *6300.00* | 4.85 |
| **8000** | 2.3447 | 70.47 | 56.54 | 27.13 | 20.11 | 39.79 | 212.9 | 2084.8 | 87 | *851.94* | 6556.85 | 6865.57 | *6711.21* | 4.60 |
| **9000** | 2.6768 | 70.50 | 55.94 | 26.21 | 19.76 | 40.10 | 214.8 | 2102.9 | 110 | *1077.2* | 6853.39 | 7202.59 | *7027.99* | 4.97 |
| **10000** | 2.9672 | 70.34 | 54.91 | 26.02 | 20.15 | 39.34 | 214.8 | 2102.9 | 138 | *1351.3* | 7263.57 | 7260.53 | *7262.05* | 0.04 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| **3000** | 0.8146 | 70.27 | 64.62 | 34.32 | 19.73 | 40.25 | 576.7 | 5647.1 | 17 | *166.47* | 4727.92 | 4953.26 | *4840.59* | 4.66 |
| **4000** | 1.0941 | 69.94 | 63.25 | 32.91 | 20.48 | 39.83 | 578.5 | 5665.2 | 29 | *283.98* | 5598.19 | 5667.94 | *5633.07* | 1.24 |
| **5000** | 1.3921 | 70.46 | 62.68 | 31.70 | 20.08 | 40.65 | 578.5 | 5665.2 | 40 | *391.7* | 6510.30 | 6743.56 | *6626.93* | 3.52 |
| **6000** | 1.6878 | 70.46 | 62.00 | 30.66 | 20.20 | 40.79 | 579.9 | 5678.8 | 57 | *558.17* | 7079.33 | 7360.45 | *7219.89* | 3.89 |
| **7000** | 1.9790 | 70.18 | 61.25 | 29.92 | 20.49 | 40.51 | 581.3 | 5692.4 | 68 | *665.88* | 7472.62 | 7781.20 | *7626.91* | 4.05 |
| **8000** | 2.2820 | 69.77 | 60.36 | 29.12 | 20.50 | 40.25 | 581.3 | 5692.4 | 85 | *832.35* | 7874.29 | 8202.40 | *8038.35* | 4.08 |
| **9000** | 2.5809 | 70.30 | 60.32 | 28.65 | 20.50 | 40.73 | 581.8 | 5696.9 | 103 | *1008.6* | 8351.26 | 8771.60 | *8561.43* | 4.91 |
| **10000** | 2.9097 | 70.20 | 59.59 | 27.59 | 20.28 | 40.93 | 583.2 | 5710.5 | 135 | *1322* | 8876.06 | 8867.70 | *8871.88* | 0.09 |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| **3000** | 0.9036 | 60.35 | 51.95 | 30.89 | 20.25 | 30.57 | 69 | 675.29 | 36 | *352.53* | 3953.88 | 4008.14 | *3981.01* | 1.36 |
| **4000** | 1.2218 | 60.50 | 51.21 | 29.43 | 20.46 | 30.91 | 69 | 675.29 | 59 | *577.75* | 4372.80 | 4569.75 | *4471.28* | 4.40 |
| **5000** | 1.5534 | 60.47 | 50.36 | 27.99 | 20.40 | 31.20 | 69.4 | 679.82 | 90 | *881.31* | 4758.78 | 4917.19 | *4837.98* | 3.27 |
| **6000** | 1.8799 | 60.45 | 49.57 | 27.18 | 20.47 | 31.14 | 69.4 | 679.82 | 123 | *1204.5* | 5121.22 | 5261.28 | *5191.25* | 2.70 |
| **7000** | 2.2099 | 60.50 | 49.00 | 26.57 | 20.42 | 31.18 | 69.4 | 679.82 | 170 | *1664.7* | 5413.05 | 5669.16 | *5541.11* | 4.62 |
| **8000** | 2.5468 | 60.45 | 48.25 | 25.83 | 20.44 | 31.09 | 70.3 | 688.89 | 227 | *2222.9* | 5744.42 | 5729.12 | *5736.77* | 0.27 |
| **9000** | 2.8798 | 60.45 | 47.81 | 25.39 | 20.44 | 31.06 | 71.3 | 697.95 | 283 | *2771.2* | 5951.53 | 5949.96 | *5950.75* | 0.03 |
| **10000** | 3.2136 | 60.45 | 47.41 | 25.02 | 20.44 | 31.01 | 71.3 | 697.95 | 345 | *3378.4* | 6139.81 | 6143.82 | *6141.81* | 0.07 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| **3000** | 0.8766 | 60.42 | 54.86 | 33.63 | 20.25 | 30.53 | 181 | 1776.6 | 35 | *342.73* | 4652.61 | 4888.14 | *4770.37* | 4.94 |
| **4000** | 1.1888 | 60.45 | 53.85 | 31.86 | 20.48 | 30.92 | 181 | 1776.6 | 57 | *558.17* | 5522.88 | 5639.23 | *5581.06* | 2.08 |
| **5000** | 1.5088 | 60.40 | 53.16 | 30.53 | 20.44 | 31.27 | 181 | 1776.6 | 88 | *861.73* | 6058.43 | 6347.11 | *6202.77* | 4.65 |
| **6000** | 1.8376 | 60.46 | 52.42 | 29.33 | 20.32 | 31.61 | 181 | 1776.6 | 120 | *1175.1* | 6727.87 | 6904.07 | *6815.97* | 2.59 |
| **7000** | 2.1590 | 60.47 | 51.87 | 28.53 | 20.50 | 31.65 | 181 | 1776.6 | 160 | *1566.8* | 7196.48 | 7229.76 | *7213.12* | 0.46 |
| **8000** | 2.4935 | 60.44 | 51.33 | 27.71 | 20.40 | 31.82 | 182 | 1785.7 | 217 | *2124.9* | 7623.25 | 7604.03 | *7613.64* | 0.25 |
| **9000** | 2.8225 | 60.44 | 50.95 | 27.17 | 20.40 | 31.89 | 182 | 1785.7 | 272 | *2663.5* | 7941.23 | 7972.42 | *7956.82* | 0.39 |
| **10000** | 3.1535 | 60.44 | 50.58 | 26.69 | 20.40 | 31.93 | 183 | 1794.7 | 333 | *3260.9* | 8250.85 | 8276.36 | *8263.60* | 0.31 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| **3000** | 0.8677 | 70.30 | 60.17 | 34.32 | 20.50 | 37.79 | 68.5 | 670.76 | 32 | *313.36* | 4768.19 | 4996.73 | *4882.46* | 4.68 |
| **4000** | 1.1900 | 70.12 | 58.37 | 31.80 | 20.45 | 38.12 | 69.4 | 679.82 | 55 | *538.58* | 5530.73 | 5630.04 | *5580.38* | 1.78 |
| **5000** | 1.5141 | 70.44 | 57.60 | 30.39 | 20.27 | 38.67 | 69.4 | 679.82 | 88 | *861.73* | 6043.79 | 6388.37 | *6216.08* | 5.54 |
| **6000** | 1.8458 | 70.44 | 56.67 | 29.04 | 20.22 | 38.87 | 69.4 | 679.82 | 119 | *1165.3* | 6481.54 | 6788.69 | *6635.11* | 4.63 |
| **7000** | 2.1666 | 70.46 | 55.90 | 28.27 | 20.45 | 38.72 | 70.3 | 688.89 | 160 | *1566.8* | 6853.39 | 7065.79 | *6959.59* | 3.05 |
| **8000** | 2.4997 | 70.45 | 55.12 | 27.52 | 20.37 | 38.70 | 70.3 | 688.89 | 202 | *1978.1* | 7215.83 | 7454.31 | *7335.07* | 3.25 |
| **9000** | 2.8254 | 70.50 | 54.82 | 27.00 | 20.48 | 38.74 | 70.3 | 688.89 | 261 | *2555.8* | 7380.58 | 7683.58 | *7532.08* | 4.02 |
| **10000** | 3.1665 | 70.39 | 53.73 | 26.34 | 20.39 | 38.44 | 71.3 | 697.95 | 335 | *3280.4* | 7840.52 | 7857.18 | *7848.85* | 0.21 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| **3000** | 0.8409 | 70.30 | 63.49 | 37.23 | 20.50 | 37.81 | 181 | 1776.6 | 31 | *303.56* | 5698.61 | 5859.97 | *5779.29* | 2.79 |
| **4000** | 1.1554 | 70.34 | 62.16 | 34.72 | 20.22 | 38.69 | 181 | 1767.5 | 56 | *548.37* | 6845.02 | 6980.89 | *6912.96* | 1.97 |
| **5000** | 1.4639 | 70.20 | 61.26 | 33.21 | 20.49 | 38.85 | 181 | 1776.6 | 80 | *783.39* | 7480.99 | 7760.51 | *7620.75* | 3.67 |
| **6000** | 1.7856 | 70.10 | 60.18 | 31.72 | 20.50 | 39.03 | 181 | 1776.6 | 115 | *1126.1* | 8301.06 | 8351.15 | *8326.10* | 0.60 |
| **7000** | 2.1168 | 70.20 | 59.69 | 30.58 | 20.20 | 39.55 | 182 | 1785.7 | 155 | *1517.8* | 8794.77 | 9161.03 | *8977.90* | 4.08 |
| **8000** | 2.4353 | 70.37 | 59.27 | 29.76 | 20.43 | 39.72 | 182 | 1785.7 | 195 | *1909.5* | 9288.48 | 9473.90 | *9381.19* | 1.98 |
| **9000** | 2.7593 | 70.40 | 58.65 | 29.14 | 20.42 | 39.73 | 182 | 1785.7 | 250 | *2448.1* | 9832.40 | 10033.1 | *9932.75* | 2.02 |
| **10000** | 3.0959 | 70.45 | 58.32 | 28.43 | 20.27 | 40.00 | 183 | 1794.7 | 315 | *3084.6* | 10150.4 | 10535.3 | *10342.8* | 3.72 |

**Table C-8:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e=1 mm, p= 20 mm).

| Re Annul-us | $Q_c$ $10^{-4}$ ($m^3/s$) | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| | | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | $N/m^2$ | $mmH_2O$ | $N/m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | | | | | | | |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.859 | 59.91 | 53.25 | 29.2 | 20.08 | 31.92 | 212 | 2075.7 | 16 | 156.68 | 3134.86 | 3266.99 | 3200.93 | 4.13 |
| 4000 | 1.1601 | 59.98 | 52.24 | 28.03 | 20.13 | 32.03 | 211 | 2066.7 | 26 | 254.6 | 3643.22 | 3822.17 | 3732.69 | 4.79 |
| 5000 | 1.4646 | 60.12 | 51.33 | 27.06 | 20.23 | 32.07 | 212 | 2075.7 | 38 | 372.11 | 4137.45 | 4172.42 | 4154.93 | 0.84 |
| 6000 | 1.7779 | 60.23 | 50.83 | 26.16 | 20.13 | 32.36 | 212.9 | 2084.8 | 53 | 519 | 4424.58 | 4472.27 | 4448.42 | 1.07 |
| 7000 | 2.0774 | 60.15 | 50.08 | 25.91 | 20.25 | 31.98 | 215.7 | 2112 | 70 | 685.47 | 4739.95 | 4904.95 | 4822.45 | 3.42 |
| 8000 | 2.3891 | 60.23 | 49.51 | 25.27 | 20.35 | 31.97 | 212.9 | 2084.8 | 85 | 832.35 | 5045.9 | 4903.73 | 4974.82 | 2.86 |
| 9000 | 2.7088 | 60.34 | 48.96 | 24.8 | 20.15 | 32.06 | 215.7 | 2112 | 106 | 1038 | 5356.57 | 5255.28 | 5305.92 | 1.91 |
| 10000 | 3.0105 | 60.44 | 48.58 | 24.58 | 20.35 | 31.89 | 215.7 | 2112 | 131 | 1282.8 | 5582.5 | 5313.05 | 5447.77 | 4.95 |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8453 | 60.12 | 55.62 | 30.55 | 20.16 | 32.43 | 583.2 | 5710.5 | 15 | 146.89 | 3765.6 | 3661.81 | 3713.71 | 2.79 |
| 4000 | 1.1392 | 60.23 | 54.94 | 29.53 | 20.23 | 32.66 | 583.2 | 5710.5 | 25 | 244.81 | 4426.67 | 4417.67 | 4422.17 | 0.2 |
| 5000 | 1.4343 | 60.33 | 54.29 | 28.78 | 20.34 | 32.74 | 581.3 | 5692.4 | 37 | 362.32 | 5054.27 | 5048.25 | 5051.26 | 0.12 |
| 6000 | 1.7616 | 60.12 | 53.73 | 27.21 | 19.88 | 33.38 | 583.2 | 5710.5 | 52 | 509.2 | 5347.15 | 5385.94 | 5366.55 | 0.72 |
| 7000 | 2.0512 | 60.45 | 53.62 | 27.13 | 20.13 | 33.4 | 585 | 5728.7 | 68 | 665.88 | 5715.34 | 5988.86 | 5852.1 | 4.67 |
| 8000 | 2.3528 | 60.15 | 53.12 | 26.6 | 20.34 | 33.16 | 585 | 5728.7 | 83 | 812.77 | 5882.7 | 6143.68 | 6013.19 | 4.34 |
| 9000 | 2.6659 | 60.23 | 52.62 | 26.15 | 20.17 | 33.26 | 585.9 | 5737.7 | 104 | 1018.4 | 6368.05 | 6650.44 | 6509.24 | 4.34 |
| 10000 | 2.9763 | 60.08 | 52.3 | 25.71 | 20.2 | 33.22 | 585.9 | 5737.7 | 129 | 1263.2 | 6510.3 | 6841.38 | 6675.84 | 4.96 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8313 | 70.45 | 61.41 | 32 | 20.21 | 39.81 | 208.3 | 2039.5 | 14 | 137.09 | 4255.13 | 4085.56 | 4170.34 | 4.07 |
| 4000 | 1.1191 | 70.34 | 60.28 | 31.01 | 20.34 | 39.63 | 208.3 | 2039.5 | 24 | 235.02 | 4735.24 | 4977.84 | 4856.54 | 5 |
| 5000 | 1.4277 | 70.41 | 59.07 | 29.35 | 20.18 | 39.97 | 209.2 | 2048.5 | 36 | 352.53 | 5337.74 | 5459.21 | 5398.47 | 2.25 |
| 6000 | 1.7269 | 70.5 | 58.17 | 28.65 | 20.18 | 39.89 | 209.2 | 2048.5 | 50 | 489.62 | 5803.73 | 6099.69 | 5951.71 | 4.97 |
| 7000 | 2.0413 | 70.49 | 57.38 | 27.64 | 20.04 | 40.03 | 209.2 | 2048.5 | 66 | 646.3 | 6170.88 | 6470.6 | 6320.74 | 4.74 |
| 8000 | 2.3209 | 70.28 | 56.3 | 27.63 | 20.5 | 39.13 | 210.1 | 2057.6 | 80 | 783.39 | 6580.39 | 6901.65 | 6741.02 | 4.77 |
| 9000 | 2.6302 | 70.5 | 55.85 | 26.99 | 20.5 | 39.29 | 210.1 | 2057.6 | 100 | 979.24 | 6895.76 | 7119.94 | 7007.85 | 3.2 |
| 10000 | 2.9656 | 70.5 | 54.95 | 26.06 | 20.16 | 39.42 | 211 | 2066.7 | 126 | 1233.8 | 7319.39 | 7299.06 | 7309.22 | 0.28 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8029 | 70.2 | 64.26 | 35.3 | 20.08 | 39.36 | 576.7 | 5647.1 | 13 | 127.3 | 4970.59 | 5091.97 | 5031.28 | 2.41 |
| 4000 | 1.088 | 69.8 | 62.96 | 33.41 | 20.49 | 39.35 | 576.7 | 5647.1 | 22 | 215.43 | 5723.71 | 5858.12 | 5790.92 | 2.32 |
| 5000 | 1.38 | 70 | 62.42 | 32.11 | 20.46 | 39.89 | 578.5 | 5665.2 | 34 | 332.94 | 6342.94 | 6701.34 | 6522.14 | 5.5 |
| 6000 | 1.6901 | 69.6 | 61.42 | 30.44 | 20.3 | 40.13 | 578.5 | 5665.2 | 46 | 450.45 | 6845.02 | 7144.97 | 6995 | 4.29 |
| 7000 | 1.9844 | 70.07 | 61.2 | 29.76 | 20.41 | 40.55 | 580.4 | 5683.3 | 62 | 607.13 | 7422.42 | 7736.26 | 7579.34 | 4.14 |
| 8000 | 2.2859 | 69.99 | 60.44 | 28.97 | 20.5 | 40.48 | 581.3 | 5692.4 | 78 | 763.81 | 7991.44 | 8073.5 | 8032.47 | 1.02 |
| 9000 | 2.5915 | 69.99 | 60.06 | 28.29 | 20.5 | 40.62 | 581.3 | 5692.4 | 95 | 930.28 | 8309.42 | 8418.85 | 8364.13 | 1.31 |
| 10000 | 2.8962 | 70.13 | 59.68 | 27.78 | 20.5 | 40.74 | 581.3 | 5692.4 | 117 | 1145.7 | 8744.56 | 8793.32 | 8768.94 | 0.56 |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | | | | | | | |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8989 | 60.5 | 52.31 | 31.13 | 20.48 | 30.58 | 68.5 | 670.76 | 29 | 283.98 | 3855.03 | 3990.7 | 3922.87 | 3.46 |
| 4000 | 1.2236 | 60.5 | 51.14 | 29.38 | 20.38 | 30.94 | 68.96 | 675.29 | 52 | 509.2 | 4405.75 | 4591.84 | 4498.8 | 4.14 |
| 5000 | 1.5529 | 60.5 | 50.4 | 28.06 | 20.36 | 31.22 | 69.42 | 679.82 | 83 | 812.77 | 4754.07 | 4986.73 | 4870.4 | 4.78 |
| 6000 | 1.8829 | 60.49 | 49.77 | 27.01 | 20.5 | 31.33 | 69.42 | 679.82 | 119 | 1165.3 | 5045.9 | 5112.75 | 5079.33 | 1.32 |
| 7000 | 2.2186 | 60.4 | 48.8 | 26.35 | 20.3 | 31.19 | 70.35 | 688.89 | 166 | 1625.5 | 5460.12 | 5599.12 | 5529.62 | 2.51 |
| 8000 | 2.5462 | 60.5 | 48.9 | 25.85 | 20.44 | 31.45 | 70.35 | 688.89 | 210 | 2056.4 | 5460.12 | 5746.2 | 5603.16 | 5.11 |
| 9000 | 2.8771 | 60.49 | 48.59 | 25.41 | 20.5 | 31.46 | 70.35 | 688.89 | 264 | 2585.2 | 5601.33 | 5893.19 | 5747.26 | 5.08 |
| 10000 | 3.2187 | 60.48 | 47.77 | 24.9 | 20.42 | 31.28 | 71.28 | 697.95 | 326 | 3192.3 | 5983.94 | 6012.09 | 5998.02 | 0.47 |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8775 | 60.5 | 54.84 | 33.42 | 20.37 | 30.63 | 180.5 | 1767.5 | 28 | 274.19 | 4736.29 | 4772.34 | 4754.31 | 0.76 |
| 4000 | 1.1913 | 60.4 | 53.9 | 31.67 | 20.48 | 31.02 | 180.5 | 1767.5 | 50 | 489.62 | 5439.2 | 5556.9 | 5498.05 | 2.14 |
| 5000 | 1.5136 | 60.49 | 53.14 | 30.27 | 20.42 | 31.45 | 181.4 | 1776.6 | 80 | 783.39 | 6150.48 | 6215.81 | 6183.15 | 1.06 |
| 6000 | 1.8364 | 60.5 | 52.72 | 29.25 | 20.46 | 31.75 | 180.5 | 1767.5 | 113 | 1106.5 | 6510.3 | 6730.88 | 6620.59 | 3.33 |
| 7000 | 2.1666 | 60.17 | 51.98 | 28.26 | 20.46 | 31.71 | 181.4 | 1776.6 | 155 | 1517.8 | 6853.39 | 7047.72 | 6950.56 | 2.8 |
| 8000 | 2.4931 | 60.28 | 51.66 | 27.66 | 20.46 | 31.9 | 182.4 | 1785.7 | 201 | 1968.3 | 7213.22 | 7486.52 | 7349.87 | 3.72 |
| 9000 | 2.8247 | 60.38 | 51.34 | 27.05 | 20.45 | 32.09 | 182.4 | 1785.7 | 251 | 2457.9 | 7564.67 | 7776.05 | 7670.36 | 2.76 |
| 10000 | 3.1585 | 60.17 | 50.81 | 26.5 | 20.45 | 31.99 | 182.4 | 1785.7 | 314 | 3074.8 | 7832.45 | 7970.83 | 7901.64 | 1.75 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8642 | 70.13 | 59.83 | 34.69 | 20.5 | 37.35 | 68.5 | 670.76 | 27 | 264.39 | 4848.21 | 5109.67 | 4978.94 | 5.25 |
| 4000 | 1.1888 | 70.14 | 58.47 | 31.95 | 20.39 | 38.13 | 68.5 | 670.76 | 50 | 489.62 | 5493.07 | 5728.43 | 5610.75 | 4.19 |
| 5000 | 1.5103 | 70.13 | 57.61 | 30.4 | 20.48 | 38.42 | 69.42 | 679.82 | 77 | 754.01 | 5893.16 | 6246.53 | 6069.85 | 5.82 |
| 6000 | 1.8397 | 70.13 | 56.87 | 29.07 | 20.48 | 38.68 | 69.42 | 679.82 | 114 | 1116.3 | 6241.48 | 6589.76 | 6415.62 | 5.43 |
| 7000 | 2.1686 | 70.43 | 56.34 | 28.18 | 20.46 | 38.98 | 70.35 | 688.89 | 155 | 1517.8 | 6632.16 | 6981.86 | 6807.01 | 5.14 |
| 8000 | 2.5048 | 70.43 | 55.7 | 27.25 | 20.46 | 39.08 | 70.35 | 688.89 | 203 | 1987.9 | 6933.41 | 7093.75 | 7013.58 | 2.29 |
| 9000 | 2.8361 | 70.5 | 55.35 | 26.72 | 20.43 | 39.18 | 70.35 | 688.89 | 260 | 2546 | 7131.11 | 7440.99 | 7286.05 | 4.25 |
| 10000 | 3.1695 | 70.43 | 55.26 | 26.19 | 20.46 | 39.33 | 70.81 | 693.42 | 316 | 3094.4 | 7140.52 | 7575.67 | 7358.1 | 5.91 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8358 | 70.14 | 63.22 | 37.9 | 20.41 | 37.28 | 180.5 | 1767.5 | 25 | 244.81 | 5790.66 | 6088 | 5939.33 | 5.01 |
| 4000 | 1.1442 | 70.46 | 62.27 | 35.34 | 20.5 | 38.35 | 180.5 | 1767.5 | 47 | 460.24 | 6853.39 | 7074.4 | 6963.9 | 3.17 |
| 5000 | 1.4593 | 70.34 | 61.3 | 33.51 | 20.48 | 38.79 | 181.4 | 1776.6 | 73 | 714.84 | 7564.67 | 7924.13 | 7744.4 | 4.64 |
| 6000 | 1.7779 | 70.5 | 60.65 | 32.14 | 20.47 | 39.26 | 181.4 | 1776.6 | 106 | 1038 | 8242.48 | 8648.24 | 8445.36 | 4.8 |
| 7000 | 2.1029 | 70.48 | 60.1 | 30.87 | 20.5 | 39.6 | 182.4 | 1785.7 | 146 | 1429.7 | 8685.98 | 9091.38 | 8888.68 | 4.56 |
| 8000 | 2.4546 | 69.89 | 59.15 | 29.33 | 20.16 | 39.77 | 182.4 | 1785.7 | 195 | 1909.5 | 8987.23 | 9386.04 | 9186.64 | 4.34 |
| 9000 | 2.7844 | 70.3 | 58.98 | 28.57 | 20.19 | 40.24 | 182.4 | 1785.7 | 243 | 2379.5 | 9472.58 | 9730.68 | 9601.63 | 2.69 |
| 10000 | 3.1278 | 70.1 | 58.41 | 27.8 | 20 | 40.32 | 182.4 | 1785.7 | 308 | 3016.1 | 9782.19 | 10175.6 | 9978.88 | 3.94 |

**Table C-9:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil e=1 mm, p= 30 mm).

| Re | $Q_c$ $10^{-4}$ | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| Annul -us | ($m^3$/s) | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | N/$m^2$ | $mmH_2O$ | N/$m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8657 | 60.28 | 53.61 | 28.68 | 19.92 | 32.63 | 210.1 | 2057.6 | 11.5 | *112.61* | 3139.57 | 3162.62 | *3151.09* | 0.73 |
| 4000 | 1.1789 | 59.72 | 52.18 | 27.07 | 19.69 | 32.57 | 210.1 | 2057.6 | 19.5 | *190.95* | 3549.08 | 3629.04 | *3589.06* | 2.23 |
| 5000 | 1.4811 | 60.05 | 51.52 | 26.4 | 19.92 | 32.61 | 211 | 2066.7 | 30 | *293.77* | 4015.07 | 4003.61 | *4009.34* | 0.29 |
| 6000 | 1.7759 | 60.39 | 51.3 | 26.13 | 20.26 | 32.62 | 211 | 2066.7 | 40 | *391.7* | 4278.66 | 4348.51 | *4313.59* | 1.62 |
| 7000 | 2.0716 | 60.51 | 50.9 | 25.9 | 20.5 | 32.46 | 210.1 | 2057.6 | 53 | *519* | 4523.43 | 4666.51 | *4594.97* | 3.11 |
| 8000 | 2.391 | 60.5 | 50.45 | 25.23 | 20.32 | 32.63 | 211 | 2066.7 | 66.5 | *651.19* | 4730.54 | 4897.79 | *4814.16* | 3.47 |
| 9000 | 2.7241 | 60.5 | 49.82 | 24.55 | 19.92 | 32.83 | 212 | 2075.7 | 83 | *812.77* | 5027.08 | 5262.49 | *5144.78* | 4.58 |
| 10000 | 3.0119 | 60.5 | 49.48 | 24.61 | 20.28 | 32.43 | 212.9 | 2084.8 | 102 | *998.82* | 5187.11 | 5441.22 | *5314.17* | 4.78 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8576 | 59.89 | 55.52 | 29.75 | 19.68 | 32.91 | 580.8 | 5687.9 | 11 | *107.72* | 3656.82 | 3601.12 | *3628.97* | 1.53 |
| 4000 | 1.1611 | 59.78 | 54.66 | 28.38 | 19.7 | 33.15 | 581.3 | 5692.4 | 19 | *186.06* | 4284.42 | 4203.43 | *4243.92* | 1.91 |
| 5000 | 1.4631 | 59.83 | 54.04 | 27.47 | 19.91 | 33.24 | 581.3 | 5692.4 | 29 | *283.98* | 4845.07 | 4613.55 | *4729.31* | 4.9 |
| 6000 | 1.7541 | 59.94 | 53.61 | 27.2 | 20.26 | 33.04 | 581.3 | 5692.4 | 39 | *381.9* | 5296.94 | 5077.51 | *5187.23* | 4.23 |
| 7000 | 2.0575 | 60.5 | 53.56 | 26.73 | 20.26 | 33.53 | 582.2 | 5701.5 | 52 | *509.2* | 5807.39 | 5552.83 | *5680.11* | 4.48 |
| 8000 | 2.3517 | 60.4 | 53.26 | 26.48 | 20.5 | 33.34 | 582.2 | 5701.5 | 65 | *636.5* | 5974.75 | 5866.15 | *5920.45* | 1.83 |
| 9000 | 2.6678 | 60.47 | 52.81 | 25.97 | 20.29 | 33.5 | 583.2 | 5710.5 | 81 | *793.18* | 6409.89 | 6321.24 | *6365.56* | 1.39 |
| 10000 | 2.9635 | 60.5 | 52.58 | 25.78 | 20.5 | 33.38 | 583.2 | 5710.5 | 100 | *979.24* | 6627.46 | 6527.45 | *6577.45* | 1.52 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8461 | 70.11 | 61.55 | 30.83 | 19.8 | 40.5 | 206.4 | 2021.3 | 10.5 | *102.82* | 4029.19 | 3890.9 | *3960.04* | 3.49 |
| 4000 | 1.1324 | 70.46 | 60.73 | 29.79 | 20.5 | 40.45 | 208.3 | 2039.5 | 18 | *176.26* | 4579.91 | 4386.36 | *4483.14* | 4.32 |
| 5000 | 1.4374 | 70.07 | 59.44 | 28.48 | 20.45 | 40.28 | 208.3 | 2039.5 | 27 | *264.39* | 5003.54 | 4813.49 | *4908.51* | 3.87 |
| 6000 | 1.7387 | 70.21 | 58.75 | 27.75 | 20.48 | 40.33 | 208.3 | 2039.5 | 38 | *372.11* | 5394.22 | 5271.79 | *5333* | 2.3 |
| 7000 | 2.045 | 70.33 | 58.33 | 27.02 | 20.5 | 40.51 | 208.3 | 2039.5 | 49 | *479.83* | 5648.4 | 5561.39 | *5604.9* | 1.55 |
| 8000 | 2.3654 | 70.5 | 57.66 | 26.26 | 20.22 | 40.75 | 209.2 | 2048.5 | 63.5 | *621.82* | 6043.79 | 5959.66 | *6001.72* | 1.4 |
| 9000 | 2.6573 | 70.32 | 57.07 | 26.1 | 20.5 | 40.27 | 209.2 | 2048.5 | 78 | *763.81* | 6236.78 | 6207.49 | *6222.13* | 0.47 |
| 10000 | 2.9615 | 70.32 | 56.69 | 25.84 | 20.5 | 40.19 | 209.2 | 2048.5 | 95 | *930.28* | 6415.64 | 6597 | *6506.32* | 2.79 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8205 | 69.89 | 64.23 | 33.37 | 20.03 | 40.24 | 573 | 5610.8 | 10 | *97.924* | 4736.29 | 4561.66 | *4648.97* | 3.76 |
| 4000 | 1.1133 | 70.11 | 63.58 | 31.78 | 20.03 | 40.88 | 573 | 5610.8 | 17.5 | *171.37* | 5464.3 | 5453.37 | *5458.84* | 0.2 |
| 5000 | 1.4225 | 70.06 | 62.59 | 30.05 | 19.8 | 41.38 | 573.9 | 5619.9 | 27 | *264.39* | 6250.9 | 6079.92 | *6165.41* | 2.77 |
| 6000 | 1.7202 | 70.11 | 62.04 | 29.25 | 19.92 | 41.49 | 575.8 | 5638 | 38 | *372.11* | 6752.98 | 6692.87 | *6722.92* | 0.89 |
| 7000 | 2.0135 | 70.5 | 61.87 | 28.68 | 20.2 | 41.74 | 577.6 | 5656.1 | 48 | *470.03* | 7221.58 | 7120.62 | *7171.1* | 1.41 |
| 8000 | 2.3056 | 70.5 | 61.33 | 28.28 | 20.43 | 41.56 | 578.5 | 5665.2 | 61 | *597.34* | 7673.46 | 7547.99 | *7610.72* | 1.65 |
| 9000 | 2.6101 | 70.48 | 60.84 | 27.75 | 20.41 | 41.57 | 578.5 | 5665.2 | 77.5 | *758.91* | 8066.75 | 7990.27 | *8028.51* | 0.95 |
| 10000 | 2.9101 | 70.5 | 60.52 | 27.43 | 20.43 | 41.56 | 579.5 | 5674.3 | 93 | *910.69* | 8351.26 | 8496.23 | *8423.75* | 1.72 |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.9102 | 60.29 | 52.94 | 30.02 | 20.47 | 31.36 | 68.5 | 670.76 | 23 | *225.22* | 3459.65 | 3624.11 | *3541.88* | 4.64 |
| 4000 | 1.2371 | 60.09 | 51.79 | 28.3 | 20.49 | 31.54 | 68.5 | 670.76 | 39.5 | *386.8* | 3906.81 | 4029.19 | *3968* | 3.08 |
| 5000 | 1.5662 | 60.19 | 51.15 | 27.19 | 20.48 | 31.82 | 68.5 | 670.76 | 56 | *548.37* | 4255.13 | 4383.39 | *4319.26* | 2.97 |
| 6000 | 1.8964 | 60.5 | 50.83 | 26.42 | 20.47 | 32.18 | 69.42 | 679.82 | 79 | *773.6* | 4551.67 | 4706.74 | *4629.2* | 3.35 |
| 7000 | 2.245 | 60.3 | 50 | 25.47 | 20.16 | 32.27 | 69.42 | 679.82 | 103 | *1008.6* | 4848.21 | 4973.33 | *4910.77* | 2.55 |
| 8000 | 2.5642 | 60.38 | 49.76 | 25.22 | 20.46 | 32.14 | 69.42 | 679.82 | 136 | *1331.8* | 4998.83 | 5092.09 | *5045.46* | 1.85 |
| 9000 | 2.9159 | 60.25 | 49.36 | 24.6 | 20.16 | 32.32 | 69.42 | 679.82 | 163 | *1596.2* | 5125.92 | 5401.77 | *5263.85* | 5.24 |
| 10000 | 3.239 | 60.29 | 48.75 | 24.4 | 20.38 | 31.98 | 69.42 | 679.82 | 195 | *1909.5* | 5429.86 | 5426.86 | *5428.36* | 0.06 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8944 | 60.09 | 55.17 | 31.57 | 20.49 | 31.5 | 180.5 | 1767.5 | 21 | *205.64* | 4117.06 | 4130.88 | *4123.97* | 0.34 |
| 4000 | 1.2225 | 60.19 | 54.53 | 29.36 | 20.48 | 32.41 | 181 | 1772.1 | 35 | *342.73* | 4736.29 | 4526.48 | *4631.39* | 4.53 |
| 5000 | 1.5308 | 60.27 | 53.87 | 29.23 | 20.45 | 32.22 | 181.4 | 1776.6 | 54 | *528.79* | 5355.52 | 5604.61 | *5480.06* | 4.55 |
| 6000 | 1.858 | 60.37 | 53.4 | 28.3 | 20.38 | 32.54 | 181.4 | 1776.6 | 74 | *724.64* | 5832.5 | 6136.66 | *5984.58* | 5.08 |
| 7000 | 2.1892 | 60.45 | 52.9 | 27.49 | 20.32 | 32.77 | 181.4 | 1776.6 | 96 | *940.07* | 6317.84 | 6546.82 | *6432.33* | 3.56 |
| 8000 | 2.5227 | 60.18 | 52.41 | 26.63 | 20.46 | 32.74 | 182.4 | 1785.7 | 121 | *1184.9* | 6501.94 | 6492.56 | *6497.25* | 0.14 |
| 9000 | 2.843 | 60.43 | 52.23 | 26.44 | 20.5 | 32.85 | 182.4 | 1785.7 | 159 | *1557* | 6861.76 | 7044.13 | *6952.95* | 2.62 |
| 10000 | 3.1808 | 60.28 | 51.64 | 25.9 | 20.44 | 32.77 | 182.4 | 1785.7 | 190 | *1860.6* | 7232.34 | 7244.89 | *7238.62* | 0.17 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8846 | 70.34 | 61.3 | 32.56 | 20.49 | 39.28 | 68.04 | 666.23 | 20 | *195.85* | 4255.13 | 4450.42 | *4352.77* | 4.49 |
| 4000 | 1.2067 | 70.5 | 59.99 | 30.67 | 20.33 | 39.74 | 68.5 | 670.76 | 33.5 | *328.04* | 4947.06 | 5201.73 | *5074.4* | 5.02 |
| 5000 | 1.5291 | 70.5 | 59.07 | 29.36 | 20.42 | 39.88 | 68.5 | 670.76 | 52 | *509.2* | 5380.1 | 5700.23 | *5540.17* | 5.78 |
| 6000 | 1.866 | 70.43 | 58.06 | 28.05 | 20.25 | 40.05 | 68.5 | 670.76 | 73 | *714.84* | 5822.56 | 6070.18 | *5946.37* | 4.16 |
| 7000 | 2.1862 | 70.38 | 57.63 | 27.43 | 20.5 | 39.97 | 68.5 | 670.76 | 93.5 | *915.59* | 6001.43 | 6318.91 | *6160.17* | 5.15 |
| 8000 | 2.5248 | 70.4 | 57.05 | 26.62 | 20.4 | 40.11 | 68.5 | 670.76 | 116 | *1135.9* | 6283.85 | 6550.5 | *6417.17* | 4.16 |
| 9000 | 2.8588 | 70.43 | 56.18 | 26.06 | 20.4 | 39.92 | 68.5 | 670.76 | 146 | *1429.7* | 6705.12 | 6751.89 | *6728.51* | 0.7 |
| 10000 | 3.1924 | 70.43 | 55.69 | 25.63 | 20.4 | 39.85 | 68.5 | 670.76 | 180 | *1762.6* | 6935.76 | 6967.29 | *6951.53* | 0.45 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8613 | 70.2 | 64.14 | 35.04 | 20.46 | 39.27 | 180 | 1763 | 20 | *195.85* | 5071.01 | 5232.28 | *5151.65* | 3.13 |
| 4000 | 1.1695 | 70.26 | 63.12 | 33.33 | 20.5 | 39.71 | 180.5 | 1767.5 | 32 | *313.36* | 5974.75 | 6253.07 | *6113.91* | 4.55 |
| 5000 | 1.4923 | 70.31 | 62.22 | 31.63 | 20.33 | 40.26 | 180.5 | 1767.5 | 50 | *489.62* | 6769.71 | 7029.39 | *6899.55* | 3.76 |
| 6000 | 1.8189 | 70.09 | 61.27 | 30.33 | 20.23 | 40.4 | 180.5 | 1767.5 | 67 | *656.09* | 7380.58 | 7659.57 | *7520.07* | 3.71 |
| 7000 | 2.149 | 70.07 | 60.69 | 29.28 | 20.16 | 40.66 | 181.4 | 1776.6 | 90 | *881.31* | 7849.18 | 8172.68 | *8010.93* | 4.04 |
| 8000 | 2.4706 | 70.19 | 60.06 | 28.58 | 20.34 | 40.66 | 181.4 | 1776.6 | 112 | *1096.7* | 8473.44 | 8493.89 | *8483.66* | 0.24 |
| 9000 | 2.7995 | 70.19 | 59.58 | 27.95 | 20.34 | 40.72 | 181.4 | 1776.6 | 140 | *1370.9* | 8875.1 | 8889.58 | *8882.34* | 0.16 |
| 10000 | 3.1294 | 70.19 | 59.15 | 27.42 | 20.34 | 40.76 | 181.4 | 1776.6 | 172 | *1684.3* | 9234.92 | 9246.2 | *9240.56* | 0.12 |

**Table C-10:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e=1 mm, p= 40 mm).

| Re Annul-us | $Q_c$ $10^{-4}$ ($m^3/s$) | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| | | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | $N/m^2$ | $mmH_2O$ | $N/m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8747 | 60.05 | 53.96 | 27.78 | 19.91 | 33.15 | 208.3 | 2039.5 | 11 | *107.72* | 2866.56 | 2871.3 | *2868.93* | 0.17 |
| 4000 | 1.1806 | 59.99 | 53.03 | 26.76 | 19.87 | 33.19 | 208.3 | 2039.5 | 17 | *166.47* | 3276.07 | 3393.23 | *3334.65* | 3.51 |
| 5000 | 1.4982 | 59.94 | 52.21 | 25.65 | 19.68 | 33.4 | 210.1 | 2057.6 | 25 | *244.81* | 3638.51 | 3731.62 | *3685.07* | 2.53 |
| 6000 | 1.7785 | 60.27 | 52.1 | 25.79 | 20.47 | 33.03 | 211.1 | 2066.7 | 35 | *342.73* | 3845.62 | 3947.07 | *3896.34* | 2.6 |
| 7000 | 2.1064 | 60.5 | 51.76 | 24.9 | 20.07 | 33.61 | 212 | 2075.7 | 45 | *440.66* | 4113.92 | 4244.66 | *4179.29* | 3.13 |
| 8000 | 2.3949 | 60.33 | 51.19 | 24.95 | 20.46 | 33 | 211 | 2066.7 | 56 | *548.37* | 4302.2 | 4486.22 | *4394.21* | 4.19 |
| 9000 | 2.7025 | 60.25 | 50.68 | 24.65 | 20.5 | 32.82 | 212 | 2075.7 | 66 | *646.3* | 4504.6 | 4679.14 | *4591.87* | 3.8 |
| 10000 | 3.0674 | 60.48 | 50.14 | 23.59 | 19.75 | 33.54 | 212.9 | 2084.8 | 82 | *802.98* | 4867.04 | 4915.21 | *4891.13* | 0.98 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8653 | 59.94 | 56.03 | 28.85 | 19.79 | 33.6 | 573.9 | 5619.9 | 10 | *97.924* | 3271.89 | 3269.42 | *3270.65* | 0.08 |
| 4000 | 1.166 | 59.83 | 55.27 | 27.92 | 19.79 | 33.66 | 576.7 | 5647.1 | 16 | *156.68* | 3815.81 | 3953.96 | *3884.88* | 3.56 |
| 5000 | 1.469 | 60.05 | 54.94 | 27.12 | 19.91 | 33.97 | 583.2 | 5710.5 | 24 | *235.02* | 4276.05 | 4417.89 | *4346.97* | 3.26 |
| 6000 | 1.7591 | 59.94 | 54.39 | 26.85 | 20.36 | 33.56 | 583.2 | 5710.5 | 33 | *323.15* | 4644.24 | 4762.08 | *4703.16* | 2.51 |
| 7000 | 2.0592 | 59.94 | 53.96 | 26.45 | 20.47 | 32 | 583.2 | 5710.5 | 44 | *430.86* | 5004.06 | 5136.47 | *5070.27* | 2.61 |
| 8000 | 2.3744 | 60.5 | 53.94 | 25.87 | 20.28 | 34.14 | 585 | 5728.7 | 54 | *528.79* | 5489.41 | 5536.97 | *5513.19* | 0.86 |
| 9000 | 2.6687 | 60.37 | 53.63 | 25.73 | 20.5 | 33.88 | 585 | 5728.7 | 65 | *636.5* | 5640.03 | 5822.48 | *5731.26* | 3.18 |
| 10000 | 2.9957 | 60.5 | 53.11 | 25.15 | 20.2 | 34.12 | 585 | 5728.7 | 81 | *793.18* | 6183.95 | 6186.66 | *6185.31* | 0.04 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8575 | 70.17 | 62.82 | 29.53 | 19.91 | 41.76 | 203.6 | 1994.2 | 10 | *97.924* | 3459.65 | 3439.8 | *3449.72* | 0.58 |
| 4000 | 1.1466 | 70.28 | 61.65 | 29.05 | 20.14 | 41.37 | 205.5 | 2012.3 | 15 | *146.89* | 4062.14 | 4260.08 | *4161.11* | 4.76 |
| 5000 | 1.4736 | 69.9 | 60.35 | 26.91 | 19.85 | 41.73 | 208.3 | 2039.5 | 23 | *225.22* | 4495.19 | 4339.6 | *4417.39* | 3.52 |
| 6000 | 1.7746 | 69.8 | 59.64 | 26.36 | 20.09 | 41.46 | 208.3 | 2039.5 | 32 | *313.36* | 4782.31 | 4641.58 | *4711.94* | 2.99 |
| 7000 | 2.0663 | 70.34 | 59.34 | 26.22 | 20.4 | 41.48 | 208.3 | 2039.5 | 42 | *411.28* | 5177.7 | 5016.55 | *5097.13* | 3.16 |
| 8000 | 2.3703 | 69.96 | 58.46 | 25.8 | 20.5 | 40.98 | 211 | 2066.7 | 53 | *519* | 5413.05 | 5240.52 | *5326.78* | 3.24 |
| 9000 | 2.6815 | 70.13 | 58.2 | 25.39 | 20.43 | 41.16 | 210.1 | 2057.6 | 64 | *626.71* | 5615.45 | 5548.5 | *5581.97* | 1.2 |
| 10000 | 2.9839 | 70.4 | 58.59 | 25.19 | 20.5 | 41.55 | 212.9 | 2084.8 | 78 | *763.81* | 5558.97 | 5838.31 | *5698.64* | 4.9 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.843 | 69.97 | 65.1 | 31.3 | 19.65 | 41.97 | 568.3 | 5565.5 | 9 | *88.131* | 4075.22 | 4094.74 | *4084.98* | 0.48 |
| 4000 | 1.1353 | 69.53 | 63.78 | 30.15 | 19.91 | 41.58 | 570.2 | 5583.6 | 15 | *146.89* | 4811.6 | 4847.58 | *4829.59* | 0.75 |
| 5000 | 1.4312 | 69.74 | 63.35 | 29.17 | 20.14 | 41.88 | 570.2 | 5583.6 | 22 | *215.43* | 5347.15 | 5389.4 | *5368.28* | 0.79 |
| 6000 | 1.7247 | 70.49 | 63.44 | 28.77 | 20.17 | 42.49 | 572.1 | 5601.8 | 31 | *303.56* | 5899.44 | 6185.49 | *6042.47* | 4.73 |
| 7000 | 2.0509 | 70.29 | 62.71 | 27.21 | 20.06 | 42.86 | 573.9 | 5619.9 | 41 | *401.49* | 6342.94 | 6116.49 | *6229.71* | 3.64 |
| 8000 | 2.3217 | 69.92 | 61.94 | 27.6 | 20.5 | 41.88 | 573.9 | 5619.9 | 52 | *509.2* | 6677.66 | 6874.99 | *6776.33* | 2.91 |
| 9000 | 2.6287 | 69.9 | 61.56 | 27.08 | 20.46 | 41.95 | 573.9 | 5619.9 | 63 | *616.92* | 6978.91 | 7258.35 | *7118.63* | 3.93 |
| 10000 | 2.9642 | 70.5 | 61.38 | 26.36 | 19.9 | 42.8 | 573.9 | 5619.9 | 77 | *754.01* | 7631.62 | 7988.11 | *7809.86* | 4.56 |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.9145 | 60.2 | 52.88 | 29.74 | 20.33 | 31.49 | 69.42 | 679.82 | 19 | *186.06* | 3445.52 | 3588.07 | *3516.8* | 4.05 |
| 4000 | 1.2389 | 60.38 | 52.24 | 28.16 | 20.5 | 31.98 | 69.42 | 679.82 | 30 | *293.77* | 3831.5 | 3957.71 | *3894.61* | 3.24 |
| 5000 | 1.5686 | 60.49 | 51.66 | 27.09 | 20.45 | 32.29 | 69.42 | 679.82 | 44 | *430.86* | 4156.28 | 4344.2 | *4250.24* | 4.42 |
| 6000 | 1.9017 | 60.5 | 51.09 | 26.19 | 20.46 | 32.44 | 69.42 | 679.82 | 60 | *587.54* | 4429.29 | 4545.4 | *4487.35* | 2.59 |
| 7000 | 2.2338 | 60.37 | 50.59 | 25.62 | 20.44 | 32.4 | 70.35 | 688.89 | 77 | *754.01* | 4603.45 | 4827.15 | *4715.3* | 4.74 |
| 8000 | 2.5693 | 60.27 | 50.17 | 25.07 | 20.44 | 32.39 | 70.81 | 693.42 | 96 | *940.07* | 4754.07 | 4962.93 | *4858.5* | 4.3 |
| 9000 | 2.9016 | 60.32 | 49.8 | 24.74 | 20.44 | 32.37 | 71.28 | 697.95 | 117 | *1145.7* | 4951.76 | 5205.55 | *5078.66* | 5 |
| 10000 | 3.2395 | 60.49 | 49.54 | 24.32 | 20.45 | 32.5 | 71.28 | 697.95 | 139 | *1361.1* | 5154.17 | 5230.82 | *5192.49* | 1.48 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8908 | 60.32 | 55.41 | 31.92 | 20.5 | 31.54 | 180.5 | 1767.5 | 18 | *176.26* | 4108.69 | 4240.49 | *4174.59* | 3.16 |
| 4000 | 1.211 | 60.28 | 54.63 | 30.18 | 20.5 | 32.07 | 180.5 | 1767.5 | 29 | *283.98* | 4727.92 | 4887.38 | *4807.65* | 3.32 |
| 5000 | 1.5457 | 60.37 | 54.09 | 28.58 | 20.25 | 32.8 | 181.4 | 1776.6 | 43 | *421.07* | 5255.1 | 5369.36 | *5312.23* | 2.15 |
| 6000 | 1.8624 | 60.25 | 53.54 | 27.97 | 20.5 | 32.66 | 181.4 | 1776.6 | 57 | *558.17* | 5614.93 | 5801.99 | *5708.46* | 3.28 |
| 7000 | 2.198 | 60.49 | 53.35 | 27.11 | 20.35 | 33.19 | 182.4 | 1785.7 | 75 | *734.43* | 5974.75 | 6197.54 | *6086.14* | 3.66 |
| 8000 | 2.5196 | 60.4 | 52.95 | 26.7 | 20.5 | 33.07 | 182.4 | 1785.7 | 93 | *910.69* | 6234.16 | 6515.79 | *6374.97* | 4.42 |
| 9000 | 2.8575 | 60.27 | 52.49 | 26.06 | 20.44 | 33.12 | 182.4 | 1785.7 | 113 | *1106.5* | 6510.3 | 6698.94 | *6604.62* | 2.86 |
| 10000 | 3.1912 | 60.48 | 52.28 | 25.62 | 20.44 | 33.33 | 183.3 | 1794.7 | 135 | *1322* | 6861.76 | 6895.93 | *6878.84* | 0.5 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8846 | 70.45 | 61.43 | 32.55 | 20.5 | 39.4 | 66.65 | 652.63 | 18 | *176.26* | 4245.71 | 4443.05 | *4344.38* | 4.54 |
| 4000 | 1.2049 | 70.5 | 60.05 | 30.7 | 20.43 | 39.71 | 66.65 | 652.63 | 29 | *283.98* | 4918.82 | 5158.93 | *5038.87* | 4.77 |
| 5000 | 1.5434 | 70.3 | 58.93 | 28.8 | 20.16 | 40.12 | 66.65 | 652.63 | 42 | *411.28* | 5351.86 | 5560.87 | *5456.37* | 3.83 |
| 6000 | 1.8812 | 70.2 | 58.15 | 27.54 | 20.05 | 40.34 | 67.57 | 661.7 | 58 | *567.96* | 5671.94 | 5876.96 | *5774.45* | 3.55 |
| 7000 | 2.2199 | 70.42 | 57.67 | 26.71 | 19.89 | 40.67 | 67.57 | 661.7 | 76 | *744.22* | 6001.43 | 6315.42 | *6158.42* | 5.1 |
| 8000 | 2.5233 | 70.19 | 57.14 | 26.57 | 20.5 | 40.03 | 68.5 | 670.76 | 93 | *910.69* | 6142.64 | 6388.82 | *6265.73* | 3.93 |
| 9000 | 2.8601 | 70.46 | 56.98 | 26.02 | 20.4 | 40.38 | 68.5 | 670.76 | 112 | *1096.7* | 6345.04 | 6705.2 | *6525.12* | 5.52 |
| 10000 | 3.1875 | 70.45 | 56.54 | 25.67 | 20.49 | 40.26 | 68.96 | 675.29 | 134 | *1312.2* | 6547.44 | 6887.85 | *6717.64* | 5.07 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8623 | 69.68 | 63.76 | 34.89 | 20.5 | 38.87 | 177.7 | 1740.4 | 17 | *166.47* | 4953.86 | 5170.33 | *5062.09* | 4.28 |
| 4000 | 1.1743 | 70.11 | 63 | 32.95 | 20.5 | 39.77 | 177.7 | 1740.4 | 27 | *264.39* | 5949.65 | 6093.52 | *6021.58* | 2.39 |
| 5000 | 1.4949 | 70.18 | 62.33 | 31.3 | 20.5 | 40.34 | 177.7 | 1740.4 | 40 | *391.7* | 6568.88 | 6730.44 | *6649.66* | 2.43 |
| 6000 | 1.815 | 70.09 | 61.58 | 30.26 | 20.49 | 40.46 | 178.2 | 1744.9 | 54 | *528.79* | 7121.17 | 7393.37 | *7257.27* | 3.75 |
| 7000 | 2.1408 | 70.05 | 61.11 | 29.28 | 20.5 | 40.69 | 178.7 | 1749.4 | 71 | *695.26* | 7480.99 | 7837.5 | *7659.25* | 4.65 |
| 8000 | 2.47 | 69.97 | 60.57 | 28.44 | 20.5 | 40.8 | 178.7 | 1749.4 | 89 | *871.52* | 7865.92 | 8178.42 | *8022.17* | 3.9 |
| 9000 | 2.8542 | 69.89 | 60 | 26.93 | 19.67 | 41.63 | 179.6 | 1758.5 | 113 | *1106.5* | 8275.95 | 8643.69 | *8459.82* | 4.35 |
| 10000 | 3.1875 | 70.31 | 59.89 | 26.38 | 19.78 | 41.99 | 179.6 | 1758.5 | 134 | *1312.2* | 8719.46 | 8776.03 | *8747.74* | 0.65 |

**Table C-11:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e= 2.2 mm, p= 10 mm).

| Re | $Q_c$ $10^{-4}$ | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| Annul-us | ($m^3$/s) | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | N/$m^2$ | $mmH_2O$ | N/$m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | | | | | | | |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8564 | 60.16 | 52.94 | 29.52 | 20.03 | 31.76 | 203.6 | 1994.2 | 38 | *372.11* | 3398.45 | 3389.06 | *3393.75* | 0.28 |
| 4000 | 1.1673 | 60.16 | 51.86 | 27.82 | 19.8 | 32.2 | 205.5 | 2012.3 | 62 | *607.13* | 3906.81 | 3904.53 | *3905.67* | 0.06 |
| 5000 | 1.4687 | 60.16 | 51.09 | 27.02 | 20.03 | 32.09 | 204.6 | 2003.2 | 96 | *940.07* | 4269.25 | 4282.09 | *4275.67* | 0.3 |
| 6000 | 1.7858 | 60.27 | 50.55 | 26.11 | 19.8 | 32.43 | 203.6 | 1994.2 | 130 | *1273* | 4575.2 | 4700.81 | *4638.01* | 2.71 |
| 7000 | 2.0776 | 60.04 | 50.01 | 25.89 | 20.26 | 31.9 | 205.5 | 2012.3 | 178 | *1743* | 4721.12 | 4879.52 | *4800.32* | 3.3 |
| 8000 | 2.3774 | 60.14 | 49.47 | 25.61 | 20.43 | 31.71 | 205.5 | 2012.3 | 208 | *2036.8* | 5022.37 | 5137.48 | *5079.92* | 2.27 |
| 9000 | 2.6849 | 60.5 | 49.34 | 25.32 | 20.39 | 31.96 | 207.3 | 2030.4 | 272 | *2663.5* | 5253.01 | 5522.06 | *5387.54* | 4.99 |
| 10000 | 2.9916 | 60.49 | 48.92 | 24.98 | 20.49 | 31.84 | 207.8 | 2034.9 | 310 | *3035.6* | 5446 | 5603.82 | *5524.91* | 2.86 |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8434 | 60.11 | 55.39 | 31 | 19.91 | 32.19 | 574.8 | 5628.9 | 35 | *342.73* | 3949.7 | 3899.67 | *3924.69* | 1.27 |
| 4000 | 1.1299 | 60.5 | 54.9 | 30.1 | 20.39 | 32.41 | 575.3 | 5633.5 | 58 | *567.96* | 4686.08 | 4574.27 | *4630.17* | 2.41 |
| 5000 | 1.4304 | 60.44 | 54.03 | 29.02 | 20.34 | 32.54 | 575.8 | 5638 | 87 | *851.94* | 5363.89 | 5177.55 | *5270.72* | 3.54 |
| 6000 | 1.7288 | 60.02 | 53.15 | 28.25 | 20.48 | 32.22 | 576.7 | 5647.1 | 128 | *1253.4* | 5748.82 | 5602.01 | *5675.42* | 2.59 |
| 7000 | 2.0299 | 60.24 | 52.83 | 27.69 | 20.48 | 32.45 | 577.1 | 5651.6 | 163 | *1596.2* | 6200.69 | 6103.88 | *6152.28* | 1.57 |
| 8000 | 2.3321 | 60.13 | 52.27 | 27.23 | 20.48 | 32.34 | 578.5 | 5665.2 | 207 | *2027* | 6577.25 | 6565.62 | *6571.43* | 0.18 |
| 9000 | 2.6414 | 59.67 | 51.63 | 26.65 | 20.47 | 32.08 | 578.5 | 5665.2 | 261 | *2555.8* | 6727.87 | 6809.04 | *6768.46* | 1.2 |
| 10000 | 2.9791 | 60.49 | 51.73 | 25.89 | 19.94 | 33.18 | 579.5 | 5674.3 | 307 | *3006.3* | 7330.37 | 7394.64 | *7362.5* | 0.87 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8317 | 69.88 | 61.33 | 32.14 | 20.03 | 39.49 | 201.8 | 1976 | 35 | *342.73* | 4024.49 | 4198.33 | *4111.41* | 4.23 |
| 4000 | 1.1258 | 70.26 | 60.35 | 30.56 | 20.25 | 39.9 | 202.3 | 1980.6 | 57 | *558.17* | 4664.64 | 4839.34 | *4751.99* | 3.68 |
| 5000 | 1.4163 | 70.21 | 59.48 | 29.75 | 20.49 | 39.72 | 202.7 | 1985.1 | 88 | *861.73* | 5050.61 | 5468.36 | *5259.48* | 7.94 |
| 6000 | 1.7239 | 69.8 | 57.9 | 28.55 | 20.43 | 39.33 | 203.6 | 1994.2 | 125 | *1224* | 5601.33 | 5837.58 | *5719.45* | 4.13 |
| 7000 | 2.0366 | 70.45 | 57.74 | 27.49 | 20.39 | 40.09 | 205.5 | 2012.3 | 170 | *1664.7* | 5982.6 | 6030.93 | *6006.76* | 0.8 |
| 8000 | 2.3369 | 70.5 | 57.15 | 27.12 | 20.41 | 39.97 | 206.4 | 2021.3 | 206 | *2017.2* | 6283.85 | 6540.34 | *6412.09* | 4 |
| 9000 | 2.6469 | 70.5 | 56.55 | 26.51 | 20.43 | 39.93 | 206.9 | 2025.9 | 258 | *2526.4* | 6566.27 | 6712.91 | *6639.59* | 2.21 |
| 10000 | 2.9584 | 70.4 | 55.75 | 26 | 20.43 | 39.69 | 208.3 | 2039.5 | 302 | *2957.3* | 6895.76 | 6873.9 | *6884.83* | 0.32 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8122 | 70.49 | 64.92 | 34.3 | 20.03 | 40.38 | 572.1 | 5601.8 | 33 | *323.15* | 4660.98 | 4829.64 | *4745.31* | 3.55 |
| 4000 | 1.1019 | 70.33 | 63.5 | 32.59 | 20.15 | 40.48 | 572.7 | 5608.1 | 56 | *548.37* | 5715.34 | 5713.74 | *5714.54* | 0.03 |
| 5000 | 1.3861 | 70.49 | 62.96 | 31.68 | 20.49 | 40.61 | 574 | 5620.8 | 84 | *822.56* | 6301.1 | 6465.64 | *6383.37* | 2.58 |
| 6000 | 1.6752 | 70.08 | 61.47 | 31.03 | 20.5 | 40 | 573.9 | 5619.9 | 117 | *1145.7* | 7204.85 | 7353.86 | *7279.35* | 2.05 |
| 7000 | 1.9918 | 70.44 | 60.89 | 29.89 | 19.95 | 40.74 | 574.8 | 5628.9 | 157 | *1537.4* | 7991.44 | 8255.4 | *8123.42* | 3.25 |
| 8000 | 2.2859 | 70.36 | 60.26 | 29.18 | 20.29 | 40.57 | 575.8 | 5638 | 199 | *1948.7* | 8451.68 | 8473.83 | *8462.76* | 0.26 |
| 9000 | 2.5771 | 70.25 | 59.55 | 28.78 | 20.5 | 40.25 | 577.1 | 5651.6 | 234 | *2291.4* | 8953.76 | 8898.26 | *8926.01* | 0.62 |
| 10000 | 2.883 | 70.46 | 59.49 | 28.3 | 20.38 | 40.62 | 577.6 | 5656.1 | 298 | *2918.1* | 9179.7 | 9522.41 | *9351.05* | 3.66 |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | | | | | | | |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.9115 | 60.28 | 51.88 | 30.29 | 20.07 | 30.89 | 72.2 | 707.02 | 81.5 | *798.08* | 3953.88 | 3884.1 | *3918.99* | 1.78 |
| 4000 | 1.2403 | 60.28 | 51.3 | 28.49 | 20.07 | 31.51 | 72.2 | 707.02 | 145 | *1419.9* | 4224.99 | 4355.39 | *4290.19* | 3.04 |
| 5000 | 1.5637 | 60.29 | 50.78 | 27.39 | 20.42 | 31.61 | 72.2 | 707.02 | 225 | *2203.3* | 4475.38 | 4545.86 | *4510.62* | 1.56 |
| 6000 | 1.8936 | 60.36 | 50.42 | 26.52 | 20.5 | 31.84 | 73.1 | 716.08 | 320 | *3133.6* | 4679.95 | 4754.91 | *4717.43* | 1.59 |
| 7000 | 2.2388 | 60.46 | 50.15 | 25.62 | 20.25 | 32.31 | 73.6 | 720.61 | 440 | *4308.6* | 4852.92 | 5015.37 | *4934.14* | 3.29 |
| 8000 | 2.5801 | 60.47 | 49.84 | 25 | 20.15 | 32.5 | 73.1 | 716.08 | 581 | *5684.5* | 5002.75 | 5220.85 | *5111.8* | 4.27 |
| 9000 | 2.8993 | 60.12 | 49.21 | 24.75 | 20.5 | 31.92 | 73.1 | 716.08 | 715 | *7001.6* | 5134.91 | 5140.78 | *5137.85* | 0.11 |
| 10000 | 3.2533 | 60.32 | 48.88 | 24.13 | 20.28 | 32.25 | 73.1 | 716.08 | 880 | *8617.3* | 5386.15 | 5226.03 | *5306.09* | 3.02 |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8836 | 59.5 | 53.67 | 33.11 | 20.05 | 29.86 | 184 | 1803.8 | 78.5 | *768.7* | 4878.54 | 4809.55 | *4844.05* | 1.42 |
| 4000 | 1.2049 | 60.03 | 53.48 | 30.95 | 20.18 | 31.14 | 182 | 1785.7 | 140 | *1370.9* | 5477.92 | 5410.1 | *5444.01* | 1.25 |
| 5000 | 1.5276 | 59.9 | 52.91 | 29.45 | 20.42 | 31.46 | 182 | 1785.7 | 219 | *2144.5* | 5848.6 | 5751.71 | *5800.15* | 1.67 |
| 6000 | 1.8733 | 59.93 | 52.58 | 28.01 | 19.95 | 32.27 | 182 | 1785.7 | 312 | *3055.2* | 6151.46 | 6297.19 | *6224.32* | 2.34 |
| 7000 | 2.1963 | 59.65 | 51.99 | 27.23 | 20.3 | 32.06 | 184 | 1803.8 | 425 | *4161.8* | 6407.53 | 6348.24 | *6377.88* | 0.93 |
| 8000 | 2.53 | 59.8 | 51.88 | 26.54 | 20.3 | 32.41 | 183 | 1794.7 | 570 | *5581.7* | 6629.35 | 6585.35 | *6607.35* | 0.67 |
| 9000 | 2.8519 | 60.25 | 52.09 | 26.22 | 20.45 | 32.82 | 182 | 1785.7 | 701 | *6864.5* | 6825.01 | 6864.1 | *6844.55* | 0.57 |
| 10000 | 3.2126 | 59.87 | 51.5 | 25.25 | 20.24 | 32.91 | 183 | 1794.7 | 863 | *8450.8* | 7000.03 | 6720.49 | *6860.26* | 4.07 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8793 | 70.22 | 59.86 | 33.42 | 20.18 | 38.22 | 71.3 | 697.95 | 75 | *734.43* | 4876.45 | 4852.04 | *4864.25* | 0.5 |
| 4000 | 1.2073 | 70.1 | 58.8 | 31.01 | 19.94 | 38.97 | 72.2 | 707.02 | 134 | *1312.2* | 5318.91 | 5572.12 | *5445.52* | 4.65 |
| 5000 | 1.5229 | 70.45 | 58.15 | 29.72 | 20.42 | 39.21 | 71.3 | 697.95 | 214 | *2095.6* | 5789.58 | 5905.5 | *5847.54* | 1.98 |
| 6000 | 1.8905 | 70.5 | 57.56 | 27.64 | 19.52 | 40.4 | 71.3 | 697.95 | 324 | *3172.7* | 6090.79 | 6403.16 | *6246.98* | 5 |
| 7000 | 2.197 | 70.48 | 57 | 27.33 | 20.17 | 39.91 | 72.2 | 707.02 | 418 | *4093.2* | 6345.47 | 6561.21 | *6453.34* | 3.34 |
| 8000 | 2.5146 | 70.5 | 56.55 | 26.95 | 20.42 | 39.72 | 73.1 | 716.08 | 550 | *5385.8* | 6566.08 | 6849.06 | *6707.57* | 4.22 |
| 9000 | 2.8571 | 70.5 | 56.14 | 26.25 | 20.26 | 39.92 | 73.1 | 716.08 | 695 | *6805.7* | 6760.67 | 7139.14 | *6949.9* | 5.45 |
| 10000 | 3.2038 | 70.06 | 55.15 | 25.59 | 20.13 | 39.56 | 73.6 | 720.61 | 865 | *8470.4* | 7018.14 | 7297.73 | *7157.93* | 3.91 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8618 | 70.1 | 63.25 | 35.73 | 19.72 | 38.77 | 182 | 1781.1 | 72 | *705.05* | 5732.08 | 5748.61 | *5740.35* | 0.29 |
| 4000 | 1.1679 | 70.25 | 61.94 | 34.11 | 19.84 | 39.04 | 181 | 1776.6 | 130 | *1273* | 6953.81 | 6945.66 | *6949.73* | 0.12 |
| 5000 | 1.4804 | 69.93 | 60.84 | 32.5 | 20.18 | 39.02 | 182 | 1785.7 | 201 | *1968.3* | 7606.51 | 7602.33 | *7604.42* | 0.06 |
| 6000 | 1.8181 | 70.11 | 59.97 | 30.88 | 19.72 | 39.74 | 182 | 1785.7 | 305 | *2986.7* | 8485.15 | 8459.61 | *8472.38* | 0.3 |
| 7000 | 2.1228 | 70.47 | 60.21 | 30.33 | 20.2 | 40.07 | 181 | 1776.6 | 408 | *3995.3* | 8585.57 | 8965.76 | *8775.66* | 4.33 |
| 8000 | 2.434 | 70.44 | 59.72 | 29.74 | 20.5 | 39.96 | 182 | 1785.7 | 535 | *5238.9* | 8970.5 | 9377.18 | *9173.84* | 4.43 |
| 9000 | 2.7664 | 70.25 | 59.05 | 28.93 | 20.4 | 39.97 | 182 | 1785.7 | 680 | *6658.8* | 9372.16 | 9840.32 | *9606.24* | 4.87 |
| 10000 | 3.1257 | 70.22 | 58.24 | 27.78 | 20.08 | 40.26 | 182 | 1785.7 | 845 | *8274.6* | 10026.1 | 10038.1 | *10032.1* | 0.12 |

**Table C-12:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e= 2.2 mm, p= 20 mm).

| Re | $Q_c$ $10^{-4}$ | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| Annul -us | ($m^3$/s) | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | $N/m^2$ | $mmH_2O$ | $N/m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8523 | 60.26 | 52.62 | 30.09 | 19.89 | 31.43 | 206.4 | 2021.3 | 28 | 274.19 | 3596.15 | 3624.78 | 3610.47 | 0.79 |
| 4000 | 1.1627 | 60.09 | 51.42 | 28.19 | 19.77 | 31.77 | 207.3 | 2030.4 | 47 | 460.24 | 4080.97 | 4083.18 | 4082.07 | 0.05 |
| 5000 | 1.4473 | 60.04 | 50.77 | 27.87 | 20.46 | 31.23 | 207.3 | 2030.4 | 71 | 695.26 | 4363.39 | 4472.6 | 4417.99 | 2.47 |
| 6000 | 1.7499 | 60.31 | 50.3 | 27.21 | 20.46 | 31.44 | 208.3 | 2039.5 | 97 | 949.86 | 4711.71 | 4926.5 | 4819.1 | 4.46 |
| 7000 | 2.0585 | 60 | 49.55 | 26.45 | 20.5 | 31.25 | 208.3 | 2039.5 | 134 | 1312.2 | 4918.82 | 5108.92 | 5013.87 | 3.79 |
| 8000 | 2.367 | 60.34 | 48.97 | 25.97 | 20.45 | 31.35 | 209.7 | 2053.1 | 167 | 1635.3 | 5351.86 | 5450.39 | 5401.13 | 1.82 |
| 9000 | 2.6904 | 60.17 | 48.34 | 25.28 | 20.26 | 31.37 | 210.1 | 2057.6 | 215 | 2105.4 | 5569.95 | 5640.07 | 5605.01 | 1.25 |
| 10000 | 3.002 | 60.17 | 47.83 | 24.81 | 20.36 | 31.25 | 210.1 | 2057.6 | 275 | 2692.9 | 5810.01 | 5573.56 | 5691.78 | 4.15 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8376 | 60.14 | 55.13 | 31.76 | 19.77 | 31.74 | 576.7 | 5647.1 | 27 | 264.39 | 4192.37 | 4186.74 | 4189.55 | 0.13 |
| 4000 | 1.1336 | 59.92 | 54.25 | 30.31 | 19.89 | 31.93 | 577.6 | 5656.1 | 45 | 440.66 | 4744.66 | 4924.94 | 4834.8 | 3.73 |
| 5000 | 1.4181 | 60.03 | 53.7 | 29.63 | 20.5 | 31.78 | 577.6 | 5656.1 | 67 | 656.09 | 5296.94 | 5398.34 | 5347.64 | 1.9 |
| 6000 | 1.7179 | 59.86 | 52.96 | 28.79 | 20.5 | 31.76 | 579.5 | 5674.3 | 95 | 930.28 | 5773.92 | 5938.66 | 5856.29 | 2.81 |
| 7000 | 2.0227 | 60.41 | 52.85 | 28 | 20.48 | 32.39 | 580.4 | 5683.3 | 131 | 1282.8 | 6326.21 | 6343.61 | 6334.91 | 0.27 |
| 8000 | 2.3286 | 60.2 | 52.19 | 27.34 | 20.5 | 32.27 | 580.4 | 5683.3 | 163 | 1596.2 | 6702.77 | 6643.16 | 6672.96 | 0.89 |
| 9000 | 2.6477 | 60.09 | 51.61 | 26.64 | 20.27 | 32.38 | 581.8 | 5696.9 | 210 | 2056.4 | 7098.85 | 7031.6 | 7065.22 | 0.95 |
| 10000 | 2.9559 | 60.09 | 51.29 | 26.23 | 20.27 | 32.42 | 583.2 | 5710.5 | 269 | 2634.2 | 7366.63 | 7344.79 | 7355.71 | 0.3 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8299 | 69.61 | 60.03 | 32.7 | 19.66 | 38.61 | 203.6 | 1994.2 | 26 | 254.6 | 4509.31 | 4511.13 | 4510.22 | 0.04 |
| 4000 | 1.1217 | 69.84 | 59.05 | 31.09 | 20.05 | 38.87 | 205.5 | 2012.3 | 43 | 421.07 | 5078.85 | 5162.68 | 5120.77 | 1.64 |
| 5000 | 1.4295 | 69.72 | 57.96 | 29.53 | 19.89 | 39.12 | 206.4 | 2021.3 | 65 | 636.5 | 5535.43 | 5746.24 | 5640.83 | 3.74 |
| 6000 | 1.7298 | 70.5 | 57.54 | 28.72 | 19.96 | 39.64 | 206.4 | 2021.3 | 93 | 910.69 | 6100.27 | 6319.42 | 6209.84 | 3.53 |
| 7000 | 2.0195 | 70.46 | 56.86 | 28.24 | 20.38 | 39.28 | 206.4 | 2021.3 | 130 | 1273 | 6401.52 | 6619.75 | 6510.64 | 3.35 |
| 8000 | 2.3509 | 70.06 | 55.56 | 26.99 | 20.02 | 39.18 | 206.4 | 2021.3 | 160 | 1566.8 | 6825.15 | 6834.92 | 6830.03 | 0.14 |
| 9000 | 2.6637 | 70.03 | 54.95 | 26.4 | 19.99 | 39.13 | 206.4 | 2021.3 | 205 | 2007.4 | 7098.94 | 7118.83 | 7108.89 | 0.28 |
| 10000 | 2.9787 | 70 | 54.36 | 25.88 | 19.96 | 39.06 | 206.4 | 2021.3 | 262 | 2565.6 | 7361.75 | 7356.49 | 7359.12 | 0.07 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8025 | 70.18 | 63.74 | 35.66 | 19.77 | 39.05 | 575.8 | 5638 | 24 | 235.02 | 5388.99 | 5313.2 | 5351.1 | 1.42 |
| 4000 | 1.0962 | 70.07 | 62.65 | 33.32 | 19.89 | 39.68 | 576.2 | 5642.5 | 43 | 421.07 | 6209.06 | 6136.21 | 6172.63 | 1.18 |
| 5000 | 1.3783 | 69.85 | 61.68 | 32.22 | 20.46 | 39.4 | 576.7 | 5647.1 | 64 | 626.71 | 6836.66 | 6756.3 | 6796.48 | 1.18 |
| 6000 | 1.6721 | 70.51 | 61.7 | 31.28 | 20.42 | 40.25 | 577.6 | 5656.1 | 92 | 900.9 | 7372.21 | 7569.82 | 7471.01 | 2.64 |
| 7000 | 1.9667 | 70.47 | 61.06 | 30.47 | 20.5 | 40.28 | 578.5 | 5665.2 | 126 | 1233.8 | 7874.29 | 8174.74 | 8024.51 | 3.74 |
| 8000 | 2.2697 | 70.29 | 60.3 | 29.65 | 20.45 | 40.24 | 578.5 | 5665.2 | 157 | 1537.4 | 8359.63 | 8706.53 | 8533.08 | 4.07 |
| 9000 | 2.5957 | 70.23 | 59.68 | 28.4 | 20.25 | 40.62 | 579.9 | 5678.8 | 202 | 1978.1 | 8826.85 | 8824.06 | 8825.45 | 0.03 |
| 10000 | 2.9035 | 70.23 | 59.26 | 27.81 | 20.25 | 40.69 | 580.4 | 5683.3 | 258 | 2526.4 | 9178.3 | 9156.93 | 9167.62 | 0.23 |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.9161 | 59.85 | 51.69 | 29.96 | 19.95 | 30.81 | 71.7 | 702.49 | 71 | 695.26 | 3840.91 | 3823.81 | 3832.36 | 0.45 |
| 4000 | 1.2357 | 59.96 | 50.98 | 28.42 | 20.47 | 31.02 | 72.2 | 707.02 | 119 | 1165.3 | 4226.89 | 4096.71 | 4161.8 | 3.13 |
| 5000 | 1.5625 | 59.78 | 50.36 | 27.38 | 20.5 | 31.11 | 72.2 | 707.02 | 179 | 1752.8 | 4433.99 | 4483.53 | 4458.76 | 1.11 |
| 6000 | 1.8938 | 60.29 | 50.15 | 26.51 | 20.5 | 31.67 | 74.1 | 725.15 | 251 | 2457.9 | 4772.9 | 4747.56 | 4760.23 | 0.53 |
| 7000 | 2.2427 | 59.7 | 49.41 | 25.54 | 20.18 | 31.63 | 71.3 | 697.95 | 332 | 3251.1 | 4843.5 | 5014.85 | 4929.18 | 3.48 |
| 8000 | 2.5717 | 60.3 | 49.51 | 25.25 | 20.18 | 32.11 | 73.1 | 716.08 | 393 | 3848.4 | 5078.85 | 5439.69 | 5259.27 | 6.86 |
| 9000 | 2.8925 | 59.87 | 49.05 | 24.94 | 20.51 | 31.63 | 71.3 | 697.95 | 485 | 4749.3 | 5092.97 | 5345.89 | 5219.43 | 4.85 |
| 10000 | 3.2397 | 59.96 | 48.71 | 24.44 | 20.33 | 31.82 | 72.2 | 707.02 | 593 | 5806.9 | 5297.39 | 5559.27 | 5428.33 | 4.82 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8814 | 60.23 | 54.7 | 32.96 | 20.42 | 30.64 | 181 | 1776.6 | 68 | 665.88 | 4627.5 | 4606.76 | 4617.13 | 0.45 |
| 4000 | 1.2137 | 60.12 | 53.71 | 30.53 | 19.95 | 31.63 | 181 | 1776.6 | 116 | 1135.9 | 5363.89 | 5353.92 | 5358.9 | 0.19 |
| 5000 | 1.5395 | 60 | 53.04 | 29 | 20.18 | 31.92 | 181 | 1776.6 | 179 | 1752.8 | 5824.13 | 5662.42 | 5743.28 | 2.82 |
| 6000 | 1.8592 | 60.2 | 52.73 | 28.2 | 20.42 | 32.15 | 182 | 1785.7 | 246 | 2408.9 | 6250.9 | 6032.35 | 6141.62 | 3.56 |
| 7000 | 2.1845 | 59.75 | 52.11 | 27.5 | 20.5 | 31.93 | 182 | 1785.7 | 321 | 3143.4 | 6393.15 | 6377.57 | 6385.36 | 0.24 |
| 8000 | 2.502 | 59.5 | 51.66 | 27.06 | 20.75 | 31.67 | 184 | 1803.8 | 380 | 3721.1 | 6560.51 | 6584.65 | 6572.58 | 0.37 |
| 9000 | 2.8492 | 59.97 | 51.69 | 26.38 | 20.37 | 32.44 | 183 | 1794.7 | 470 | 4602.4 | 6925.91 | 7142.94 | 7034.43 | 3.09 |
| 10000 | 3.1823 | 59.97 | 51.44 | 25.93 | 20.37 | 32.53 | 183 | 1794.7 | 572 | 5601.2 | 7135.11 | 7381.03 | 7258.07 | 3.39 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8793 | 70.02 | 59.57 | 33.65 | 19.95 | 37.97 | 69.4 | 679.82 | 68 | 665.88 | 4918.82 | 5020.61 | 4969.71 | 2.05 |
| 4000 | 1.2042 | 70.22 | 58.64 | 31.23 | 19.95 | 38.84 | 69.4 | 679.82 | 115 | 1126.1 | 5450.71 | 5663.09 | 5556.9 | 3.82 |
| 5000 | 1.5269 | 70.22 | 57.6 | 29.73 | 20.18 | 38.93 | 69.4 | 679.82 | 173 | 1694.1 | 5940.23 | 6080.16 | 6010.2 | 2.33 |
| 6000 | 1.866 | 70.12 | 56.88 | 28.23 | 20.07 | 39.3 | 70.3 | 688.89 | 241 | 2360 | 6232.07 | 6350.34 | 6291.21 | 1.88 |
| 7000 | 2.2003 | 70.22 | 56.36 | 27.3 | 20.07 | 39.51 | 70.3 | 688.89 | 315 | 3084.6 | 6523.9 | 6635.35 | 6579.63 | 1.69 |
| 8000 | 2.5382 | 70.32 | 55.94 | 26.49 | 20.07 | 39.72 | 70.3 | 688.89 | 378 | 3701.5 | 6768.67 | 6797.48 | 6783.07 | 0.42 |
| 9000 | 2.8473 | 69.82 | 55.23 | 26.33 | 20.48 | 38.96 | 69.4 | 679.82 | 468 | 4582.8 | 6867.51 | 6947.92 | 6907.72 | 1.16 |
| 10000 | 3.209 | 70.13 | 54.88 | 25.47 | 20.11 | 39.51 | 70.8 | 693.42 | 560 | 5483.7 | 7180.19 | 7175.87 | 7178.03 | 0.06 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8563 | 69.52 | 62.35 | 36.2 | 19.84 | 37.73 | 181 | 1767.5 | 67 | 656.09 | 5999.63 | 5836.49 | 5918.06 | 2.76 |
| 4000 | 1.16 | 70 | 61.63 | 34.5 | 20.07 | 38.45 | 181 | 1767.5 | 112 | 1096.7 | 7002.99 | 6975.56 | 6989.28 | 0.39 |
| 5000 | 1.4791 | 70.17 | 60.87 | 32.53 | 20.23 | 39.12 | 181 | 1767.5 | 170 | 1664.7 | 7781.26 | 7583.21 | 7682.23 | 2.58 |
| 6000 | 1.7969 | 70.25 | 60.19 | 31.4 | 20.25 | 39.39 | 181 | 1776.6 | 234 | 2291.4 | 8417.15 | 8352.35 | 8384.75 | 0.77 |
| 7000 | 2.1261 | 70.24 | 59.54 | 30.21 | 20.18 | 39.69 | 181 | 1776.6 | 307 | 3006.3 | 8954.78 | 8891.37 | 8923.08 | 0.71 |
| 8000 | 2.4444 | 70.34 | 59.08 | 29.45 | 20.41 | 39.77 | 182 | 1781.1 | 370 | 3623.2 | 9420.51 | 9213.98 | 9317.24 | 2.22 |
| 9000 | 2.7803 | 70.46 | 58.71 | 28.51 | 20.38 | 40.11 | 182 | 1785.7 | 457 | 4475.1 | 9831.3 | 9426.3 | 9628.8 | 4.21 |
| 10000 | 3.1129 | 70.25 | 58.06 | 27.97 | 20.25 | 40 | 182 | 1785.7 | 545 | 5336.8 | 10198.8 | 10022.4 | 10110.6 | 1.74 |

**Table C-13:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e= 2.2 mm, p= 30 mm).

| Re | $Q_c$ $10^{-4}$ | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Annul -us | ($m^3$/s) | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | Inner tube mm$H_2O$ | Inner tube N/$m^2$ | Annulus mm$H_2O$ | Annulus N/$m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | | | | | | | |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8503 | 60.37 | 52.83 | 29.97 | 20.22 | 31.49 | 205.5 | 2012.3 | 23 | *225.22* | 3549.08 | 3456.6 | *3502.84* | 2.64 |
| 4000 | 1.1536 | 60.5 | 52.18 | 28.31 | 20.34 | 32.01 | 205.5 | 2012.3 | 36 | *352.53* | 3916.22 | 3834.33 | *3875.28* | 2.11 |
| 5000 | 1.4606 | 60.41 | 51.44 | 27.23 | 20.3 | 32.15 | 207.3 | 2030.4 | 50 | *489.62* | 4222.18 | 4221.73 | *4221.96* | 0.01 |
| 6000 | 1.7622 | 60.43 | 50.97 | 26.56 | 20.5 | 32.14 | 207.3 | 2030.4 | 68 | *665.88* | 4452.82 | 4454.32 | *4453.57* | 0.03 |
| 7000 | 2.075 | 60.37 | 50.05 | 25.83 | 20.43 | 32.02 | 208.3 | 2039.5 | 97 | *949.86* | 4857.62 | 4674.16 | *4765.89* | 3.85 |
| 8000 | 2.3769 | 60.33 | 49.77 | 25.56 | 20.5 | 31.94 | 208.3 | 2039.5 | 115 | *1126.1* | 4970.59 | 5017.29 | *4993.94* | 0.94 |
| 9000 | 2.7311 | 60.44 | 49.25 | 24.43 | 19.82 | 32.61 | 209.2 | 2048.5 | 145 | *1419.9* | 5267.13 | 5253.46 | *5260.29* | 0.26 |
| 10000 | 3.0125 | 60.41 | 49.06 | 24.57 | 20.3 | 32.17 | 210.1 | 2057.6 | 175 | *1713.7* | 5341.1 | 5365.21 | *5353.15* | 0.45 |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8314 | 60.04 | 55.01 | 32.12 | 20.08 | 31.29 | 576.7 | 5647.1 | 22 | *215.43* | 4209.1 | 4172.66 | *4190.88* | 0.87 |
| 4000 | 1.1263 | 59.77 | 53.97 | 30.46 | 20.31 | 31.43 | 577.6 | 5656.1 | 34 | *332.94* | 4853.44 | 4766.39 | *4809.92* | 1.81 |
| 5000 | 1.4358 | 60.38 | 53.99 | 28.97 | 20.06 | 32.65 | 578.3 | 5663.4 | 50 | *489.62* | 5347.15 | 5334.87 | *5341.01* | 0.23 |
| 6000 | 1.7473 | 60.38 | 53.5 | 27.8 | 20 | 33.04 | 578.5 | 5665.2 | 68 | *665.88* | 5757.18 | 5684.28 | *5720.73* | 1.27 |
| 7000 | 2.0308 | 60.43 | 53.24 | 27.63 | 20.5 | 32.77 | 578.5 | 5665.2 | 90 | *881.31* | 6016.59 | 6038.94 | *6027.77* | 0.37 |
| 8000 | 2.3564 | 60.25 | 52.72 | 26.61 | 20.2 | 33.08 | 579.9 | 5678.8 | 110 | *1077.2* | 6301.1 | 6300.43 | *6300.77* | 0.01 |
| 9000 | 2.67 | 60.5 | 52.57 | 25.96 | 20.23 | 33.43 | 580.4 | 5683.3 | 139 | *1361.1* | 6635.82 | 6382.11 | *6508.97* | 3.9 |
| 10000 | 2.9785 | 60.25 | 52.15 | 25.65 | 20.2 | 33.26 | 580.4 | 5683.3 | 165 | *1615.7* | 6778.08 | 6775.43 | *6776.75* | 0.04 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8258 | 70.49 | 61.21 | 32.9 | 19.91 | 39.42 | 203.6 | 1994.2 | 20 | *195.85* | 4368.1 | 4471.27 | *4419.69* | 2.33 |
| 4000 | 1.1119 | 69.94 | 59.62 | 31.43 | 20.5 | 38.81 | 203.6 | 1994.2 | 31 | *303.56* | 4857.62 | 5065.95 | *4961.79* | 4.2 |
| 5000 | 1.4179 | 70.45 | 58.85 | 29.75 | 20.39 | 39.57 | 206 | 2016.8 | 46 | *450.45* | 5460.12 | 5533.7 | *5496.91* | 1.34 |
| 6000 | 1.728 | 70.5 | 58.26 | 28.59 | 20.18 | 39.96 | 206.9 | 2025.9 | 64 | *626.71* | 5761.37 | 6060.66 | *5911.01* | 5.06 |
| 7000 | 2.0453 | 70.33 | 57.2 | 27.51 | 20 | 39.94 | 207.8 | 2034.9 | 89 | *871.52* | 6180.29 | 6406.58 | *6293.44* | 3.6 |
| 8000 | 2.3418 | 70.41 | 56.7 | 27.03 | 20.32 | 39.78 | 208.3 | 2039.5 | 106 | *1038* | 6453.3 | 6554.01 | *6503.65* | 1.55 |
| 9000 | 2.657 | 70.37 | 55.98 | 26.37 | 20.24 | 39.73 | 208.3 | 2039.5 | 130 | *1273* | 6773.37 | 6794.2 | *6783.78* | 0.31 |
| 10000 | 2.9711 | 70.33 | 55.43 | 25.86 | 20.2 | 39.67 | 208.7 | 2044 | 158 | *1547.2* | 7013.43 | 7015.28 | *7014.35* | 0.03 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8049 | 70.04 | 64.02 | 35.26 | 19.89 | 39.27 | 572.7 | 5608.1 | 18 | *176.26* | 5037.54 | 5155.15 | *5096.34* | 2.31 |
| 4000 | 1.0857 | 70.39 | 63.39 | 33.59 | 20.5 | 39.77 | 573.4 | 5615.3 | 29 | *283.98* | 5857.6 | 5922.72 | *5890.16* | 1.11 |
| 5000 | 1.3824 | 69.46 | 61.79 | 31.91 | 20.5 | 39.39 | 574.8 | 5628.9 | 43 | *421.07* | 6418.26 | 6575.05 | *6496.65* | 2.41 |
| 6000 | 1.6722 | 70.23 | 61.61 | 31.19 | 20.5 | 40.07 | 574.8 | 5628.9 | 60 | *587.54* | 7213.22 | 7452.16 | *7332.69* | 3.26 |
| 7000 | 1.9698 | 70.34 | 61.12 | 30.33 | 20.5 | 40.31 | 575.8 | 5638 | 82 | *802.98* | 7715.3 | 8072.73 | *7894.01* | 4.53 |
| 8000 | 2.2717 | 70.4 | 60.59 | 29.56 | 20.46 | 40.48 | 575.8 | 5638 | 99 | *969.45* | 8209.01 | 8619.74 | *8414.38* | 4.88 |
| 9000 | 2.5891 | 70.14 | 59.74 | 28.48 | 20.39 | 40.49 | 576.7 | 5647.1 | 122 | *1194.7* | 8705.51 | 8733.07 | *8719.29* | 0.32 |
| 10000 | 2.8958 | 70.14 | 59.1 | 27.9 | 20.39 | 40.45 | 577.6 | 5656.1 | 150 | *1468.9* | 9241.06 | 9067.9 | *9154.48* | 1.89 |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | | | | | | | |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.908 | 60.2 | 51.92 | 30.65 | 20.05 | 30.7 | 71.3 | 697.95 | 52 | *509.2* | 3897.4 | 4013 | *3955.2* | 2.92 |
| 4000 | 1.2234 | 60.19 | 51.05 | 29.27 | 20.5 | 30.73 | 72.2 | 707.02 | 90 | *881.31* | 4302.2 | 4473.98 | *4388.09* | 3.91 |
| 5000 | 1.5541 | 59.6 | 49.97 | 27.85 | 20.5 | 30.6 | 73.1 | 716.08 | 138 | *1351.3* | 4532.84 | 4763.9 | *4648.37* | 4.97 |
| 6000 | 1.8829 | 60.44 | 49.93 | 27.13 | 20.38 | 31.39 | 72.2 | 707.02 | 198 | *1938.9* | 4947.06 | 5301.24 | *5124.15* | 6.91 |
| 7000 | 2.2153 | 60.24 | 49.22 | 26.32 | 20.46 | 31.27 | 73.1 | 716.08 | 262 | *2565.6* | 5187.11 | 5415.07 | *5301.09* | 4.3 |
| 8000 | 2.5577 | 60.46 | 48.81 | 25.65 | 20.25 | 31.58 | 73.1 | 716.08 | 335 | *3280.4* | 5483.66 | 5761.84 | *5622.75* | 4.95 |
| 9000 | 2.8943 | 60.19 | 48.15 | 25.04 | 20.36 | 31.33 | 73.1 | 716.08 | 419 | *4103* | 5666.44 | 5655.15 | *5660.8* | 0.2 |
| 10000 | 3.2298 | 60.19 | 47.79 | 24.67 | 20.36 | 31.3 | 73.1 | 716.08 | 510 | *4994.1* | 5835.9 | 5812.39 | *5824.14* | 0.4 |
| Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8814 | 60.43 | 54.86 | 33.31 | 20.07 | 30.8 | 181 | 1776.6 | 50 | *489.62* | 4660.98 | 4863.92 | *4762.45* | 4.26 |
| 4000 | 1.1904 | 60.03 | 53.62 | 31.72 | 20.5 | 30.65 | 182 | 1785.7 | 85 | *832.35* | 5363.89 | 5567.43 | *5465.66* | 3.72 |
| 5000 | 1.5243 | 60.46 | 53.23 | 30.03 | 20.03 | 31.79 | 181 | 1776.6 | 136 | *1331.8* | 6050.06 | 6355.79 | *6202.93* | 4.93 |
| 6000 | 1.8426 | 60.27 | 52.32 | 29.04 | 20.37 | 31.59 | 181 | 1776.6 | 195 | *1909.5* | 6652.56 | 6661.79 | *6657.17* | 0.14 |
| 7000 | 2.1622 | 60.25 | 52.06 | 28.4 | 20.5 | 31.7 | 182 | 1785.7 | 260 | *2546* | 6853.39 | 7123.33 | *6988.36* | 3.86 |
| 8000 | 2.4903 | 60.24 | 51.64 | 27.72 | 20.5 | 31.83 | 182 | 1785.7 | 330 | *3231.5* | 7196.48 | 7498.66 | *7347.57* | 4.11 |
| 9000 | 2.8163 | 60.12 | 51.31 | 27.26 | 20.5 | 31.82 | 181 | 1767.5 | 400 | *3917* | 7372.21 | 7940.61 | *7656.41* | 7.42 |
| 10000 | 3.1635 | 60.26 | 50.65 | 26.46 | 20.35 | 32.02 | 182 | 1785.7 | 502 | *4915.8* | 8039.26 | 8058.98 | *8049.12* | 0.25 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8705 | 70.39 | 60.01 | 34.34 | 20.18 | 37.91 | 71.3 | 697.95 | 48 | *470.03* | 4885.87 | 5136.62 | *5011.24* | 5 |
| 4000 | 1.193 | 70.49 | 58.65 | 31.84 | 20.18 | 38.56 | 71.3 | 697.95 | 83 | *812.77* | 5573.09 | 5798.76 | *5685.92* | 3.97 |
| 5000 | 1.5253 | 70.26 | 57.5 | 30 | 20 | 38.86 | 72.2 | 707.02 | 133 | *1302.4* | 6006.13 | 6360.13 | *6183.13* | 5.73 |
| 6000 | 1.8516 | 70.15 | 56.57 | 28.75 | 20.23 | 38.82 | 73.1 | 716.08 | 192 | *1880.1* | 6392.11 | 6578.86 | *6485.48* | 2.88 |
| 7000 | 2.1773 | 70.29 | 56.12 | 27.94 | 20.35 | 38.97 | 72.2 | 707.02 | 255 | *2497.1* | 6669.82 | 6892.01 | *6780.91* | 3.28 |
| 8000 | 2.5043 | 70.3 | 55.6 | 27.31 | 20.42 | 38.95 | 73.1 | 716.08 | 331 | *3241.3* | 6919.29 | 7196.56 | *7057.92* | 3.93 |
| 9000 | 2.8325 | 70.45 | 55.3 | 26.79 | 20.47 | 39.08 | 74.1 | 725.15 | 420 | *4112.8* | 7131.11 | 7466.93 | *7299.02* | 4.6 |
| 10000 | 3.186 | 70.33 | 54.38 | 25.94 | 20.26 | 39.03 | 74.1 | 725.15 | 498 | *4876.6* | 7509.01 | 7547.14 | *7528.08* | 0.51 |
| Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s | | | | | | | | | | | | | | |
| 3000 | 0.8416 | 70.39 | 63.37 | 37.58 | 20.07 | 37.81 | 181 | 1767.5 | 45 | *440.66* | 5874.34 | 6138.48 | *6006.41* | 4.4 |
| 4000 | 1.1437 | 70.31 | 62.06 | 35.38 | 20.5 | 38.15 | 181 | 1767.5 | 77 | *754.01* | 6903.6 | 7090.37 | *6996.99* | 2.67 |
| 5000 | 1.4593 | 70.22 | 61.13 | 33.49 | 20.5 | 38.65 | 181 | 1767.5 | 125 | *1224* | 7606.51 | 7899.8 | *7753.16* | 3.78 |
| 6000 | 1.7955 | 69.57 | 59.79 | 31.44 | 20.28 | 38.82 | 181 | 1767.5 | 180 | *1762.6* | 8183.9 | 8353.26 | *8268.58* | 2.05 |
| 7000 | 2.1266 | 70.39 | 59.69 | 30.19 | 20.18 | 39.85 | 181 | 1776.6 | 253 | *2477.5* | 8953.76 | 8875.66 | *8914.71* | 0.88 |
| 8000 | 2.4624 | 70.49 | 59.27 | 29.26 | 19.95 | 40.27 | 181 | 1776.6 | 323 | *3162.9* | 9388.9 | 9559.92 | *9474.41* | 1.81 |
| 9000 | 2.754 | 70 | 58.54 | 29.24 | 20.49 | 39.39 | 182 | 1785.7 | 395 | *3868* | 9589.73 | 10048.1 | *9818.91* | 4.67 |
| 10000 | 3.1061 | 70.2 | 58.03 | 28.13 | 20.28 | 39.87 | 182 | 1781.1 | 490 | *4798.3* | 10180.3 | 10166.9 | *10173.6* | 0.13 |

**Table C-14:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e= 2.2 mm, p= 40 mm).

| Re Annul -us | $Q_c$ $10^{-4}$ ($m^3/s$) | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| | | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | $N/m^2$ | $mmH_2O$ | $N/m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.848 | 59.95 | 53.05 | 30 | 20.43 | 31.27 | 202.7 | 1985.1 | 18 | *176.26* | 3247.83 | 3383.54 | *3315.69* | 4.09 |
| 4000 | 1.1482 | 60.22 | 52.26 | 28.56 | 20.5 | 31.71 | 203.6 | 1994.2 | 30 | *293.77* | 3746.77 | 3859.42 | *3803.1* | 2.96 |
| 5000 | 1.468 | 60.48 | 51.68 | 27.1 | 19.99 | 32.53 | 203.6 | 1994.2 | 46 | *450.45* | 4142.16 | 4353.57 | *4247.87* | 4.98 |
| 6000 | 1.7652 | 60.39 | 50.9 | 26.45 | 20.46 | 32.16 | 204.6 | 2003.2 | 65 | *636.5* | 4466.94 | 4410.57 | *4438.75* | 1.27 |
| 7000 | 2.0723 | 60.5 | 50.5 | 26.03 | 20.34 | 32.27 | 205.5 | 2012.3 | 85 | *832.35* | 4707 | 4918.84 | *4812.92* | 4.4 |
| 8000 | 2.3852 | 60.49 | 50.05 | 25.37 | 20.39 | 32.31 | 205.5 | 2012.3 | 108 | *1057.6* | 4914.11 | 4955.37 | *4934.74* | 0.84 |
| 9000 | 2.6905 | 60.25 | 49.35 | 25.09 | 20.44 | 31.93 | 207.3 | 2030.4 | 131 | *1282.8* | 5130.63 | 5219.47 | *5175.05* | 1.72 |
| 10000 | 3.0073 | 60.35 | 49.19 | 24.71 | 20.31 | 32.14 | 207.3 | 2030.4 | 160 | *1566.8* | 5253.01 | 5520.7 | *5386.86* | 4.97 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8393 | 60.49 | 55.79 | 31.3 | 20.05 | 32.35 | 573.9 | 5619.9 | 16.5 | *161.57* | 3932.96 | 3936.32 | *3934.64* | 0.09 |
| 4000 | 1.1411 | 59.9 | 54.75 | 29.49 | 20.12 | 32.47 | 573.9 | 5619.9 | 28 | *274.19* | 4309.52 | 4458.54 | *4384.03* | 3.4 |
| 5000 | 1.4321 | 60.42 | 54.57 | 28.86 | 20.4 | 32.85 | 574.8 | 5628.9 | 42 | *411.28* | 4895.28 | 5052.1 | *4973.69* | 3.15 |
| 6000 | 1.7365 | 60.4 | 53.96 | 27.84 | 20.5 | 33.01 | 576.7 | 5647.1 | 60 | *587.54* | 5388.99 | 5315.8 | *5352.4* | 1.37 |
| 7000 | 2.0453 | 60.35 | 53.4 | 27.17 | 20.34 | 33.12 | 576.7 | 5647.1 | 76 | *744.22* | 5815.76 | 5826.49 | *5821.12* | 0.18 |
| 8000 | 2.3428 | 60.5 | 52.98 | 26.81 | 20.5 | 33.08 | 576.7 | 5647.1 | 103 | *1008.6* | 6292.74 | 6166.17 | *6229.45* | 2.03 |
| 9000 | 2.6475 | 60.38 | 52.59 | 26.44 | 20.48 | 33.02 | 577.6 | 5656.1 | 126 | *1233.8* | 6518.67 | 6581.95 | *6550.31* | 0.97 |
| 10000 | 2.9646 | 60.44 | 52.06 | 25.94 | 20.31 | 33.11 | 577.6 | 5656.1 | 150 | *1468.9* | 7012.38 | 6962.59 | *6987.49* | 0.71 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8331 | 69.92 | 61.26 | 32.03 | 19.99 | 39.56 | 201.8 | 1976 | 15.5 | *151.78* | 4076.26 | 4181.09 | *4128.68* | 2.54 |
| 4000 | 1.1333 | 70.35 | 60.4 | 30.11 | 20.11 | 40.26 | 202.3 | 1980.6 | 26.5 | *259.5* | 4683.47 | 4725.36 | *4704.41* | 0.89 |
| 5000 | 1.4347 | 70.29 | 59.4 | 28.85 | 20.25 | 40.28 | 202.7 | 1985.1 | 39.5 | *386.8* | 5125.92 | 5145.13 | *5135.53* | 0.37 |
| 6000 | 1.7344 | 70.35 | 59.01 | 28 | 20.45 | 40.43 | 203.6 | 1994.2 | 56.5 | *553.27* | 5337.74 | 5460.96 | *5399.35* | 2.28 |
| 7000 | 2.035 | 70.2 | 58.27 | 27.45 | 20.5 | 40.21 | 203.6 | 1994.2 | 73 | *714.84* | 5615.45 | 5898.74 | *5757.09* | 4.92 |
| 8000 | 2.3453 | 70.34 | 57.23 | 26.72 | 20.5 | 40.08 | 205.5 | 2012.3 | 92 | *900.9* | 6170.88 | 6084.58 | *6127.73* | 1.41 |
| 9000 | 2.6959 | 70.39 | 57 | 25.55 | 19.81 | 40.9 | 206.4 | 2021.3 | 117 | *1145.7* | 6302.67 | 6455.87 | *6379.27* | 2.4 |
| 10000 | 2.9715 | 70.5 | 56.68 | 25.68 | 20.37 | 40.42 | 206.4 | 2021.3 | 141 | *1380.7* | 6505.07 | 6582.24 | *6543.66* | 1.18 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8162 | 69.6 | 64.04 | 34 | 19.87 | 39.73 | 567.4 | 5556.4 | 15 | *146.89* | 4652.61 | 4806.66 | *4729.63* | 3.26 |
| 4000 | 1.1105 | 69.77 | 63.45 | 31.99 | 20.05 | 40.53 | 567.4 | 5556.4 | 25 | *244.81* | 5288.58 | 5527.25 | *5407.91* | 4.41 |
| 5000 | 1.3979 | 70.33 | 63.22 | 30.94 | 20.47 | 41.05 | 567.4 | 5556.4 | 37 | *362.32* | 5949.65 | 6101.54 | *6025.59* | 2.52 |
| 6000 | 1.6971 | 70.48 | 62.76 | 29.87 | 20.5 | 41.43 | 569.3 | 5574.6 | 53 | *519* | 6460.1 | 6630.18 | *6545.14* | 2.6 |
| 7000 | 1.9997 | 70.32 | 61.82 | 29.19 | 20.3 | 41.32 | 569.3 | 5574.6 | 72 | *705.05* | 7112.8 | 7412.91 | *7262.86* | 4.13 |
| 8000 | 2.3043 | 70.49 | 61.36 | 28.5 | 20.26 | 41.54 | 569.7 | 5579.1 | 90 | *881.31* | 7639.98 | 7918.44 | *7779.21* | 3.58 |
| 9000 | 2.6212 | 70.17 | 60.64 | 27.55 | 20.24 | 41.5 | 571.1 | 5592.7 | 115 | *1126.1* | 7970.52 | 7989.73 | *7980.13* | 0.24 |
| 10000 | 2.9275 | 70.17 | 60.15 | 27.1 | 20.24 | 41.47 | 571.1 | 5592.7 | 137 | *1341.6* | 8380.55 | 8374.43 | *8377.49* | 0.07 |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.9221 | 60.05 | 51.56 | 29.61 | 19.72 | 31.13 | 69.4 | 679.82 | 43 | *421.07* | 3996.24 | 3803.08 | *3899.66* | 4.95 |
| 4000 | 1.2343 | 60.06 | 50.85 | 28.57 | 20.42 | 30.96 | 69.4 | 679.82 | 74 | *724.64* | 4335.15 | 4194.95 | *4265.05* | 3.29 |
| 5000 | 1.5625 | 59.58 | 49.85 | 27.38 | 20.5 | 30.75 | 69.4 | 679.82 | 110 | *1077.2* | 4579.91 | 4483.53 | *4531.72* | 2.13 |
| 6000 | 1.8962 | 59.8 | 49.62 | 26.43 | 20.47 | 31.21 | 70.3 | 688.89 | 156 | *1527.6* | 4791.73 | 4714.1 | *4752.91* | 1.63 |
| 7000 | 2.2256 | 59.99 | 49.2 | 25.88 | 20.5 | 31.33 | 70.3 | 688.89 | 202 | *1978.1* | 5078.85 | 4994.78 | *5036.82* | 1.67 |
| 8000 | 2.5538 | 60.47 | 49.08 | 25.53 | 20.5 | 31.65 | 71.3 | 697.95 | 260 | *2546* | 5361.27 | 5358.87 | *5360.07* | 0.04 |
| 9000 | 2.8986 | 60.04 | 48.19 | 24.77 | 20.5 | 31.33 | 71.3 | 697.95 | 320 | *3133.6* | 5577.8 | 5163.75 | *5370.77* | 7.71 |
| 10000 | 3.2297 | 60 | 48.09 | 24.53 | 20.5 | 31.36 | 71.7 | 702.49 | 395 | *3868* | 5605.36 | 5430.37 | *5517.87* | 3.17 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8951 | 59.93 | 54.41 | 32.15 | 19.84 | 31.05 | 181 | 1767.5 | 41 | *401.49* | 4619.14 | 4593.06 | *4606.1* | 0.57 |
| 4000 | 1.2136 | 59.93 | 53.85 | 30.42 | 20.07 | 31.6 | 181 | 1767.5 | 70 | *685.47* | 5087.74 | 5236.93 | *5162.34* | 2.89 |
| 5000 | 1.5401 | 59.8 | 52.94 | 29 | 20.15 | 31.78 | 181 | 1776.6 | 105 | *1028.2* | 5740.45 | 5683.64 | *5712.04* | 0.99 |
| 6000 | 1.8748 | 59.5 | 52.21 | 27.91 | 19.98 | 31.91 | 182 | 1785.7 | 154 | *1508* | 6100.27 | 6200.63 | *6150.45* | 1.63 |
| 7000 | 2.2031 | 59.81 | 51.88 | 27.19 | 20.07 | 32.21 | 182 | 1785.7 | 205 | *2007.4* | 6635.82 | 6542.75 | *6589.29* | 1.41 |
| 8000 | 2.5417 | 59.95 | 51.56 | 26.49 | 19.95 | 32.53 | 182 | 1785.7 | 254 | *2487.3* | 7020.75 | 6934.25 | *6977.5* | 1.24 |
| 9000 | 2.8293 | 59.4 | 51.05 | 26.76 | 20.6 | 31.53 | 183 | 1794.7 | 316 | *3094.4* | 6987.28 | 7269.45 | *7128.36* | 3.96 |
| 10000 | 3.1925 | 59.97 | 50.93 | 25.93 | 20.09 | 32.41 | 183 | 1794.7 | 389 | *3809.2* | 7564.67 | 7772.1 | *7668.39* | 2.71 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8838 | 70.1 | 59.64 | 33.19 | 19.95 | 38.28 | 69 | 675.29 | 40 | *391.7* | 4923.52 | 4876.93 | *4900.22* | 0.95 |
| 4000 | 1.1963 | 69.91 | 58.48 | 31.29 | 20.48 | 38.31 | 68.5 | 670.76 | 69 | *675.67* | 5380.1 | 5391.16 | *5385.63* | 0.21 |
| 5000 | 1.5222 | 69.55 | 57.37 | 29.68 | 20.5 | 38.35 | 69 | 675.29 | 105 | *1028.2* | 5733.13 | 5826.65 | *5779.89* | 1.62 |
| 6000 | 1.8483 | 69.55 | 56.58 | 28.64 | 20.5 | 38.44 | 69.4 | 679.82 | 150 | *1468.9* | 6104.98 | 6273.91 | *6189.45* | 2.73 |
| 7000 | 2.179 | 69.49 | 55.94 | 27.72 | 20.5 | 38.52 | 69.4 | 679.82 | 200 | *1958.5* | 6377.99 | 6561.33 | *6469.66* | 2.83 |
| 8000 | 2.51 | 69.6 | 55.49 | 27.03 | 20.5 | 38.66 | 69.9 | 684.36 | 255 | *2497.1* | 6641.58 | 6836.36 | *6738.97* | 2.89 |
| 9000 | 2.8527 | 69.7 | 54.96 | 26.24 | 20.41 | 38.84 | 71.3 | 697.95 | 310 | *3035.6* | 6938.12 | 6943.45 | *6940.78* | 0.08 |
| 10000 | 3.1877 | 69.7 | 54.46 | 25.75 | 20.41 | 38.79 | 71.3 | 697.95 | 385 | *3770.1* | 7173.47 | 7107.67 | *7140.57* | 0.92 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8565 | 69.5 | 62.66 | 35.9 | 20.12 | 37.89 | 180 | 1758.5 | 38 | *372.11* | 5723.71 | 5630.8 | *5677.26* | 1.64 |
| 4000 | 1.1613 | 69.47 | 61.58 | 33.97 | 20.5 | 38.22 | 179 | 1749.4 | 62 | *607.13* | 6602.35 | 6518.68 | *6560.52* | 1.28 |
| 5000 | 1.483 | 70.08 | 61.25 | 32.24 | 20.28 | 39.38 | 179 | 1749.4 | 98 | *959.65* | 7388.94 | 7393.4 | *7391.17* | 0.06 |
| 6000 | 1.8055 | 70.08 | 60.49 | 30.94 | 20.28 | 39.67 | 180 | 1758.5 | 145 | *1419.9* | 8024.91 | 8024.1 | *8024.51* | 0.01 |
| 7000 | 2.1218 | 70.5 | 60.53 | 30.11 | 20.46 | 40.23 | 180 | 1758.5 | 188 | *1841* | 8342.9 | 8537.05 | *8439.97* | 2.3 |
| 8000 | 2.4521 | 70.46 | 59.8 | 29.27 | 20.31 | 40.33 | 181 | 1767.5 | 241 | *2360* | 8920.29 | 9161.67 | *9040.98* | 2.67 |
| 9000 | 2.7997 | 70.44 | 59.35 | 28.33 | 19.95 | 40.74 | 181 | 1767.5 | 301 | *2947.5* | 9280.11 | 9784.59 | *9532.35* | 5.29 |
| 10000 | 3.1178 | 70.08 | 58.35 | 27.81 | 20.27 | 40.14 | 181 | 1767.5 | 379 | *3711.3* | 9812.08 | 9802.57 | *9807.32* | 0.1 |

**Table C-15:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Circular Rib, e= 2.2 mm, p= 10 mm).

| Re | $Q_c$ $10^{-4}$ | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| Annul -us | ($m^3$/s) | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | N/$m^2$ | $mmH_2O$ | N/$m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8659 | 59.8 | 52.9 | 28.81 | 19.77 | 32.05 | 200.9 | 1967 | 53.8 | *527.3* | 3249.13 | 3264.46 | *3256.79* | 0.47 |
| 4000 | 1.1618 | 60.07 | 52.13 | 27.92 | 20.11 | 32.09 | 201.8 | 1976 | 90 | *881.31* | 3736.86 | 3784.3 | *3760.58* | 1.26 |
| 5000 | 1.4639 | 60.3 | 51.56 | 27.02 | 20.31 | 32.25 | 201.8 | 1976 | 134 | *1312.2* | 4115.17 | 4097.21 | *4106.19* | 0.44 |
| 6000 | 1.7713 | 60.37 | 50.97 | 26.35 | 20.26 | 32.34 | 202.7 | 1985.1 | 188 | *1841* | 4424.27 | 4499.91 | *4462.09* | 1.7 |
| 7000 | 2.089 | 60.28 | 50.33 | 25.55 | 20.13 | 32.41 | 203.2 | 1989.6 | 251 | *2457.9* | 4685.62 | 4723.48 | *4704.55* | 0.8 |
| 8000 | 2.3907 | 60.32 | 49.88 | 25.24 | 20.32 | 32.24 | 203.6 | 1994.2 | 317 | *3104.2* | 4912 | 4907.19 | *4909.6* | 0.1 |
| 9000 | 2.6996 | 60.24 | 49.38 | 24.91 | 20.33 | 32.09 | 204.6 | 2003.2 | 391 | *3828.8* | 5111.69 | 5158.49 | *5135.09* | 0.91 |
| 10000 | 3.0126 | 60.47 | 49.23 | 24.58 | 20.29 | 32.29 | 206 | 2016.8 | 475 | *4651.4* | 5290.32 | 5392.23 | *5341.27* | 1.91 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8414 | 60 | 55.58 | 31.06 | 20.06 | 32.12 | 570.8 | 5590 | 51 | *499.41* | 3700.16 | 3858.85 | *3779.51* | 4.2 |
| 4000 | 1.1397 | 59.95 | 54.62 | 29.6 | 20.12 | 32.38 | 571.6 | 5597.2 | 86 | *842.14* | 4462.58 | 4505.22 | *4483.9* | 0.95 |
| 5000 | 1.4285 | 60.43 | 54.39 | 29.02 | 20.46 | 32.65 | 573 | 5610.8 | 128 | *1253.4* | 5053.95 | 5098.97 | *5076.46* | 0.89 |
| 6000 | 1.731 | 60.26 | 53.64 | 28.23 | 20.39 | 32.64 | 573.9 | 5619.9 | 179 | *1752.8* | 5537.14 | 5659.64 | *5598.39* | 2.19 |
| 7000 | 2.0324 | 60.32 | 53.21 | 27.69 | 20.37 | 32.74 | 573.9 | 5619.9 | 237 | *2320.8* | 5945.67 | 6204.88 | *6075.27* | 4.27 |
| 8000 | 2.334 | 60.36 | 52.83 | 27.21 | 20.43 | 32.77 | 573.9 | 5619.9 | 302 | *2957.3* | 6299.55 | 6600.15 | *6449.85* | 4.66 |
| 9000 | 2.6454 | 60.27 | 52.37 | 26.61 | 20.38 | 32.82 | 574.6 | 5626.2 | 375 | *3672.1* | 6611.7 | 6874.52 | *6743.11* | 3.9 |
| 10000 | 2.9694 | 60.1 | 51.87 | 25.89 | 20.22 | 32.91 | 574.6 | 5626.2 | 460 | *4504.5* | 6890.93 | 7023.56 | *6957.24* | 1.91 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8337 | 69.91 | 61.47 | 31.85 | 20.1 | 39.69 | 198.6 | 1944.3 | 50 | *489.62* | 3971.58 | 4083.6 | *4027.59* | 2.78 |
| 4000 | 1.136 | 70.04 | 60.23 | 30.03 | 19.98 | 40.13 | 199 | 1948.8 | 86 | *842.14* | 4618.29 | 4760.35 | *4689.32* | 3.03 |
| 5000 | 1.4256 | 70.31 | 59.43 | 29.34 | 20.32 | 40.03 | 199 | 1948.8 | 127 | *1243.6* | 5119.92 | 5361.94 | *5240.93* | 4.62 |
| 6000 | 1.7314 | 70.32 | 58.57 | 28.15 | 20.45 | 40.11 | 199 | 1948.8 | 178 | *1743* | 5529.78 | 5559.85 | *5544.81* | 0.54 |
| 7000 | 2.0369 | 70.24 | 57.76 | 27.49 | 20.38 | 40 | 199.9 | 1957.9 | 238 | *2330.6* | 5876.31 | 6040.12 | *5958.21* | 2.75 |
| 8000 | 2.3458 | 70.26 | 57.14 | 26.81 | 20.39 | 40.01 | 199.9 | 1957.9 | 305 | *2986.7* | 6176.48 | 6281.68 | *6229.08* | 1.69 |
| 9000 | 2.6454 | 70.43 | 56.75 | 26.51 | 20.48 | 39.97 | 200.9 | 1967 | 376 | *3681.9* | 6441.26 | 6653.83 | *6547.54* | 3.25 |
| 10000 | 2.957 | 70.37 | 56.18 | 26 | 20.47 | 39.88 | 200.9 | 1967 | 455 | *4455.5* | 6678.11 | 6821.35 | *6749.73* | 2.12 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8216 | 69.98 | 64.57 | 33.3 | 19.97 | 40.51 | 567.9 | 5561 | 48 | *470.03* | 4524.01 | 4564.84 | *4544.43* | 0.9 |
| 4000 | 1.1011 | 70.43 | 63.7 | 32.58 | 20.23 | 40.6 | 568.1 | 5562.8 | 81 | *793.18* | 5629.97 | 5667.97 | *5648.97* | 0.67 |
| 5000 | 1.3889 | 70.45 | 62.7 | 31.67 | 20.32 | 40.55 | 568.3 | 5565.5 | 121 | *1184.9* | 6487.81 | 6571.35 | *6529.58* | 1.28 |
| 6000 | 1.6829 | 70.35 | 61.76 | 30.9 | 20.22 | 40.49 | 568.3 | 5565.5 | 170 | *1664.7* | 7188.72 | 7493.19 | *7340.96* | 4.15 |
| 7000 | 1.9882 | 70.23 | 60.93 | 29.77 | 20.23 | 40.58 | 569.8 | 5580 | 227 | *2222.9* | 7781.33 | 7908.76 | *7845.05* | 1.62 |
| 8000 | 2.2807 | 70.41 | 60.5 | 29.19 | 20.48 | 40.62 | 570.2 | 5583.6 | 289 | *2830* | 8294.68 | 8283.31 | *8289* | 0.14 |
| 9000 | 2.5789 | 70.44 | 59.99 | 28.76 | 20.46 | 40.59 | 571.1 | 5592.7 | 358 | *3505.7* | 8747.48 | 8925.88 | *8836.68* | 2.02 |
| 10000 | 2.8876 | 70.48 | 59.54 | 28.11 | 20.43 | 40.72 | 571.1 | 5592.7 | 433 | *4240.1* | 9152.52 | 9248.73 | *9200.63* | 1.05 |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.9115 | 60.24 | 52.21 | 30.19 | 20.17 | 31.03 | 71.3 | 697.95 | 144 | *1410.1* | 3780.95 | 3808.09 | *3794.52* | 0.72 |
| 4000 | 1.2468 | 60.23 | 51.53 | 28.05 | 20.05 | 31.83 | 71.7 | 702.49 | 250 | *2448.1* | 4096.26 | 4160.14 | *4128.2* | 1.55 |
| 5000 | 1.572 | 60.25 | 51.03 | 26.96 | 20.39 | 31.95 | 72.2 | 707.02 | 377 | *3691.7* | 4340.84 | 4307.88 | *4324.36* | 0.76 |
| 6000 | 1.9008 | 60.36 | 50.71 | 26.23 | 20.46 | 32.15 | 73.1 | 716.08 | 523 | *5121.4* | 4540.68 | 4575 | *4557.84* | 0.75 |
| 7000 | 2.2484 | 60.49 | 50.48 | 25.21 | 20.29 | 32.67 | 73.1 | 716.08 | 702 | *6874.3* | 4709.63 | 4615.11 | *4662.37* | 2.03 |
| 8000 | 2.5868 | 60.47 | 50.15 | 24.72 | 20.21 | 32.76 | 73.1 | 716.08 | 892 | *8734.8* | 4855.99 | 4867.48 | *4861.73* | 0.24 |
| 9000 | 2.9047 | 60.21 | 49.62 | 24.61 | 20.48 | 32.26 | 73.1 | 716.08 | 1098 | *10752* | 4985.09 | 5005.06 | *4995.07* | 0.4 |
| 10000 | 3.257 | 60.32 | 49.49 | 24.02 | 20.29 | 32.62 | 73.6 | 720.61 | 1343 | *13151* | 5100.57 | 5065.1 | *5082.83* | 0.7 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8871 | 59.87 | 54.22 | 32.85 | 19.95 | 30.5 | 182 | 1785.7 | 135 | *1322* | 4726.29 | 4769.74 | *4748.02* | 0.92 |
| 4000 | 1.2125 | 60.13 | 53.92 | 30.45 | 20.12 | 31.69 | 182 | 1785.7 | 234 | *2291.4* | 5198.67 | 5222.07 | *5210.37* | 0.45 |
| 5000 | 1.5371 | 60.01 | 53.36 | 29.03 | 20.29 | 32.01 | 182 | 1785.7 | 360 | *3525.3* | 5565.08 | 5602.08 | *5583.58* | 0.66 |
| 6000 | 1.881 | 59.94 | 52.93 | 27.61 | 19.99 | 32.63 | 183 | 1790.2 | 515 | *5043.1* | 5864.46 | 5978.27 | *5921.36* | 1.92 |
| 7000 | 2.2084 | 59.74 | 52.43 | 26.84 | 20.21 | 32.56 | 182 | 1785.7 | 674 | *6600.1* | 6117.57 | 6107.37 | *6112.47* | 0.17 |
| 8000 | 2.5506 | 59.89 | 52.32 | 26.03 | 20.11 | 33.03 | 183 | 1794.7 | 860 | *8421.4* | 6336.84 | 6298.94 | *6317.89* | 0.6 |
| 9000 | 2.8654 | 60.14 | 52.34 | 25.87 | 20.39 | 33.09 | 183 | 1794.7 | 1062 | *10400* | 6530.24 | 6550.41 | *6540.33* | 0.31 |
| 10000 | 3.2172 | 60.03 | 52.02 | 25.21 | 20.15 | 33.32 | 183 | 1794.7 | 1305 | *12779* | 6703.24 | 6789.77 | *6746.51* | 1.28 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8813 | 70.23 | 60.16 | 33.2 | 20.19 | 38.48 | 69.4 | 679.82 | 133 | *1302.4* | 4740.95 | 4778.89 | *4759.92* | 0.8 |
| 4000 | 1.2192 | 70.11 | 58.92 | 30.25 | 19.83 | 39.48 | 69.4 | 679.82 | 243 | *2379.5* | 5265.68 | 5296.98 | *5281.33* | 0.59 |
| 5000 | 1.5288 | 70.35 | 58.3 | 29.41 | 20.39 | 39.4 | 70.3 | 688.89 | 358 | *3505.7* | 5672.69 | 5749.93 | *5711.31* | 1.35 |
| 6000 | 1.8927 | 70.44 | 57.68 | 27.44 | 19.62 | 40.48 | 70.3 | 688.89 | 518 | *5072.5* | 6005.24 | 6173.77 | *6089.5* | 2.77 |
| 7000 | 2.2038 | 70.38 | 57.02 | 26.96 | 20.27 | 39.99 | 71.3 | 697.95 | 670 | *6560.9* | 6286.41 | 6149.76 | *6218.08* | 2.2 |
| 8000 | 2.5277 | 70.48 | 56.61 | 26.54 | 20.38 | 39.96 | 71.3 | 697.95 | 850 | *8323.5* | 6529.97 | 6494.87 | *6512.42* | 0.54 |
| 9000 | 2.8694 | 70.5 | 56.17 | 25.89 | 20.25 | 40.11 | 72.2 | 707.02 | 1075 | *10527* | 6744.8 | 6751.14 | *6747.97* | 0.09 |
| 10000 | 3.2104 | 70.36 | 55.62 | 25.41 | 20.13 | 40.03 | 72.2 | 707.02 | 1312 | *12848* | 6936.98 | 7068.03 | *7002.5* | 1.87 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8597 | 70.13 | 63.27 | 35.74 | 19.93 | 38.69 | 181 | 1767.5 | 128 | *1253.4* | 5742.99 | 5663.13 | *5703.06* | 1.4 |
| 4000 | 1.1688 | 70.22 | 62.19 | 34.01 | 19.87 | 39.19 | 181 | 1767.5 | 216 | *2115.2* | 6719.44 | 6887.72 | *6803.58* | 2.47 |
| 5000 | 1.4845 | 69.97 | 61.03 | 32.31 | 20.12 | 39.26 | 182 | 1785.7 | 332 | *3251.1* | 7476.84 | 7543.17 | *7510.01* | 0.88 |
| 6000 | 1.8261 | 70.07 | 60.4 | 30.52 | 19.69 | 40.12 | 181 | 1767.5 | 490 | *4798.3* | 8095.68 | 8245.9 | *8170.79* | 1.84 |
| 7000 | 2.1278 | 70.43 | 60.13 | 30 | 20.32 | 40.12 | 181 | 1776.6 | 627 | *6139.8* | 8618.9 | 8587.93 | *8603.41* | 0.36 |
| 8000 | 2.4438 | 70.5 | 59.66 | 29.41 | 20.47 | 40.13 | 182 | 1781.1 | 820 | *8029.8* | 9072.13 | 9109.98 | *9091.06* | 0.42 |
| 9000 | 2.7756 | 70.23 | 58.91 | 28.63 | 20.41 | 40.03 | 182 | 1785.7 | 990 | *9694.5* | 9471.91 | 9514.26 | *9493.09* | 0.45 |
| 10000 | 3.1269 | 70.22 | 58.47 | 27.71 | 20.12 | 40.4 | 182 | 1785.7 | 1202 | *11770* | 9829.53 | 9904.25 | *9866.89* | 0.76 |

**Table C-16:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Circular Rib, e= 2.2 mm, p= 20 mm).

| **Re** | **$Q_c$ $10^{-4}$** | **Temperatures and Temperature Difference (°C)** | | | | | **Pressure Drop** | | | | **Heat Transfer Rate (W)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | **Inner tube** | | **Annulus** | | | | | **Dev.** |
| **Annul -us** | **($m^3$/s)** | **$T_{h1}$** | **$T_{h2}$** | **$T_{c1}$** | **$T_{c2}$** | **LMTD** | $mmH_2O$ | $N/m^2$ | $mmH_2O$ | $N/m^2$ | **$q_h$** | **$q_c$** | **$q_{avg.}$** | **%** |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8512 | 59.92 | 52.36 | 30.09 | 20 | 31.08 | 206.4 | 2021.3 | 43 | *421.07* | 3556.99 | 3581.21 | *3569.1* | 0.68 |
| 4000 | 1.1503 | 60.07 | 51.4 | 28.69 | 20.21 | 31.28 | 207.3 | 2030.4 | 71 | *695.26* | 4081.7 | 4067.99 | *4074.84* | 0.34 |
| 5000 | 1.4511 | 60.3 | 50.76 | 27.77 | 20.33 | 31.47 | 208.3 | 2039.5 | 110 | *1077.2* | 4488.69 | 4502.63 | *4495.66* | 0.31 |
| 6000 | 1.7652 | 60.3 | 50.06 | 26.75 | 20.16 | 31.69 | 208.3 | 2039.5 | 155 | *1517.8* | 4821.23 | 4852.36 | *4836.8* | 0.64 |
| 7000 | 2.0625 | 60.21 | 49.37 | 26.35 | 20.43 | 31.34 | 209.2 | 2048.5 | 202 | *1978.1* | 5102.39 | 5093.24 | *5097.81* | 0.18 |
| 8000 | 2.3791 | 60.32 | 48.96 | 25.67 | 20.31 | 31.56 | 209.7 | 2053.1 | 260 | *2546* | 5345.94 | 5319.74 | *5332.84* | 0.49 |
| 9000 | 2.6868 | 60.14 | 48.33 | 25.28 | 20.37 | 31.28 | 211 | 2066.7 | 321 | *3143.4* | 5560.76 | 5503.54 | *5532.15* | 1.03 |
| 10000 | 3.0049 | 60.17 | 47.95 | 24.81 | 20.28 | 31.36 | 212 | 2075.7 | 391 | *3828.8* | 5752.93 | 5679.12 | *5716.03* | 1.29 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8339 | 59.97 | 55.09 | 31.89 | 20.04 | 31.43 | 576.7 | 5647.1 | 41 | *401.49* | 4086.11 | 4119.27 | *4102.69* | 0.81 |
| 4000 | 1.1314 | 59.83 | 54.03 | 30.31 | 20.06 | 31.69 | 578.5 | 5665.2 | 71 | *695.26* | 4852 | 4835.24 | *4843.62* | 0.35 |
| 5000 | 1.4181 | 60.4 | 53.89 | 29.63 | 20.5 | 32.06 | 579.1 | 5670.6 | 105 | *1028.2* | 5446.07 | 5398.34 | *5422.2* | 0.88 |
| 6000 | 1.7259 | 60.2 | 53.11 | 28.59 | 20.29 | 32.21 | 579.5 | 5674.3 | 148 | *1449.3* | 5931.46 | 5973.83 | *5952.64* | 0.71 |
| 7000 | 2.0283 | 60.22 | 52.64 | 27.87 | 20.37 | 32.31 | 581.3 | 5692.4 | 196 | *1919.3* | 6341.85 | 6344.27 | *6343.06* | 0.04 |
| 8000 | 2.345 | 60 | 52 | 27 | 20.23 | 32.38 | 580.4 | 5683.3 | 253 | *2477.5* | 6697.34 | 6621.83 | *6659.59* | 1.13 |
| 9000 | 2.6475 | 60 | 51.62 | 26.64 | 20.28 | 32.34 | 581.3 | 5692.4 | 312 | *3055.2* | 7010.91 | 7023.69 | *7017.3* | 0.18 |
| 10000 | 2.9557 | 60.11 | 51.4 | 26.24 | 20.27 | 32.48 | 583.2 | 5710.5 | 378 | *3701.5* | 7291.41 | 7360.66 | *7326.03* | 0.95 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8284 | 69.85 | 60.35 | 32.82 | 19.71 | 38.8 | 206 | 2016.8 | 40 | *391.7* | 4473.81 | 4526.72 | *4500.27* | 1.18 |
| 4000 | 1.1239 | 69.96 | 58.99 | 31.09 | 19.87 | 38.99 | 206.9 | 2025.9 | 70 | *685.47* | 5164.59 | 5257.54 | *5211.07* | 1.78 |
| 5000 | 1.4272 | 70.1 | 57.99 | 29.53 | 20.03 | 39.25 | 207.3 | 2030.4 | 106 | *1038* | 5700.4 | 5653.73 | *5677.07* | 0.82 |
| 6000 | 1.728 | 69.92 | 56.88 | 28.72 | 20.05 | 38.97 | 207.3 | 2030.4 | 148 | *1449.3* | 6138.19 | 6248.02 | *6193.11* | 1.77 |
| 7000 | 2.0322 | 70.21 | 56.38 | 27.91 | 20.16 | 39.18 | 207.3 | 2030.4 | 197 | *1929.1* | 6508.33 | 6568.62 | *6538.47* | 0.92 |
| 8000 | 2.3409 | 70.25 | 55.74 | 27.21 | 20.17 | 39.19 | 207.3 | 2030.4 | 252 | *2467.7* | 6828.97 | 6873.94 | *6851.45* | 0.66 |
| 9000 | 2.6561 | 70.23 | 55.12 | 26.52 | 20.12 | 39.19 | 207.8 | 2034.9 | 314 | *3074.8* | 7111.79 | 7090.97 | *7101.38* | 0.29 |
| 10000 | 2.9721 | 70.17 | 54.52 | 26.03 | 20 | 39.14 | 207.8 | 2034.9 | 380 | *3721.1* | 7364.78 | 7476.5 | *7420.64* | 1.51 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8004 | 69.91 | 63.62 | 35.79 | 19.88 | 38.73 | 577.8 | 5658 | 38 | *372.11* | 5264.4 | 5305.92 | *5285.16* | 0.79 |
| 4000 | 1.0887 | 70.23 | 62.82 | 33.61 | 20.23 | 39.53 | 578.1 | 5660.7 | 65 | *636.5* | 6197 | 6070.72 | *6133.86* | 2.06 |
| 5000 | 1.3792 | 70.39 | 62.12 | 32.32 | 20.3 | 39.92 | 578.5 | 5665.2 | 99 | *969.45* | 6920.38 | 6910.31 | *6915.34* | 0.15 |
| 6000 | 1.6835 | 69.95 | 60.97 | 30.91 | 20.18 | 39.91 | 578.5 | 5665.2 | 141 | *1380.7* | 7511.43 | 7530.82 | *7521.13* | 0.26 |
| 7000 | 1.9826 | 70.16 | 60.59 | 30.01 | 20.24 | 40.25 | 578.5 | 5665.2 | 187 | *1831.2* | 8011.15 | 8076.42 | *8043.79* | 0.81 |
| 8000 | 2.2722 | 70.31 | 60.22 | 29.51 | 20.49 | 40.26 | 579.5 | 5674.3 | 236 | *2311* | 8444.03 | 8545.91 | *8494.97* | 1.2 |
| 9000 | 2.5941 | 70.35 | 59.8 | 28.4 | 20.3 | 40.71 | 579.9 | 5678.8 | 301 | *2947.5* | 8825.85 | 8762.93 | *8794.39* | 0.72 |
| 10000 | 2.8876 | 70.5 | 59.54 | 28.11 | 20.43 | 40.73 | 580.4 | 5683.3 | 361 | *3535* | 9167.41 | 9248.73 | *9208.07* | 0.88 |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.9153 | 59.94 | 51.86 | 29.97 | 20.02 | 30.89 | 71.3 | 697.95 | 113 | *1102.9* | 3804.1 | 3797.43 | *3800.76* | 0.18 |
| 4000 | 1.2369 | 60.03 | 51.12 | 28.41 | 20.39 | 31.17 | 72.2 | 707.02 | 191 | *1870.3* | 4193.82 | 4137.05 | *4165.44* | 1.36 |
| 5000 | 1.565 | 59.98 | 50.43 | 27.29 | 20.45 | 31.31 | 72.7 | 711.55 | 288 | *2820.2* | 4496.12 | 4464.69 | *4480.41* | 0.7 |
| 6000 | 1.8945 | 60.21 | 50.13 | 26.51 | 20.47 | 31.64 | 72.2 | 707.02 | 402 | *3936.5* | 4743.12 | 4772.93 | *4758.02* | 0.63 |
| 7000 | 2.2424 | 60.01 | 49.49 | 25.5 | 20.23 | 31.81 | 73.1 | 716.08 | 530 | *5190* | 4951.95 | 4930.07 | *4941.01* | 0.44 |
| 8000 | 2.5835 | 60.15 | 49.25 | 24.91 | 20.13 | 32.08 | 74.1 | 725.15 | 693 | *6786.1* | 5132.85 | 5152.18 | *5142.51* | 0.38 |
| 9000 | 2.9129 | 59.81 | 48.57 | 24.64 | 20.21 | 31.64 | 74.1 | 725.15 | 854 | *8362.7* | 5292.41 | 5383.87 | *5338.14* | 1.71 |
| 10000 | 3.2501 | 60.02 | 48.47 | 24.22 | 20.27 | 31.85 | 73.1 | 716.08 | 1045 | *10233* | 5435.14 | 5354.66 | *5394.9* | 1.49 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8835 | 60.21 | 54.64 | 32.95 | 20.22 | 30.7 | 181 | 1767.5 | 108 | *1057.6* | 4662.26 | 4687.5 | *4674.88* | 0.54 |
| 4000 | 1.2137 | 60.15 | 53.86 | 30.51 | 19.97 | 31.72 | 181 | 1767.5 | 188 | *1841* | 5266.73 | 5333.68 | *5300.2* | 1.26 |
| 5000 | 1.5401 | 60.12 | 53.27 | 29.02 | 20.13 | 32.11 | 181 | 1772.1 | 283 | *2771.2* | 5735.59 | 5709.33 | *5722.46* | 0.46 |
| 6000 | 1.8563 | 60.06 | 52.75 | 28.34 | 20.42 | 32.02 | 181 | 1776.6 | 390 | *3819* | 6118.67 | 6131.02 | *6124.85* | 0.2 |
| 7000 | 2.1842 | 59.86 | 52.16 | 27.53 | 20.48 | 32 | 181 | 1776.6 | 510 | *4994.1* | 6442.57 | 6422.39 | *6432.48* | 0.31 |
| 8000 | 2.5138 | 59.6 | 51.57 | 26.94 | 20.46 | 31.88 | 181 | 1776.6 | 660 | *6463* | 6723.14 | 6794.25 | *6758.69* | 1.05 |
| 9000 | 2.8568 | 60 | 51.67 | 26.24 | 20.28 | 32.56 | 182 | 1785.7 | 825 | *8078.7* | 6970.62 | 7102.55 | *7036.59* | 1.87 |
| 10000 | 3.1879 | 60.11 | 51.52 | 25.82 | 20.33 | 32.71 | 182 | 1785.7 | 1001 | *9802.2* | 7192 | 7300.91 | *7246.46* | 1.5 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8789 | 70.11 | 59.42 | 33.66 | 19.98 | 37.92 | 69.4 | 679.82 | 103 | *1008.6* | 5032.39 | 5011.06 | *5021.73* | 0.42 |
| 4000 | 1.204 | 70.17 | 58.39 | 31.21 | 19.99 | 38.68 | 70.1 | 686.17 | 177 | *1733.3* | 5544.95 | 5631.69 | *5588.32* | 1.55 |
| 5000 | 1.5283 | 70.28 | 57.66 | 29.69 | 20.14 | 39.03 | 69.4 | 679.82 | 260 | *2546* | 5942.51 | 6085.7 | *6014.11* | 2.38 |
| 6000 | 1.8643 | 70.11 | 56.8 | 28.22 | 20.16 | 39.2 | 70.3 | 688.89 | 385 | *3770.1* | 6267.35 | 6266.74 | *6267.04* | 0.01 |
| 7000 | 2.2041 | 70.24 | 56.34 | 27.19 | 20.03 | 39.59 | 71.3 | 697.95 | 527 | *5160.6* | 6541.99 | 6582.57 | *6562.28* | 0.62 |
| 8000 | 2.5344 | 70.29 | 55.89 | 26.52 | 20.17 | 39.61 | 71.3 | 697.95 | 663 | *6492.3* | 6779.9 | 6713.17 | *6746.53* | 0.99 |
| 9000 | 2.8509 | 69.87 | 55.02 | 26.32 | 20.38 | 38.93 | 70.3 | 688.89 | 802 | *7853.5* | 6989.75 | 7063.86 | *7026.81* | 1.05 |
| 10000 | 3.2097 | 70.15 | 54.9 | 25.44 | 20.12 | 39.54 | 70.3 | 688.89 | 985 | *9645.5* | 7177.47 | 7121.96 | *7149.71* | 0.78 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8533 | 69.77 | 62.57 | 36.41 | 19.96 | 37.8 | 181 | 1772.1 | 94 | *920.48* | 6021.47 | 5847.51 | *5934.49* | 2.93 |
| 4000 | 1.16 | 69.93 | 61.54 | 34.57 | 20 | 38.37 | 181 | 1767.5 | 162 | *1586.4* | 7016.77 | 7043.24 | *7030.01* | 0.38 |
| 5000 | 1.4781 | 70.12 | 60.81 | 32.6 | 20.22 | 39.04 | 181 | 1776.6 | 252 | *2467.7* | 7788.79 | 7627.41 | *7708.1* | 2.09 |
| 6000 | 1.7961 | 70.29 | 60.23 | 31.42 | 20.27 | 39.41 | 182 | 1785.7 | 365 | *3574.2* | 8419.58 | 8348.6 | *8384.09* | 0.85 |
| 7000 | 2.1242 | 70.32 | 59.62 | 30.31 | 20.16 | 39.73 | 182 | 1785.7 | 502 | *4915.8* | 8952.9 | 8989.58 | *8971.24* | 0.41 |
| 8000 | 2.4394 | 70.31 | 59.06 | 29.66 | 20.38 | 39.66 | 182 | 1781.1 | 632 | *6188.8* | 9414.88 | 9439.22 | *9427.05* | 0.26 |
| 9000 | 2.774 | 70.36 | 58.62 | 28.77 | 20.32 | 39.92 | 182 | 1785.7 | 769 | *7530.3* | 9822.38 | 9774.87 | *9798.62* | 0.48 |
| 10000 | 3.1097 | 70.23 | 58.06 | 28.09 | 20.22 | 39.95 | 182 | 1785.7 | 939 | *9195* | 10186.9 | 10206.6 | *10196.7* | 0.19 |

**Table C-17:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Circular Rib, e= 2.2 mm, p= 30 mm).

| Re | $Q_c$ $10^{-4}$ | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| Annul-us | ($m^3$/s) | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | N/$m^2$ | $mmH_2O$ | N/$m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8462 | 60.33 | 52.95 | 30.26 | 20.36 | 31.31 | 203.6 | 1994.2 | 31.6 | *309.48* | 3472.92 | 3492.68 | *3482.8* | 0.57 |
| 4000 | 1.1541 | 60.43 | 52.07 | 28.4 | 20.21 | 31.95 | 204.6 | 2003.2 | 55 | *538.58* | 3933.84 | 3941.99 | *3937.91* | 0.21 |
| 5000 | 1.4592 | 60.43 | 51.31 | 27.31 | 20.3 | 32.05 | 203.6 | 1994.2 | 81 | *793.18* | 4291.36 | 4266.51 | *4278.94* | 0.58 |
| 6000 | 1.7742 | 60.41 | 50.67 | 26.31 | 20.16 | 32.27 | 207.3 | 2030.4 | 115 | *1126.1* | 4583.48 | 4551.68 | *4567.58* | 0.7 |
| 7000 | 2.0726 | 60.45 | 50.19 | 25.95 | 20.41 | 32.08 | 207.3 | 2030.4 | 149 | *1459.1* | 4830.46 | 4789.73 | *4810.1* | 0.85 |
| 8000 | 2.3863 | 60.32 | 49.6 | 25.39 | 20.33 | 32.02 | 207.3 | 2030.4 | 194 | *1899.7* | 5044.4 | 5037.34 | *5040.87* | 0.14 |
| 9000 | 2.6949 | 60.48 | 49.36 | 25 | 20.39 | 32.12 | 208.3 | 2039.5 | 240 | *2350.2* | 5233.12 | 5183.11 | *5208.11* | 0.96 |
| 10000 | 3.0133 | 60.33 | 48.85 | 24.57 | 20.28 | 32.03 | 209.2 | 2048.5 | 290 | *2839.8* | 5401.93 | 5393.51 | *5397.72* | 0.16 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8244 | 60.34 | 55.2 | 32.75 | 20.21 | 31.15 | 576.7 | 5647.1 | 30 | *293.77* | 4298.41 | 4309.16 | *4303.79* | 0.25 |
| 4000 | 1.1268 | 60.3 | 54.42 | 30.67 | 20.06 | 31.94 | 575.8 | 5638 | 52 | *509.2* | 4922.8 | 4984.67 | *4953.73* | 1.25 |
| 5000 | 1.4229 | 60.4 | 53.94 | 29.5 | 20.33 | 32.24 | 576.7 | 5647.1 | 78 | *763.81* | 5407.12 | 5440.55 | *5423.83* | 0.62 |
| 6000 | 1.7288 | 60.42 | 53.49 | 28.45 | 20.28 | 32.58 | 577.6 | 5656.1 | 109 | *1067.4* | 5802.83 | 5890.41 | *5846.62* | 1.5 |
| 7000 | 2.0425 | 60.22 | 52.89 | 27.43 | 20.2 | 32.74 | 577.6 | 5656.1 | 147 | *1439.5* | 6137.4 | 6159.15 | *6148.27* | 0.35 |
| 8000 | 2.352 | 60.33 | 52.65 | 26.76 | 20.21 | 33 | 578.5 | 5665.2 | 188 | *1841* | 6427.22 | 6426.05 | *6426.64* | 0.02 |
| 9000 | 2.6604 | 60.33 | 52.34 | 26.22 | 20.28 | 33.08 | 579.5 | 5674.3 | 232 | *2271.8* | 6682.86 | 6592.07 | *6637.46* | 1.37 |
| 10000 | 2.9797 | 60.21 | 51.95 | 25.68 | 20.13 | 33.16 | 580.4 | 5683.3 | 283 | *2771.2* | 6911.54 | 6899.14 | *6905.34* | 0.18 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8161 | 70.37 | 60.86 | 33.62 | 20.27 | 38.64 | 205.5 | 2012.3 | 28 | *274.19* | 4476.37 | 4540.32 | *4508.35* | 1.42 |
| 4000 | 1.1177 | 70.33 | 59.46 | 31.24 | 20.22 | 39.16 | 205.5 | 2012.3 | 50 | *489.62* | 5117.03 | 5134.75 | *5125.89* | 0.35 |
| 5000 | 1.4238 | 70.21 | 58.28 | 29.64 | 20.13 | 39.35 | 205.5 | 2012.3 | 77 | *754.01* | 5613.97 | 5646.13 | *5630.05* | 0.57 |
| 6000 | 1.7421 | 69.92 | 57.13 | 28.11 | 19.95 | 39.45 | 205.5 | 2012.3 | 111 | *1087* | 6019.99 | 5928.78 | *5974.39* | 1.53 |
| 7000 | 2.0343 | 70.47 | 56.95 | 27.72 | 20.26 | 39.64 | 205.5 | 2012.3 | 145 | *1419.9* | 6363.28 | 6329.4 | *6346.34* | 0.53 |
| 8000 | 2.3401 | 70.45 | 56.3 | 27.13 | 20.28 | 39.56 | 207.3 | 2030.4 | 186 | *1821.4* | 6660.65 | 6686.1 | *6673.37* | 0.38 |
| 9000 | 2.6485 | 70.43 | 55.72 | 26.57 | 20.32 | 39.48 | 208.3 | 2039.5 | 229 | *2242.5* | 6922.95 | 6904.62 | *6913.78* | 0.27 |
| 10000 | 2.9601 | 70.42 | 55.21 | 26.09 | 20.29 | 39.44 | 209.2 | 2048.5 | 279 | *2732.1* | 7157.58 | 7161.93 | *7159.75* | 0.06 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.798 | 69.91 | 63.79 | 35.81 | 20.14 | 38.68 | 571.1 | 5592.7 | 29 | *283.98* | 5121.54 | 5209.9 | *5165.72* | 1.71 |
| 4000 | 1.0863 | 70.03 | 62.68 | 33.81 | 20.23 | 39.25 | 570.1 | 5582.7 | 48 | *470.03* | 6149.5 | 6147.83 | *6148.66* | 0.03 |
| 5000 | 1.3735 | 70.33 | 62.03 | 32.5 | 20.5 | 39.65 | 571.1 | 5592.7 | 74 | *724.64* | 6946.85 | 6869.6 | *6908.22* | 1.12 |
| 6000 | 1.6776 | 69.95 | 60.87 | 31.22 | 20.18 | 39.7 | 571.1 | 5592.7 | 105 | *1028.2* | 7598.33 | 7721.33 | *7659.83* | 1.61 |
| 7000 | 1.9786 | 70.06 | 60.32 | 30.19 | 20.24 | 39.98 | 572.1 | 5601.8 | 140 | *1370.9* | 8149.15 | 8208.42 | *8178.78* | 0.72 |
| 8000 | 2.2697 | 70.31 | 60 | 29.61 | 20.49 | 40.1 | 573.9 | 5619.9 | 176 | *1723.5* | 8626.29 | 8630.82 | *8628.56* | 0.05 |
| 9000 | 2.5701 | 70.35 | 59.54 | 29.02 | 20.5 | 40.17 | 574.8 | 5628.9 | 217 | *2124.9* | 9047.16 | 9131.08 | *9089.12* | 0.92 |
| 10000 | 2.882 | 70.25 | 58.99 | 28.28 | 20.43 | 40.24 | 576.7 | 5647.1 | 226 | *2213.1* | 9423.64 | 9434.99 | *9429.31* | 0.12 |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.9065 | 60.17 | 51.64 | 30.72 | 20.13 | 30.47 | 72.2 | 707.02 | 87.6 | *858.02* | 4013.38 | 4002.41 | *4007.9* | 0.27 |
| 4000 | 1.2254 | 60.13 | 50.6 | 29.18 | 20.45 | 30.55 | 72.2 | 707.02 | 148 | *1449.3* | 4485.57 | 4460.7 | *4473.13* | 0.56 |
| 5000 | 1.5539 | 59.81 | 49.5 | 27.91 | 20.45 | 30.45 | 73.1 | 716.08 | 225 | *2203.3* | 4851.83 | 4834.64 | *4843.24* | 0.35 |
| 6000 | 1.8834 | 60.43 | 49.49 | 27.08 | 20.41 | 31.16 | 73.1 | 716.08 | 314 | *3074.8* | 5151.09 | 5239.63 | *5195.36* | 1.7 |
| 7000 | 2.2163 | 60.27 | 48.79 | 26.31 | 20.43 | 31.08 | 73.1 | 716.08 | 418 | *4093.2* | 5404.1 | 5436.08 | *5420.09* | 0.59 |
| 8000 | 2.555 | 60.41 | 48.46 | 25.63 | 20.36 | 31.32 | 73.1 | 716.08 | 545 | *5336.8* | 5623.28 | 5617.2 | *5620.24* | 0.11 |
| 9000 | 2.8993 | 60.28 | 47.92 | 25.03 | 20.22 | 31.32 | 73.1 | 716.08 | 669 | *6551.1* | 5816.6 | 5818.15 | *5817.38* | 0.03 |
| 10000 | 3.243 | 60.21 | 47.49 | 24.54 | 20.14 | 31.33 | 74.1 | 725.15 | 802 | *7853.5* | 5989.54 | 5953.53 | *5971.53* | 0.6 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8822 | 60.33 | 54.51 | 33.3 | 20 | 30.62 | 182 | 1785.7 | 85 | *832.35* | 4873.32 | 4890.31 | *4881.81* | 0.35 |
| 4000 | 1.1909 | 60.07 | 53.3 | 31.74 | 20.44 | 30.54 | 182 | 1785.7 | 142 | *1390.5* | 5664.96 | 5609.64 | *5637.3* | 0.98 |
| 5000 | 1.5234 | 60.49 | 52.99 | 30.04 | 20.07 | 31.67 | 182 | 1785.7 | 221 | *2164.1* | 6279 | 6333.12 | *6306.06* | 0.86 |
| 6000 | 1.8433 | 60.22 | 52.12 | 29.06 | 20.32 | 31.48 | 183 | 1790.2 | 303 | *2967.1* | 6780.71 | 6717.88 | *6749.29* | 0.93 |
| 7000 | 2.1617 | 60.14 | 51.53 | 28.46 | 20.46 | 31.37 | 183 | 1794.7 | 400 | *3917* | 7204.9 | 7211.85 | *7208.37* | 0.1 |
| 8000 | 2.492 | 60.32 | 51.27 | 27.7 | 20.46 | 31.71 | 183 | 1794.7 | 505 | *4945.2* | 7572.35 | 7524.64 | *7548.49* | 0.63 |
| 9000 | 2.8231 | 60.23 | 50.79 | 27.13 | 20.42 | 31.72 | 183 | 1794.7 | 645 | *6316.1* | 7896.46 | 7901.07 | *7898.77* | 0.06 |
| 10000 | 3.1607 | 60.26 | 50.47 | 26.58 | 20.31 | 31.89 | 183 | 1794.7 | 775 | *7589.1* | 8186.39 | 8266.45 | *8226.42* | 0.97 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8701 | 70.28 | 59.19 | 34.43 | 20.13 | 37.43 | 71.3 | 697.95 | 78 | *763.81* | 5218.95 | 5185.11 | *5202.03* | 0.65 |
| 4000 | 1.1908 | 70.5 | 58.13 | 31.92 | 20.27 | 38.22 | 71.3 | 697.95 | 137 | *1341.6* | 5824.8 | 5782.74 | *5803.77* | 0.72 |
| 5000 | 1.5241 | 70.29 | 56.92 | 30.04 | 20.03 | 38.54 | 71.3 | 697.95 | 201 | *1968.3* | 6294.74 | 6361.42 | *6328.08* | 1.05 |
| 6000 | 1.8464 | 70.11 | 55.92 | 28.94 | 20.29 | 38.33 | 71.3 | 697.95 | 295 | *2888.8* | 6678.7 | 6660.13 | *6669.41* | 0.28 |
| 7000 | 2.1795 | 70.32 | 55.44 | 27.92 | 20.28 | 38.67 | 72.2 | 707.02 | 401 | *3926.7* | 7003.34 | 6944.61 | *6973.98* | 0.84 |
| 8000 | 2.5051 | 70.25 | 54.77 | 27.33 | 20.37 | 38.51 | 73.1 | 716.08 | 510 | *4994.1* | 7284.55 | 7272.2 | *7278.38* | 0.17 |
| 9000 | 2.8345 | 70.42 | 54.42 | 26.81 | 20.39 | 38.62 | 73.1 | 716.08 | 645 | *6316.1* | 7532.6 | 7590.37 | *7561.48* | 0.76 |
| 10000 | 3.1797 | 70.34 | 53.87 | 26.12 | 20.25 | 38.68 | 73.1 | 716.08 | 761 | *7452* | 7754.49 | 7784.17 | *7769.33* | 0.38 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8417 | 70.32 | 62.89 | 37.61 | 20.03 | 37.56 | 180 | 1758.5 | 76 | *744.22* | 6215.92 | 6163.68 | *6189.8* | 0.84 |
| 4000 | 1.1438 | 70.29 | 61.62 | 35.42 | 20.45 | 37.93 | 180 | 1758.5 | 135 | *1322* | 7258.48 | 7134.04 | *7196.26* | 1.73 |
| 5000 | 1.4593 | 70.18 | 60.54 | 33.53 | 20.46 | 38.34 | 181 | 1767.5 | 195 | *1909.5* | 8067.16 | 7948.45 | *8007.8* | 1.48 |
| 6000 | 1.7699 | 69.83 | 59.4 | 32.54 | 20.48 | 38.1 | 181 | 1767.5 | 280 | *2741.9* | 8727.89 | 8896.44 | *8812.17* | 1.91 |
| 7000 | 2.1046 | 70.41 | 59.31 | 31.07 | 20.23 | 39.21 | 181 | 1767.5 | 380 | *3721.1* | 9286.53 | 9510.94 | *9398.73* | 2.39 |
| 8000 | 2.4677 | 70.23 | 58.55 | 29.25 | 19.77 | 39.87 | 181 | 1776.6 | 480 | *4700.3* | 9770.45 | 9755.7 | *9763.08* | 0.15 |
| 9000 | 2.7574 | 69.91 | 57.72 | 29.26 | 20.36 | 38.98 | 181 | 1776.6 | 623 | *6100.7* | 10197.3 | 10233.2 | *10215.2* | 0.35 |
| 10000 | 3.1024 | 70.17 | 57.52 | 28.26 | 20.25 | 39.54 | 181 | 1776.6 | 710 | *6952.6* | 10579.1 | 10358.2 | *10468.7* | 2.11 |

**Table C-18:** Experimental Results of Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Circular Rib, e= 2.2 mm, p= 40 mm).

| Re | $Q_c$ $10^{-4}$ | Temperatures and Temperature Difference (°C) | | | | | Pressure Drop | | | | Heat Transfer Rate (W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Inner tube | | Annulus | | | | | |
| Annul-us | ($m^3$/s) | $T_{h1}$ | $T_{h2}$ | $T_{c1}$ | $T_{c2}$ | LMTD | $mmH_2O$ | N/$m^2$ | $mmH_2O$ | N/$m^2$ | $q_h$ | $q_c$ | $q_{avg.}$ | Dev. % |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8477 | 60.33 | 53.06 | 30.10 | 20.36 | 31.45 | 203.2 | 1989.6 | 27 | *264.39* | 3423.56 | 3442.47 | *3433.02* | 0.55 |
| 4000 | 1.1541 | 60.23 | 51.89 | 28.40 | 20.21 | 31.76 | 203.6 | 1994.2 | 43 | *421.07* | 3925.51 | 3941.99 | *3933.75* | 0.42 |
| 5000 | 1.4514 | 60.43 | 51.26 | 27.60 | 20.48 | 31.80 | 203.6 | 1994.2 | 62 | *607.13* | 4314.84 | 4309.97 | *4312.41* | 0.11 |
| 6000 | 1.7699 | 60.20 | 50.36 | 26.52 | 20.16 | 31.91 | 207.3 | 2030.4 | 85 | *832.35* | 4632.96 | 4695.57 | *4664.27* | 1.34 |
| 7000 | 2.0661 | 60.45 | 50.04 | 26.13 | 20.50 | 31.87 | 206.4 | 2021.3 | 111 | *1087* | 4901.92 | 4852.22 | *4877.07* | 1.02 |
| 8000 | 2.3805 | 60.12 | 49.21 | 25.60 | 20.33 | 31.62 | 207.3 | 2030.4 | 139 | *1361.1* | 5134.90 | 5233.49 | *5184.19* | 1.90 |
| 9000 | 2.6915 | 60.48 | 49.13 | 25.11 | 20.39 | 31.94 | 208.3 | 2039.5 | 176 | *1723.5* | 5340.41 | 5299.91 | *5320.16* | 0.76 |
| 10000 | 3.0045 | 60.33 | 48.59 | 24.74 | 20.36 | 31.77 | 208.3 | 2039.5 | 220 | *2154.3* | 5524.24 | 5490.42 | *5507.33* | 0.61 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8301 | 60.34 | 55.65 | 32.00 | 20.34 | 31.70 | 575.2 | 5632.6 | 26 | *254.6* | 3928.22 | 4034.63 | *3981.42* | 2.67 |
| 4000 | 1.1286 | 60.30 | 54.69 | 30.23 | 20.36 | 32.15 | 575.8 | 5638 | 42 | *411.28* | 4696.68 | 4644.37 | *4670.53* | 1.12 |
| 5000 | 1.4221 | 60.40 | 54.08 | 29.49 | 20.39 | 32.28 | 576.7 | 5647.1 | 60 | *587.54* | 5292.75 | 5395.94 | *5344.34* | 1.93 |
| 6000 | 1.7296 | 60.42 | 53.51 | 28.41 | 20.28 | 32.62 | 577.6 | 5656.1 | 83 | *812.77* | 5779.77 | 5864.26 | *5822.01* | 1.45 |
| 7000 | 2.0394 | 60.22 | 52.82 | 27.45 | 20.31 | 32.64 | 577.6 | 5656.1 | 109 | *1067.4* | 6191.54 | 6073.33 | *6132.43* | 1.93 |
| 8000 | 2.3361 | 60.43 | 52.60 | 27.11 | 20.45 | 32.73 | 577.6 | 5656.1 | 137 | *1341.6* | 6548.23 | 6489.34 | *6518.79* | 0.90 |
| 9000 | 2.6439 | 60.33 | 52.13 | 26.65 | 20.39 | 32.70 | 578.5 | 5665.2 | 173 | *1694.1* | 6862.85 | 6903.60 | *6883.23* | 0.59 |
| 10000 | 2.9618 | 60.21 | 51.67 | 26.10 | 20.23 | 32.76 | 578.5 | 5665.2 | 218 | *2134.7* | 7144.29 | 7252.60 | *7198.45* | 1.50 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8243 | 70.29 | 61.23 | 32.73 | 20.25 | 39.25 | 203.6 | 1994.2 | 26 | *254.6* | 4263.32 | 4287.59 | *4275.46* | 0.57 |
| 4000 | 1.1256 | 70.33 | 59.99 | 30.61 | 20.22 | 39.74 | 203.6 | 1994.2 | 41 | *401.49* | 4868.95 | 4875.78 | *4872.37* | 0.14 |
| 5000 | 1.4319 | 70.21 | 58.87 | 29.12 | 20.15 | 39.89 | 205.5 | 2012.3 | 59 | *577.75* | 5338.71 | 5356.05 | *5347.38* | 0.32 |
| 6000 | 1.7423 | 69.86 | 57.70 | 28.00 | 20.05 | 39.72 | 206 | 2016.8 | 81 | *793.18* | 5722.53 | 5776.87 | *5749.70* | 0.95 |
| 7000 | 2.0441 | 70.27 | 57.42 | 27.30 | 20.26 | 40.00 | 206 | 2016.8 | 110 | *1077.2* | 6047.05 | 6002.16 | *6024.6* | 0.75 |
| 8000 | 2.3509 | 70.33 | 56.89 | 26.72 | 20.29 | 40.00 | 205.5 | 2012.3 | 138 | *1351.3* | 6328.15 | 6305.38 | *6316.77* | 0.36 |
| 9000 | 2.6579 | 70.42 | 56.45 | 26.26 | 20.32 | 40.01 | 206.4 | 2021.3 | 172 | *1684.3* | 6576.11 | 6585.92 | *6581.01* | 0.15 |
| 10000 | 2.9635 | 70.45 | 56.01 | 25.86 | 20.42 | 39.92 | 206.4 | 2021.3 | 212 | *2076* | 6797.91 | 6725.25 | *6761.58* | 1.07 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8060 | 69.83 | 64.05 | 34.89 | 20.14 | 39.25 | 568.7 | 5569.1 | 24 | *235.02* | 4840.03 | 4953.73 | *4896.88* | 2.32 |
| 4000 | 1.1008 | 70.03 | 63.11 | 32.73 | 20.10 | 40.09 | 569.6 | 5577.3 | 39 | *381.9* | 5793.51 | 5795.19 | *5794.35* | 0.03 |
| 5000 | 1.3906 | 70.43 | 62.62 | 31.60 | 20.28 | 40.56 | 571.1 | 5592.7 | 58 | *567.96* | 6533.07 | 6562.08 | *6547.58* | 0.44 |
| 6000 | 1.6977 | 69.95 | 61.42 | 30.34 | 20.00 | 40.51 | 571.1 | 5592.7 | 81 | *793.18* | 7137.35 | 7319.04 | *7228.19* | 2.51 |
| 7000 | 2.0001 | 70.06 | 60.92 | 29.33 | 20.14 | 40.76 | 572.1 | 5601.8 | 107 | *1047.8* | 7648.25 | 7664.82 | *7656.53* | 0.22 |
| 8000 | 2.2871 | 70.37 | 60.70 | 28.93 | 20.49 | 40.82 | 573.9 | 5619.9 | 134 | *1312.2* | 8090.82 | 8049.50 | *8070.16* | 0.51 |
| 9000 | 2.5959 | 70.35 | 60.21 | 28.22 | 20.42 | 40.95 | 573.9 | 5619.9 | 168 | *1645.1* | 8481.19 | 8444.20 | *8462.69* | 0.44 |
| 10000 | 2.9025 | 70.27 | 59.72 | 27.76 | 20.33 | 40.93 | 573.9 | 5619.9 | 208 | *2036.8* | 8830.39 | 8994.20 | *8912.29* | 1.84 |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.9148 | 60.18 | 51.72 | 30.12 | 19.92 | 30.92 | 70.8 | 693.42 | 68.9 | *675.07* | 3979.94 | 3890.63 | *3935.28* | 2.27 |
| 4000 | 1.2277 | 60.19 | 50.86 | 28.97 | 20.49 | 30.79 | 70.3 | 688.89 | 114 | *1116.3* | 4392.21 | 4341.38 | *4366.79* | 1.16 |
| 5000 | 1.5575 | 59.74 | 49.73 | 27.66 | 20.50 | 30.63 | 71.3 | 697.95 | 175 | *1713.7* | 4711.98 | 4650.93 | *4681.46* | 1.30 |
| 6000 | 1.8881 | 59.93 | 49.36 | 26.77 | 20.50 | 30.96 | 71.3 | 697.95 | 245 | *2399.1* | 4973.26 | 4938 | *4955.63* | 0.71 |
| 7000 | 2.2250 | 60.11 | 49.08 | 25.95 | 20.45 | 31.31 | 71.3 | 697.95 | 335 | *3280.4* | 5194.17 | 5105 | *5149.58* | 1.73 |
| 8000 | 2.5648 | 60.34 | 48.90 | 25.31 | 20.35 | 31.68 | 70.3 | 688.89 | 419 | *4103* | 5385.53 | 5307.29 | *5346.41* | 1.46 |
| 9000 | 2.8905 | 60.17 | 48.37 | 25.07 | 20.44 | 31.38 | 70.3 | 688.89 | 506 | *4954.9* | 5554.32 | 5583.3 | *5568.81* | 0.52 |
| 10000 | 3.2237 | 60.09 | 47.97 | 24.77 | 20.42 | 31.28 | 70.3 | 688.89 | 625 | *6120.2* | 5705.30 | 5850.51 | *5777.91* | 2.51 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8900 | 60.13 | 54.55 | 32.43 | 20.07 | 30.96 | 181 | 1776.6 | 65 | *636.5* | 4673.31 | 4585.43 | *4629.37* | 1.90 |
| 4000 | 1.2001 | 60.16 | 53.68 | 31.19 | 20.30 | 31.12 | 181 | 1776.6 | 110 | *1077.2* | 5420.75 | 5448.2 | *5434.48* | 0.51 |
| 5000 | 1.5233 | 60.07 | 52.90 | 29.74 | 20.38 | 31.41 | 181 | 1776.6 | 165 | *1615.7* | 6000.51 | 5944.96 | *5972.73* | 0.93 |
| 6000 | 1.8632 | 59.73 | 51.99 | 28.23 | 20.20 | 31.65 | 185 | 1812.9 | 230 | *2252.2* | 6474.21 | 6239.82 | *6357.01* | 3.69 |
| 7000 | 2.1773 | 60.02 | 51.80 | 27.98 | 20.31 | 31.77 | 183 | 1794.7 | 320 | *3133.6* | 6874.72 | 6964.65 | *6919.68* | 1.30 |
| 8000 | 2.5216 | 60.18 | 51.55 | 26.96 | 20.17 | 32.29 | 183 | 1794.7 | 403 | *3946.3* | 7221.65 | 7141.65 | *7181.65* | 1.11 |
| 9000 | 2.8358 | 59.63 | 50.63 | 26.75 | 20.41 | 31.53 | 185 | 1812.9 | 501 | *4906.0* | 7527.67 | 7499.27 | *7513.47* | 0.38 |
| 10000 | 3.1760 | 60.21 | 50.89 | 26.21 | 20.26 | 32.28 | 184 | 1803.8 | 605 | *5924.4* | 7801.41 | 7879.04 | *7840.22* | 0.99 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.874 | 70.33 | 59.58 | 33.97 | 20.18 | 37.86 | 68.5 | 670.76 | 63 | *616.92* | 5059.26 | 5022.89 | *5041.07* | 0.72 |
| 4000 | 1.1900 | 70.14 | 58.19 | 31.75 | 20.50 | 38.04 | 68.5 | 670.76 | 99 | *969.45* | 5624.80 | 5580.44 | *5602.62* | 0.79 |
| 5000 | 1.5141 | 69.78 | 56.90 | 30.17 | 20.49 | 37.99 | 69.4 | 679.82 | 163 | *1596.2* | 6063.46 | 6110.61 | *6087.04* | 0.77 |
| 6000 | 1.8449 | 69.72 | 56.08 | 28.82 | 20.48 | 38.19 | 70.3 | 688.89 | 233 | *2281.6* | 6421.88 | 6416.29 | *6419.09* | 0.09 |
| 7000 | 2.1795 | 69.72 | 55.43 | 27.71 | 20.49 | 38.37 | 70.3 | 688.89 | 310 | *3035.6* | 6724.91 | 6562.84 | *6643.88* | 2.44 |
| 8000 | 2.5026 | 69.83 | 54.99 | 27.32 | 20.47 | 38.37 | 70.3 | 688.89 | 402 | *3936.5* | 6987.42 | 7149.81 | *7068.61* | 2.30 |
| 9000 | 2.8358 | 70.00 | 54.66 | 26.66 | 20.50 | 38.57 | 69.4 | 679.82 | 505 | *4945.2* | 7218.96 | 7286.36 | *7252.66* | 0.93 |
| 10000 | 3.1783 | 69.93 | 54.15 | 25.96 | 20.45 | 38.61 | 70.3 | 688.89 | 609 | *5963.6* | 7426.08 | 7305.26 | *7365.67* | 1.64 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | | | |
| 3000 | 0.8478 | 69.73 | 62.62 | 36.64 | 20.33 | 37.50 | 178 | 1740.4 | 58 | *567.96* | 5948.00 | 5760.04 | *5854.02* | 3.21 |
| 4000 | 1.1530 | 69.77 | 61.39 | 34.65 | 20.48 | 37.94 | 179 | 1749.4 | 103 | *1008.6* | 7010.17 | 6807.78 | *6908.98* | 2.93 |
| 5000 | 1.4811 | 70.01 | 60.65 | 32.52 | 20.12 | 38.99 | 179 | 1749.4 | 150 | *1468.9* | 7834.05 | 7655.11 | *7744.58* | 2.31 |
| 6000 | 1.8110 | 69.66 | 59.49 | 31.04 | 19.91 | 39.10 | 180 | 1758.5 | 218 | *2134.7* | 8507.22 | 8403.49 | *8455.35* | 1.23 |
| 7000 | 2.1126 | 70.41 | 59.56 | 30.55 | 20.41 | 39.51 | 180 | 1758.5 | 300 | *2937.7* | 9076.37 | 8931 | *9003.68* | 1.61 |
| 8000 | 2.4441 | 70.22 | 58.78 | 29.77 | 20.10 | 39.56 | 181 | 1767.5 | 382 | *3740.7* | 9569.39 | 9854.98 | *9712.19* | 2.94 |
| 9000 | 2.7920 | 70.33 | 58.37 | 28.64 | 19.88 | 40.07 | 181 | 1767.5 | 479 | *4690.6* | 10004.3 | 10200 | *10102.2* | 1.94 |
| 10000 | 3.1077 | 70.02 | 57.60 | 28.19 | 20.18 | 39.58 | 181 | 1767.5 | 565 | *5532.7* | 10393.3 | 10387 | *10390.2* | 0.06 |

**Table C-19:** Predicted Results ($Re_{s,c}$, Pr, $f$, h, Nu and empirical values of $f_{s,i}$, and $Nu_{s,i}$) for Tube-Side Heat Transfer Enhancement for Two Sizes of Inner Tube (Enhancement Status: Smooth Tube).

| Re Inner tube | $U_o$ W/m².C | Annulus (smooth)† | | | | | Inner Tube (smooth) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Empirical | |
| | | $Re_{s,c}$ | $Pr_c$ | $f_{s,o}$ | $Nu_s$ | $h_{s,o}$ W/m².C | $Pr_h$ | $f_{s,i}$ | $h_{s,i}$ W/m².C | $Nu_{s,i}$ | $f_{s,i}$ | $Nu_{s,i}$ |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 511.81 | 3226.3 | 6.7748 | 0.0474 | 26.14 | 1014 | 3.2351 | 0.0412 | 1176.7 | 20.03 | 0.0386 | 16.4 |
| 10000 | 645.6 | 3243.8 | 6.7342 | 0.0474 | 26.29 | 1020.5 | 3.154 | 0.036 | 2004 | 34.03 | 0.0315 | 32.4 |
| 15000 | 728.52 | 3248.1 | 6.7243 | 0.0444 | 25.26 | 980.48 | 3.1132 | 0.0309 | 3240 | 54.95 | 0.0282 | 46.9 |
| 20000 | 725.35 | 3287.9 | 6.6337 | 0.0414 | 24.46 | 950.95 | 3.0749 | 0.0285 | 3496 | 59.23 | 0.0262 | 60.5 |
| 25000 | 763.91 | 3262.5 | 6.6912 | 0.0414 | 24.26 | 942.45 | 3.0739 | 0.0255 | 4619.8 | 78.26 | 0.0247 | 73.7 |
| 30000 | 827.31 | 3296.5 | 6.6144 | 0.0444 | 25.65 | 997.53 | 3.0479 | 0.0259 | 5563.6 | 94.18 | 0.0236 | 86.4 |
| 35000 | 807.7 | 3285.2 | 6.6398 | 0.0414 | 24.44 | 950.03 | 3.043 | 0.0242 | 6193.4 | 104.8 | 0.0228 | 98.8 |
| 40000 | 853.46 | 3292.6 | 6.6231 | 0.0444 | 25.62 | 996.15 | 3.0392 | 0.0237 | 6852.9 | 116 | 0.0221 | 111 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 761.14 | 4835.3 | 6.7812 | 0.046 | 44.24 | 1716 | 3.3368 | 0.0405 | 1558.7 | 26.6 | 0.0386 | 16.5 |
| 10000 | 914.55 | 4860.4 | 6.7423 | 0.0447 | 43.62 | 1692.9 | 3.2117 | 0.0341 | 2269.5 | 38.6 | 0.0315 | 32.5 |
| 15000 | 1060.7 | 4924.2 | 6.6451 | 0.0447 | 44.12 | 1714.7 | 3.1583 | 0.0309 | 3177.8 | 53.96 | 0.0282 | 47 |
| 20000 | 1158.1 | 4931.3 | 6.6345 | 0.0447 | 44.17 | 1717.1 | 3.1347 | 0.0285 | 4071.5 | 69.1 | 0.0262 | 60.7 |
| 25000 | 1213.3 | 4904.3 | 6.6752 | 0.0447 | 43.96 | 1707.9 | 3.1105 | 0.0274 | 4801.2 | 81.42 | 0.0247 | 73.8 |
| 30000 | 1258.1 | 4968.9 | 6.5787 | 0.0447 | 44.46 | 1729.9 | 3.0848 | 0.0256 | 5290.9 | 89.66 | 0.0236 | 86.5 |
| 35000 | 1314.1 | 4970.7 | 6.5761 | 0.0447 | 44.48 | 1730.5 | 3.0731 | 0.0244 | 6274.5 | 106.3 | 0.0228 | 99 |
| 40000 | 1347.1 | 4988.4 | 6.5501 | 0.0447 | 44.61 | 1736.5 | 3.0633 | 0.0235 | 6910.6 | 117 | 0.0221 | 111 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 563.46 | 3250.4 | 6.7189 | 0.0474 | 26.35 | 1023 | 2.8678 | 0.0399 | 1429 | 24.06 | 0.0386 | 16.3 |
| 10000 | 686.43 | 3298.9 | 6.6091 | 0.0473 | 26.77 | 1040.9 | 2.7457 | 0.0349 | 2300.1 | 38.59 | 0.0315 | 32 |
| 15000 | 743.39 | 3298.1 | 6.6109 | 0.0473 | 26.76 | 1040.6 | 2.6987 | 0.0325 | 2973.5 | 49.82 | 0.0282 | 46.3 |
| 20000 | 798.64 | 3324 | 6.5536 | 0.0473 | 26.98 | 1050.1 | 2.6668 | 0.0287 | 3815.7 | 63.87 | 0.0262 | 59.6 |
| 25000 | 776.84 | 3301.2 | 6.6039 | 0.0414 | 24.57 | 955.39 | 2.6297 | 0.027 | 4763.5 | 79.65 | 0.0247 | 72.4 |
| 30000 | 803.14 | 3309.1 | 6.5865 | 0.0414 | 24.63 | 958 | 2.6189 | 0.0258 | 5703.1 | 95.34 | 0.0236 | 84.9 |
| 35000 | 819.56 | 3342.5 | 6.5132 | 0.0414 | 24.88 | 969.1 | 2.5997 | 0.0247 | 6100.8 | 101.9 | 0.0228 | 96.9 |
| 40000 | 826.97 | 3332.7 | 6.5346 | 0.0414 | 24.81 | 965.83 | 2.6001 | 0.0239 | 6612.7 | 110.5 | 0.0221 | 109 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 768.13 | 4827.7 | 6.793 | 0.0474 | 44.99 | 1744.6 | 2.9604 | 0.0394 | 1563.8 | 26.4 | 0.0386 | 16.3 |
| 10000 | 914.63 | 4879.1 | 6.7135 | 0.0447 | 43.76 | 1699.3 | 2.818 | 0.0353 | 2259.9 | 38 | 0.0315 | 32.1 |
| 15000 | 1052 | 4910.1 | 6.6663 | 0.0447 | 44.01 | 1709.9 | 2.7523 | 0.0304 | 3124 | 52.43 | 0.0282 | 46.3 |
| 20000 | 1122.7 | 4941.3 | 6.6196 | 0.0447 | 44.25 | 1720.5 | 2.7027 | 0.0288 | 3696 | 61.93 | 0.0262 | 59.7 |
| 25000 | 1216 | 4985.4 | 6.5544 | 0.0447 | 44.59 | 1735.5 | 2.6862 | 0.0268 | 4653.9 | 77.95 | 0.0247 | 72.6 |
| 30000 | 1256.7 | 4964.2 | 6.5856 | 0.0447 | 44.43 | 1728.3 | 2.6586 | 0.0256 | 5283.3 | 88.42 | 0.0236 | 85 |
| 35000 | 1306.2 | 5001.4 | 6.5312 | 0.0447 | 44.71 | 1740.9 | 2.6488 | 0.0246 | 6007.2 | 100.5 | 0.0228 | 97.1 |
| 40000 | 1350.5 | 4998.4 | 6.5355 | 0.0447 | 44.69 | 1739.9 | 2.634 | 0.0241 | 6940.3 | 116.1 | 0.0221 | 109 |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 486.53 | 3017.5 | 6.7405 | 0.0573 | 25.63 | 1233.4 | 3.2329 | 0.0424 | 890.99 | 19.3 | 0.0386 | 16.6 |
| 10000 | 692.47 | 3056.1 | 6.646 | 0.0573 | 26 | 1252.9 | 3.1635 | 0.0328 | 1719.2 | 37.16 | 0.0315 | 32.7 |
| 15000 | 771.21 | 3080.1 | 6.5882 | 0.0573 | 26.23 | 1265.1 | 3.1169 | 0.0315 | 2195.7 | 47.4 | 0.0282 | 47.2 |
| 20000 | 860.01 | 3109.1 | 6.5201 | 0.0537 | 25.43 | 1228.1 | 3.0927 | 0.0291 | 3194.7 | 68.92 | 0.0262 | 61 |
| 25000 | 897.84 | 3117.5 | 6.5004 | 0.0537 | 25.51 | 1232.2 | 3.0641 | 0.0275 | 3687.5 | 79.48 | 0.0247 | 74.2 |
| 30000 | 899.09 | 3120.4 | 6.4936 | 0.0501 | 24.43 | 1180.2 | 3.0672 | 0.0262 | 4210.6 | 90.77 | 0.0236 | 87.1 |
| 35000 | 936.47 | 3122.3 | 6.4894 | 0.0501 | 24.45 | 1181.1 | 3.0443 | 0.0245 | 5051.8 | 108.8 | 0.0228 | 99.5 |
| 40000 | 949.37 | 3128.1 | 6.4758 | 0.0501 | 24.5 | 1183.7 | 3.0428 | 0.0243 | 5359.7 | 115.5 | 0.0221 | 112 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 562.83 | 4458.5 | 6.8546 | 0.0462 | 38.49 | 1849.2 | 3.2697 | 0.0433 | 897.2 | 19.45 | 0.0386 | 16.6 |
| 10000 | 841.98 | 4532.8 | 6.7297 | 0.0462 | 39.07 | 1880.5 | 3.2059 | 0.032 | 1693.1 | 36.64 | 0.0315 | 32.7 |
| 15000 | 1037.7 | 4591.7 | 6.6337 | 0.0462 | 39.52 | 1905.2 | 3.1516 | 0.0323 | 2534.5 | 54.77 | 0.0282 | 47.3 |
| 20000 | 1140.8 | 4621.8 | 6.5856 | 0.0462 | 39.75 | 1917.7 | 3.1198 | 0.029 | 3135.3 | 67.69 | 0.0262 | 61.1 |
| 25000 | 1208 | 4605.4 | 6.6118 | 0.0462 | 39.63 | 1910.9 | 3.1076 | 0.0258 | 3659.7 | 78.98 | 0.0247 | 74.3 |
| 30000 | 1258.9 | 4629.5 | 6.5735 | 0.0446 | 38.92 | 1877.8 | 3.1013 | 0.0263 | 4261.6 | 91.96 | 0.0236 | 87.2 |
| 35000 | 1321.7 | 4661.9 | 6.5226 | 0.0446 | 39.16 | 1890.9 | 3.0716 | 0.0244 | 4903.2 | 105.7 | 0.0228 | 99.7 |
| 40000 | 1349.6 | 4671.3 | 6.5081 | 0.043 | 38.31 | 1850.5 | 3.0687 | 0.0242 | 5576.2 | 120.2 | 0.0221 | 112 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 488.8 | 3025.9 | 6.7198 | 0.0573 | 25.71 | 1237.6 | 2.8173 | 0.0444 | 895.88 | 19.17 | 0.0386 | 16.4 |
| 10000 | 675.55 | 3077.6 | 6.5943 | 0.0537 | 25.15 | 1213 | 2.7288 | 0.0321 | 1693.2 | 36.14 | 0.0315 | 32.3 |
| 15000 | 779.17 | 3106.5 | 6.5261 | 0.0537 | 25.41 | 1226.9 | 2.6884 | 0.0303 | 2373.9 | 50.61 | 0.0282 | 46.6 |
| 20000 | 850.99 | 3135.1 | 6.4598 | 0.0537 | 25.67 | 1240.7 | 2.6546 | 0.0309 | 3015.9 | 64.23 | 0.0262 | 60 |
| 25000 | 898.59 | 3151.3 | 6.4228 | 0.0537 | 25.81 | 1248.4 | 2.6448 | 0.0268 | 3573 | 76.08 | 0.0247 | 73 |
| 30000 | 950.07 | 3168.3 | 6.3846 | 0.0537 | 25.97 | 1256.5 | 2.6167 | 0.0259 | 4346.3 | 92.47 | 0.0236 | 85.5 |
| 35000 | 940.73 | 3148.4 | 6.4295 | 0.0501 | 24.67 | 1193 | 2.6096 | 0.0244 | 4970 | 105.7 | 0.0228 | 97.7 |
| 40000 | 977.3 | 3163.1 | 6.3962 | 0.0501 | 24.8 | 1199.7 | 2.6012 | 0.0232 | 5899.1 | 125.4 | 0.0221 | 110 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 578.8 | 4525.2 | 6.7423 | 0.0446 | 38.14 | 1835.3 | 2.8544 | 0.0434 | 937.56 | 20.09 | 0.0386 | 16.4 |
| 10000 | 809.17 | 4571 | 6.6672 | 0.0446 | 38.48 | 1854 | 2.7853 | 0.0351 | 1594.2 | 34.08 | 0.0315 | 32.3 |
| 15000 | 1021.5 | 4610.3 | 6.6039 | 0.0446 | 38.78 | 1870 | 2.745 | 0.0311 | 2503.9 | 53.47 | 0.0282 | 46.7 |
| 20000 | 1123.1 | 4664.7 | 6.5184 | 0.0446 | 39.18 | 1892 | 2.7052 | 0.0288 | 3076.6 | 65.62 | 0.0262 | 60.1 |
| 25000 | 1211.1 | 4681.2 | 6.4928 | 0.043 | 38.39 | 1854.3 | 2.6777 | 0.0252 | 3892.3 | 82.95 | 0.0247 | 73.1 |
| 30000 | 1241.2 | 4706.6 | 6.4539 | 0.043 | 38.57 | 1864.3 | 2.6612 | 0.0246 | 4141.8 | 88.23 | 0.0236 | 85.6 |
| 35000 | 1315.7 | 4723.7 | 6.4279 | 0.043 | 38.69 | 1871 | 2.6421 | 0.0246 | 4951.9 | 105.4 | 0.0228 | 97.8 |
| 40000 | 1342.9 | 4723.1 | 6.4287 | 0.0414 | 37.75 | 1825.2 | 2.6264 | 0.0241 | 5683.5 | 120.9 | 0.0221 | 110 |

†Predicted values of smooth annulus are used to complete calculations only.

**Table C-20:** Predicted Results ($Re_{s,c}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Tube-Side Heat Transfer Enhancement for Two Sizes of Inner Tube (Enhancement Status: : Wire Coil, e=1 mm, p= 10 mm).

| Re Inner tube | $U_o$ W/m².C | Annulus (smooth)† | | | | | Inner Tube (augmented) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Augmentation†† | |
| | | $Re_{s,c}$ | $Pr_c$ | $f_{s,o}$ | $Nu_s$ | $h_{s,o}$ W/m².C | $Pr_h$ | $f_a$ | $h_{a,i}$ W/m².C | $Nu_a$ | $f_a/f_s$ | $Nu_a/Nu_s$ |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 786.85 | 3275 | 6.6628 | 0.0562 | 29.64 | 1151.9 | 3.3582 | *0.2012* | 2835.7 | *48.42* | *4.8781* | *2.3445* |
| 10000 | 907.89 | 3302.4 | 6.6013 | 0.0533 | 28.9 | 1123.9 | 3.1954 | *0.1912* | 5418.4 | *92.11* | *5.5049* | *2.2799* |
| 15000 | 932.77 | 3305.9 | 6.5934 | 0.0533 | 28.93 | 1125.4 | 3.1553 | *0.1855* | 6262.5 | *106.3* | *5.9082* | *2.2431* |
| 20000 | 1039.7 | 3314.6 | 6.5743 | 0.0562 | 30.03 | 1168.4 | 3.1248 | *0.1815* | 10936 | *185.5* | *6.2122* | *2.2174* |
| 25000 | 995.46 | 3311.8 | 6.5804 | 0.0533 | 28.99 | 1127.7 | 3.0861 | *0.1785* | 9813.1 | *166.3* | *6.4587* | *2.1976* |
| 30000 | 1001.7 | 3312.2 | 6.5795 | 0.0533 | 28.99 | 1127.9 | 3.0615 | *0.1761* | 10358 | *175.4* | *6.6674* | *2.1816* |
| 35000 | 1028.2 | 3332.3 | 6.5355 | 0.0533 | 29.18 | 1135.9 | 3.0535 | *0.1731* | 12596 | *213.3* | *6.8491* | *2.1682* |
| 40000 | 1045.6 | 3319.7 | 6.5631 | 0.0533 | 29.06 | 1130.9 | 3.0443 | *0.1729* | 16214 | *274.4* | *7.0105* | *2.1567* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 1051.4 | 4863.9 | 6.7369 | 0.0474 | 45.28 | 1757.6 | 3.4344 | *0.1979* | 2989.5 | *51.16* | | |
| 10000 | 1244.6 | 4909.6 | 6.6672 | 0.0474 | 45.65 | 1773.9 | 3.2806 | *0.1976* | 4780.5 | *81.46* | | |
| 15000 | 1380.3 | 4936.6 | 6.6266 | 0.0473 | 45.87 | 1783.5 | 3.2078 | *0.1839* | 7024.7 | *119.5* | | |
| 20000 | 1446.7 | 4960.7 | 6.5908 | 0.0473 | 46.07 | 1792.1 | 3.1651 | *0.1805* | 8661.7 | *147.1* | | |
| 25000 | 1455.9 | 4968.3 | 6.5795 | 0.046 | 45.3 | 1762.4 | 3.1336 | *0.1773* | 9674.6 | *164.2* | | |
| 30000 | 1503.7 | 4974.2 | 6.5709 | 0.046 | 45.35 | 1764.5 | 3.1112 | *0.1758* | 11803 | *200.2* | | |
| 35000 | 1512.5 | 5010.2 | 6.5184 | 0.0447 | 44.78 | 1743.9 | 3.0906 | *0.1738* | 13256 | *224.7* | | |
| 40000 | 1572.2 | 4988.4 | 6.5501 | 0.046 | 45.46 | 1769.4 | 3.0861 | *0.1721* | 16497 | *279.6* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 791.22 | 3297.7 | 6.6118 | 0.0533 | 28.85 | 1122.1 | 2.9526 | *0.2054* | 3066 | *51.76* | | *2.3418* |
| 10000 | 907.49 | 3350.8 | 6.4953 | 0.0533 | 29.35 | 1143.3 | 2.7883 | *0.1977* | 5044.9 | *84.75* | | *2.2771* |
| 15000 | 945.03 | 3348.4 | 6.5004 | 0.0533 | 29.33 | 1142.3 | 2.7173 | *0.1846* | 6286.7 | *105.4* | | *2.2402* |
| 20000 | 957.63 | 3357.5 | 6.4809 | 0.0503 | 28.35 | 1104.7 | 2.6703 | *0.1827* | 8295.4 | *138.9* | | *2.2144* |
| 25000 | 1036.9 | 3361 | 6.4733 | 0.0533 | 29.44 | 1147.4 | 2.6508 | *0.1794* | 12511 | *209.3* | | *2.1947* |
| 30000 | 1028.3 | 3374 | 6.4456 | 0.0533 | 29.56 | 1152.5 | 2.6402 | *0.1773* | 11057 | *185* | | *2.1787* |
| 35000 | 1011.3 | 3373.7 | 6.4463 | 0.0503 | 28.49 | 1110.9 | 2.6224 | *0.1753* | 13123 | *219.4* | | *2.1652* |
| 40000 | 1019.1 | 3376.6 | 6.4402 | 0.0503 | 28.52 | 1112 | 2.607 | *0.1738* | 14223 | *237.7* | | *2.1537* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 1044.9 | 4870.9 | 6.7261 | 0.0447 | 43.7 | 1696.5 | 3.0464 | *0.2078* | 3108.4 | *52.62* | | |
| 10000 | 1242.1 | 4956 | 6.5978 | 0.0473 | 46.03 | 1790.4 | 2.8687 | *0.1926* | 4646.9 | *78.25* | | |
| 15000 | 1393.6 | 4971.9 | 6.5743 | 0.0473 | 46.16 | 1796 | 2.7926 | *0.1823* | 7157.9 | *120.3* | | |
| 20000 | 1454 | 4981.9 | 6.5596 | 0.0473 | 46.24 | 1799.6 | 2.7502 | *0.1822* | 8738 | *146.6* | | |
| 25000 | 1580.7 | 5041 | 6.4741 | 0.046 | 45.87 | 1787.6 | 2.7137 | *0.178* | 15960 | *267.5* | | |
| 30000 | 1504.1 | 5000.8 | 6.5321 | 0.046 | 45.56 | 1773.7 | 2.6873 | *0.1761* | 11475 | *192.2* | | |
| 35000 | 1526.3 | 5038 | 6.4784 | 0.0447 | 44.99 | 1753.3 | 2.663 | *0.1754* | 13720 | *229.6* | | |
| 40000 | 1532.9 | 5055.2 | 6.4539 | 0.0447 | 45.13 | 1759.1 | 2.6484 | *0.1729* | 13876 | *232.2* | | |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 766.74 | 3038.2 | 6.6894 | 0.0501 | 23.72 | 1142.5 | 3.3561 | *0.1888* | 2593.3 | *56.36* | *4.7541* | *2.4296* |
| 10000 | 855.46 | 3054.6 | 6.6495 | 0.0501 | 23.86 | 1150 | 3.1959 | *0.1692* | 3722.4 | *80.54* | *5.365* | *2.3626* |
| 15000 | 930.19 | 3072.5 | 6.6065 | 0.0501 | 24.02 | 1158.2 | 3.1486 | *0.1706* | 5280.1 | *114.1* | *5.7581* | *2.3246* |
| 20000 | 973.73 | 3100.3 | 6.5407 | 0.0501 | 24.26 | 1171 | 3.1063 | *0.1678* | 6474.1 | *139.7* | *6.0543* | *2.2979* |
| 25000 | 990.64 | 3092.9 | 6.5579 | 0.0483 | 23.64 | 1140.6 | 3.0869 | *0.1665* | 8467 | *182.6* | *6.2946* | *2.2775* |
| 30000 | 1037.5 | 3136.6 | 6.4564 | 0.0501 | 24.57 | 1187.6 | 3.0752 | *0.1621* | 9237.1 | *199.2* | *6.498* | *2.2609* |
| 35000 | 1010.3 | 3135.9 | 6.4581 | 0.0465 | 23.42 | 1131.8 | 3.0446 | *0.1608* | 10614 | *228.6* | *6.675* | *2.247* |
| 40000 | 1023.9 | 3134.4 | 6.4615 | 0.0465 | 23.4 | 1131.2 | 3.0476 | *0.159* | 12213 | *263.1* | *6.8323* | *2.2351* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 952.24 | 4529 | 6.736 | 0.043 | 37.28 | 1794.2 | 3.4123 | *0.1834* | 2255.7 | *49.1* | | |
| 10000 | 1187.8 | 4582.4 | 6.6486 | 0.043 | 37.67 | 1815.4 | 3.2543 | *0.1731* | 3829.7 | *83* | | |
| 15000 | 1318.4 | 4613.6 | 6.5987 | 0.043 | 37.9 | 1827.7 | 3.1976 | *0.1717* | 5288.2 | *114.4* | | |
| 20000 | 1390.1 | 4632.8 | 6.5683 | 0.0422 | 37.58 | 1813.1 | 3.1508 | *0.1665* | 6674.7 | *144.2* | | |
| 25000 | 1474.5 | 4659.2 | 6.5269 | 0.0414 | 37.3 | 1800.9 | 3.1251 | *0.165* | 9156.3 | *197.7* | | |
| 30000 | 1471.1 | 4697.2 | 6.4682 | 0.0398 | 36.61 | 1769.4 | 3.094 | *0.1613* | 9832.7 | *212.1* | | |
| 35000 | 1485.9 | 4713.7 | 6.443 | 0.0398 | 36.72 | 1775.5 | 3.0835 | *0.1606* | 10272 | *221.5* | | |
| 40000 | 1521.6 | 4689.5 | 6.4801 | 0.0398 | 36.56 | 1766.5 | 3.076 | *0.1601* | 12425 | *267.9* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 731.83 | 3060.8 | 6.6345 | 0.0501 | 23.92 | 1152.9 | 2.928 | *0.1885* | 2227.4 | *47.82* | | *2.4267* |
| 10000 | 857.18 | 3095.9 | 6.551 | 0.0501 | 24.22 | 1169 | 2.7943 | *0.1743* | 3580.9 | *76.58* | | *2.3598* |
| 15000 | 953.99 | 3127 | 6.4784 | 0.0501 | 24.49 | 1183.2 | 2.7249 | *0.1716* | 5505.4 | *117.5* | | *2.3216* |
| 20000 | 995.64 | 3159.4 | 6.4045 | 0.0501 | 24.76 | 1198 | 2.6735 | *0.1693* | 6603.3 | *140.7* | | *2.2948* |
| 25000 | 1027.1 | 3154.3 | 6.4162 | 0.0501 | 24.72 | 1195.6 | 2.6448 | *0.166* | 8187.7 | *174.3* | | *2.2743* |
| 30000 | 1004.2 | 3145.4 | 6.4362 | 0.0465 | 23.49 | 1135.9 | 2.6351 | *0.1621* | 9752.2 | *207.6* | | *2.2578* |
| 35000 | 1026.6 | 3175 | 6.3697 | 0.0465 | 23.73 | 1148.6 | 2.6224 | *0.1611* | 10905 | *232* | | *2.2439* |
| 40000 | 1052.6 | 3188.6 | 6.3393 | 0.0465 | 23.84 | 1154.5 | 2.6125 | *0.1594* | 13529 | *287.8* | | *2.2319* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 963.3 | 4586.8 | 6.6416 | 0.043 | 37.7 | 1817.1 | 2.9973 | *0.188* | 2279.1 | *49.03* | | |
| 10000 | 1178.7 | 4661.9 | 6.5226 | 0.043 | 38.25 | 1846.8 | 2.852 | *0.1779* | 3630.8 | *77.78* | | |
| 15000 | 1329.4 | 4658.1 | 6.5286 | 0.0414 | 37.29 | 1800.4 | 2.7794 | *0.1711* | 5682.5 | *121.5* | | |
| 20000 | 1420.3 | 4703.2 | 6.4589 | 0.0414 | 37.61 | 1817.7 | 2.7324 | *0.1681* | 7286.8 | *155.5* | | |
| 25000 | 1468.1 | 4737.5 | 6.407 | 0.043 | 38.79 | 1876.4 | 2.6971 | *0.1654* | 7570.5 | *161.4* | | |
| 30000 | 1461.3 | 4744.7 | 6.3962 | 0.0398 | 36.93 | 1786.9 | 2.673 | *0.1629* | 9024.8 | *192.3* | | |
| 35000 | 1543.8 | 4755.8 | 6.3796 | 0.0398 | 37.01 | 1791 | 2.6552 | *0.161* | 12668 | *269.8* | | |
| 40000 | 1546 | 4790.7 | 6.3279 | 0.0398 | 37.24 | 1803.8 | 2.6413 | *0.1591* | 12240 | *260.6* | | |

†Predicted values of smooth annulus are used to complete calculations only.

††Augmentation values are predicted by using the proposed correlations and not experimental results.

**Table C-21:** Predicted Results ($Re_{s,c}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Tube-Side Heat Transfer Enhancement for Two Sizes of Inner Tube (Enhancement Status: : Wire Coil, e=1 mm, p= 20 mm).

| **Re** Inner tube | **$U_o$** W/m².C | **Annulus (smooth)**† | | | | | **Inner Tube (augmented)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **$Re_{s,c}$** | **$Pr_c$** | **$f_{s,o}$** | **$Nu_s$** | **$h_{s,o}$** W/m².C | **$Pr_h$** | **$f_a$** | **$h_{a,i}$** W/m².C | **$Nu_a$** | **Augmentation**†† **$f_a/f_s$** | **Augmentation**†† **$Nu_a/Nu_s$** |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 755.43 | 3242.6 | 6.7369 | 0.0533 | 28.34 | 1099.9 | 3.3471 | *0.1215* | 2754.4 | *47.02* | *2.8298* | *1.8353* |
| 10000 | 862.27 | 3293.8 | 6.6205 | 0.0533 | 28.82 | 1120.5 | 3.2062 | *0.1088* | 4284.1 | *72.85* | *3.1934* | *1.7848* |
| 15000 | 829.95 | 3293.8 | 6.6205 | 0.0503 | 27.78 | 1080.3 | 3.1344 | *0.1083* | 4099.8 | *69.57* | *3.4274* | *1.7559* |
| 20000 | 938.58 | 3303.6 | 6.5987 | 0.0533 | 28.91 | 1124.4 | 3.1155 | *0.1047* | 6528 | *110.7* | *3.6038* | *1.7358* |
| 25000 | 971.27 | 3293.8 | 6.6205 | 0.0533 | 28.82 | 1120.5 | 3.082 | *0.1025* | 8411.5 | *142.5* | *3.7468* | *1.7203* |
| 30000 | 998.66 | 3306.3 | 6.5926 | 0.0533 | 28.93 | 1125.5 | 3.0757 | *0.0991* | 10252 | *173.7* | *3.8678* | *1.7079* |
| 35000 | 983.87 | 3322.4 | 6.557 | 0.0503 | 28.04 | 1091.3 | 3.0525 | *0.0988* | 11594 | *196.3* | *3.9732* | *1.6974* |
| 40000 | 979.44 | 3305.5 | 6.5943 | 0.0503 | 27.89 | 1084.8 | 3.0589 | *0.0974* | 11699 | *198.1* | *4.0668* | *1.6884* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 1033.8 | 4854 | 6.7522 | 0.0474 | 45.2 | 1754 | 3.4104 | *0.1252* | 2875.3 | *49.17* | | |
| 10000 | 1219.3 | 4896.7 | 6.6867 | 0.046 | 44.73 | 1737.5 | 3.2663 | *0.1128* | 4684.5 | *79.79* | | |
| 15000 | 1206 | 4916.6 | 6.6566 | 0.0447 | 44.06 | 1712.1 | 3.1798 | *0.1104* | 4675.4 | *79.44* | | |
| 20000 | 1384.2 | 4928.3 | 6.6389 | 0.0473 | 45.81 | 1780.6 | 3.1459 | *0.1061* | 7155.2 | *121.5* | | |
| 25000 | 1437.5 | 4947.1 | 6.6109 | 0.046 | 45.13 | 1755.1 | 3.1187 | *0.1033* | 9174.1 | *155.6* | | |
| 30000 | 1427.9 | 4923.1 | 6.6469 | 0.046 | 44.94 | 1746.7 | 3.1092 | *0.0994* | 9034.1 | *153.2* | | |
| 35000 | 1490.1 | 4951.3 | 6.6048 | 0.046 | 45.16 | 1756.5 | 3.084 | *0.0993* | 11388 | *193* | | |
| 40000 | 1508.6 | 4950.7 | 6.6056 | 0.046 | 45.16 | 1756.3 | 3.0685 | *0.0983* | 12422 | *210.4* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 744.22 | 3298.1 | 6.6109 | 0.0503 | 27.82 | 1081.9 | 2.9266 | *0.1171* | 2722.5 | *45.92* | | *1.8332* |
| 10000 | 842.93 | 3313 | 6.5778 | 0.0533 | 29 | 1128.2 | 2.7826 | *0.1122* | 3814 | *64.06* | | *1.7825* |
| 15000 | 882.14 | 3315 | 6.5735 | 0.0503 | 27.97 | 1088.4 | 2.7081 | *0.1104* | 5339.6 | *89.49* | | *1.7536* |
| 20000 | 960.98 | 3331.9 | 6.5364 | 0.0533 | 29.17 | 1135.7 | 2.6692 | *0.1048* | 7187.8 | *120.3* | | *1.7335* |
| 25000 | 972.72 | 3354.3 | 6.4877 | 0.0533 | 29.38 | 1144.7 | 2.6452 | *0.1024* | 7454.9 | *124.7* | | *1.718* |
| 30000 | 963.03 | 3361 | 6.4733 | 0.0503 | 28.38 | 1106 | 2.632 | *0.0997* | 8592.9 | *143.7* | | *1.7055* |
| 35000 | 985.94 | 3365.4 | 6.464 | 0.0503 | 28.42 | 1107.7 | 2.6209 | *0.0989* | 10381 | *173.5* | | *1.695* |
| 40000 | 1003.1 | 3361 | 6.4733 | 0.0503 | 28.38 | 1106 | 2.6039 | *0.0976* | 12515 | *209.1* | | *1.6859* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 995.35 | 4869.7 | 6.7279 | 0.0447 | 43.69 | 1696.1 | 3.0298 | *0.1238* | 2751.1 | *46.55* | | |
| 10000 | 1195.8 | 4940.7 | 6.6205 | 0.0473 | 45.91 | 1784.9 | 2.8598 | *0.1145* | 4146.8 | *69.81* | | |
| 15000 | 1282.8 | 4954.8 | 6.5995 | 0.046 | 45.19 | 1757.7 | 2.7814 | *0.1092* | 5447.9 | *91.5* | | |
| 20000 | 1391.1 | 4979.5 | 6.5631 | 0.0473 | 46.22 | 1798.7 | 2.7461 | *0.1044* | 7063.3 | *118.5* | | |
| 25000 | 1405.4 | 5006.1 | 6.5244 | 0.0447 | 44.75 | 1742.5 | 2.6971 | *0.1021* | 8378.1 | *140.4* | | |
| 30000 | 1431.4 | 4997.8 | 6.5364 | 0.0447 | 44.69 | 1739.7 | 2.6813 | *0.101* | 9331 | *156.3* | | |
| 35000 | 1466.1 | 5023.8 | 6.4987 | 0.0447 | 44.89 | 1748.5 | 2.6586 | *0.099* | 10507 | *175.8* | | |
| 40000 | 1491.4 | 5039.2 | 6.4767 | 0.0447 | 45 | 1753.7 | 2.634 | *0.0989* | 11562 | *193.4* | | |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 709.83 | 3027 | 6.7171 | 0.0501 | 23.62 | 1137.3 | 3.3268 | *0.1267* | 2098.9 | *45.58* | *2.7579* | *1.9019* |
| 10000 | 833.44 | 3053.1 | 6.653 | 0.0501 | 23.85 | 1149.3 | 3.2023 | *0.114* | 3377.5 | *73.09* | *3.1123* | *1.8495* |
| 15000 | 899.3 | 3086 | 6.5743 | 0.0519 | 24.68 | 1190.9 | 3.1403 | *0.1131* | 4095.9 | *88.48* | *3.3403* | *1.8197* |
| 20000 | 932.09 | 3100.6 | 6.5398 | 0.0501 | 24.26 | 1171.2 | 3.1047 | *0.1095* | 5101.8 | *110.1* | *3.5122* | *1.7989* |
| 25000 | 982.78 | 3118.6 | 6.4979 | 0.0501 | 24.42 | 1179.4 | 3.0809 | *0.1071* | 6604.8 | *142.4* | *3.6516* | *1.7829* |
| 30000 | 969.32 | 3121.9 | 6.4902 | 0.0465 | 23.3 | 1125.8 | 3.07 | *0.105* | 7830.9 | *168.8* | *3.7695* | *1.7699* |
| 35000 | 981 | 3138.4 | 6.4522 | 0.0465 | 23.44 | 1132.9 | 3.05 | *0.1034* | 8219.5 | *177.1* | *3.8722* | *1.759* |
| 40000 | 990.69 | 3137 | 6.4556 | 0.0465 | 23.42 | 1132.3 | 3.0418 | *0.1029* | 8911.4 | *192* | *3.9635* | *1.7497* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 953.9 | 4504.5 | 6.7766 | 0.0446 | 37.98 | 1826.9 | 3.4107 | *0.1262* | 2218.9 | *48.29* | | |
| 10000 | 1159.7 | 4600.5 | 6.6196 | 0.0446 | 38.7 | 1866 | 3.2366 | *0.1166* | 3412.8 | *73.93* | | |
| 15000 | 1287 | 4608.7 | 6.6065 | 0.0446 | 38.76 | 1869.4 | 3.1899 | *0.115* | 4611.6 | *99.76* | | |
| 20000 | 1379.6 | 4633.4 | 6.5674 | 0.043 | 38.04 | 1835.5 | 3.1575 | *0.1091* | 6218.6 | *134.4* | | |
| 25000 | 1352.1 | 4666.9 | 6.5149 | 0.0414 | 37.35 | 1803.8 | 3.1216 | *0.1067* | 6042.9 | *130.5* | | |
| 30000 | 1406.7 | 4671.3 | 6.5081 | 0.0414 | 37.38 | 1805.5 | 3.0937 | *0.1038* | 7141.1 | *154.1* | | |
| 35000 | 1458.9 | 4704.4 | 6.4573 | 0.0414 | 37.61 | 1818.1 | 3.084 | *0.1033* | 8296.5 | *178.9* | | |
| 40000 | 1467.4 | 4672.9 | 6.5056 | 0.0398 | 36.45 | 1760.4 | 3.0742 | *0.1019* | 9937.8 | *214.3* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 677.67 | 3069.5 | 6.6135 | 0.0501 | 23.99 | 1156.9 | 2.9066 | *0.1146* | 1817.2 | *38.99* | | *1.8996* |
| 10000 | 841.41 | 3117.1 | 6.5013 | 0.0501 | 24.4 | 1178.7 | 2.7858 | *0.1134* | 3274.6 | *70.01* | | *1.8473* |
| 15000 | 911.28 | 3120.1 | 6.4945 | 0.0501 | 24.43 | 1180 | 2.7202 | *0.109* | 4465.3 | *95.28* | | *1.8174* |
| 20000 | 930.62 | 3155.4 | 6.4137 | 0.0465 | 23.57 | 1140.2 | 2.6712 | *0.1079* | 5661.9 | *120.6* | | *1.7964* |
| 25000 | 980.19 | 3163.9 | 6.3945 | 0.0483 | 24.23 | 1172.2 | 2.647 | *0.1064* | 6705.7 | *142.8* | | *1.7804* |
| 30000 | 977.16 | 3174.6 | 6.3705 | 0.0465 | 23.73 | 1148.5 | 2.6293 | *0.1048* | 7348.4 | *156.4* | | *1.7675* |
| 35000 | 990.96 | 3171.6 | 6.3771 | 0.0465 | 23.7 | 1147.2 | 2.6107 | *0.1032* | 8173.7 | *173.9* | | *1.7566* |
| 40000 | 1022.8 | 3180.1 | 6.3582 | 0.0465 | 23.77 | 1150.9 | 2.6008 | *0.1021* | 10368 | *220.5* | | *1.7472* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 880.03 | 4529.5 | 6.7351 | 0.043 | 37.28 | 1794.4 | 2.9894 | *0.1235* | 1918.6 | *41.27* | | |
| 10000 | 1155.7 | 4607.6 | 6.6083 | 0.043 | 37.85 | 1825.4 | 2.8476 | *0.1149* | 3509.8 | *75.18* | | |
| 15000 | 1260 | 4647.6 | 6.545 | 0.043 | 38.14 | 1841.2 | 2.7782 | *0.1114* | 4454.4 | *95.21* | | |
| 20000 | 1313.1 | 4685.6 | 6.486 | 0.0414 | 37.48 | 1810.9 | 2.7195 | *0.1087* | 5338.2 | *113.9* | | |
| 25000 | 1383.9 | 4728.7 | 6.4203 | 0.0414 | 37.78 | 1827.3 | 2.6888 | *0.1058* | 6387 | *136.2* | | |
| 30000 | 1450.8 | 4733.6 | 6.4128 | 0.0414 | 37.82 | 1829.2 | 2.6768 | *0.1046* | 7873.8 | *167.8* | | |
| 35000 | 1495.4 | 4745.8 | 6.3945 | 0.0414 | 37.9 | 1833.9 | 2.6526 | *0.1032* | 9119.2 | *194.2* | | |
| 40000 | 1516 | 4774.1 | 6.3524 | 0.0398 | 37.13 | 1797.7 | 2.6404 | *0.1021* | 10920 | *232.5* | | |

**Table C-22:** Predicted Results ($Re_{s,c}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Tube-Side Heat Transfer Enhancement for Two Sizes of Inner Tube (Enhancement Status: : Wire Coil, e=1 mm, p= 30 mm).

| Re Inner tube | $U_o$ W/m².C | Annulus (smooth)† | | | | | Inner Tube (augmented) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Re_{s,c}$ | $Pr_c$ | $f_{s,o}$ | $Nu_s$ | $h_{s,o}$ W/m².C | $Pr_h$ | $f_a$ | $h_{a,i}$ W/m².C | $Nu_a$ | Augmentation†† | |
| | | | | | | | | | | | $f_a/f_s$ | $Nu_a/Nu_s$ |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 644.64 | 3220 | 6.7894 | 0.0474 | 26.09 | 1011.7 | 3.2976 | *0.0856* | 2026.2 | *34.54* | *2.0579* | *1.5902* |
| 10000 | 755.36 | 3256.2 | 6.7055 | 0.0474 | 26.4 | 1025.1 | 3.1765 | *0.0735* | 3280.7 | *55.74* | *2.3223* | *1.5465* |
| 15000 | 902.8 | 3266.8 | 6.6814 | 0.0503 | 27.54 | 1069.9 | 3.1465 | *0.0718* | 6647.4 | *112.8* | *2.4925* | *1.5216* |
| 20000 | 848.09 | 3269.5 | 6.6752 | 0.0474 | 26.51 | 1030 | 3.1013 | *0.0689* | 5509.1 | *93.4* | *2.6207* | *1.5042* |
| 25000 | 875.19 | 3291 | 6.6266 | 0.0473 | 26.7 | 1038 | 3.0817 | *0.0666* | 6413.5 | *108.7* | *2.7247* | *1.4908* |
| 30000 | 918.15 | 3299.7 | 6.6074 | 0.0503 | 27.84 | 1082.5 | 3.0742 | *0.0641* | 6956.1 | *117.8* | *2.8127* | *1.48* |
| 35000 | 915.12 | 3309.5 | 6.5856 | 0.0473 | 26.86 | 1044.7 | 3.0541 | *0.0632* | 8507.8 | *144* | *2.8894* | *1.4709* |
| 40000 | 928.33 | 3295.4 | 6.617 | 0.0473 | 26.73 | 1039.6 | 3.0662 | *0.0619* | 10034 | *169.9* | *2.9575* | *1.4631* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 913.34 | 4869.7 | 6.7279 | 0.0474 | 45.33 | 1759.7 | 3.3861 | *0.0902* | 2166.3 | *37.02* | | |
| 10000 | 1081 | 4896.1 | 6.6876 | 0.0474 | 45.54 | 1769.1 | 3.2456 | *0.0775* | 3175.8 | *54.06* | | |
| 15000 | 1202 | 4917.2 | 6.6557 | 0.0474 | 45.72 | 1776.6 | 3.1781 | *0.0723* | 4255.5 | *72.31* | | |
| 20000 | 1329.1 | 4938.3 | 6.624 | 0.0447 | 44.23 | 1719.5 | 3.1518 | *0.0691* | 6732.2 | *114.3* | | |
| 25000 | 1369.1 | 4951.8 | 6.6039 | 0.046 | 45.17 | 1756.7 | 3.1153 | *0.0674* | 7139.3 | *121.1* | | |
| 30000 | 1315.6 | 4937.1 | 6.6258 | 0.0447 | 44.22 | 1719.1 | 3.1121 | *0.0648* | 6442.4 | *109.3* | | |
| 35000 | 1414.5 | 4985.4 | 6.5544 | 0.0447 | 44.59 | 1735.5 | 3.0817 | *0.0633* | 8825.8 | *149.5* | | |
| 40000 | 1445.3 | 4976 | 6.5683 | 0.0447 | 44.52 | 1732.3 | 3.0739 | *0.062* | 10091 | *170.9* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 709.99 | 3250 | 6.7198 | 0.0533 | 28.41 | 1102.9 | 2.9107 | *0.0813* | 2273.9 | *38.34* | | *1.5885* |
| 10000 | 777.32 | 3305.9 | 6.5934 | 0.0473 | 26.83 | 1043.5 | 2.7591 | *0.0753* | 3484.7 | *58.49* | | *1.5446* |
| 15000 | 845.75 | 3313 | 6.5778 | 0.0503 | 27.95 | 1087.6 | 2.7 | *0.0715* | 4354.8 | *72.97* | | *1.5196* |
| 20000 | 896.04 | 3337.8 | 6.5235 | 0.0503 | 28.18 | 1097.1 | 2.6659 | *0.0688* | 5610.3 | *93.91* | | *1.5022* |
| 25000 | 905.69 | 3320.9 | 6.5605 | 0.0473 | 26.95 | 1048.9 | 2.6399 | *0.0667* | 7638.6 | *127.8* | | *1.4888* |
| 30000 | 925.14 | 3355.5 | 6.4852 | 0.0473 | 27.25 | 1061.6 | 2.618 | *0.0648* | 8298.3 | *138.7* | | *1.4779* |
| 35000 | 962.76 | 3356.7 | 6.4826 | 0.0503 | 28.34 | 1104.4 | 2.611 | *0.0633* | 8662.7 | *144.8* | | *1.4688* |
| 40000 | 945.55 | 3342.1 | 6.5141 | 0.0473 | 27.13 | 1056.7 | 2.6072 | *0.0627* | 10402 | *173.8* | | *1.461* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 951.76 | 4833 | 6.7848 | 0.0474 | 45.03 | 1746.5 | 3.0121 | *0.0834* | 2386.8 | *40.36* | | |
| 10000 | 1095.9 | 4910.7 | 6.6654 | 0.0447 | 44.01 | 1710.1 | 2.8541 | *0.0775* | 3489.2 | *58.73* | | |
| 15000 | 1178.5 | 4933.6 | 6.631 | 0.0447 | 44.19 | 1717.9 | 2.7757 | *0.0716* | 4297.5 | *72.17* | | |
| 20000 | 1349.8 | 4963 | 6.5873 | 0.0473 | 46.09 | 1792.9 | 2.7321 | *0.0699* | 6275.7 | *105.3* | | |
| 25000 | 1355.8 | 5010.8 | 6.5175 | 0.0447 | 44.79 | 1744.1 | 2.6931 | *0.0665* | 7006.2 | *117.4* | | |
| 30000 | 1372.5 | 4975.4 | 6.5691 | 0.0447 | 44.51 | 1732.1 | 2.6746 | *0.0653* | 7615.3 | *127.5* | | |
| 35000 | 1407 | 5015.5 | 6.5107 | 0.0447 | 44.82 | 1745.7 | 2.6595 | *0.0632* | 8362.6 | *140* | | |
| 40000 | 1471.3 | 5050.5 | 6.4606 | 0.0447 | 45.09 | 1757.5 | 2.6359 | *0.0631* | 10455 | *174.9* | | |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 682.13 | 3024.4 | 6.7234 | 0.0537 | 24.66 | 1187.2 | 3.3218 | *0.0911* | 1780.8 | *38.67* | *2.0057* | *1.6481* |
| 10000 | 801.92 | 3056.8 | 6.6442 | 0.0519 | 24.42 | 1177.2 | 3.1962 | *0.0822* | 2799.2 | *60.57* | *2.2634* | *1.6028* |
| 15000 | 875.53 | 3078.7 | 6.5917 | 0.0519 | 24.62 | 1187.5 | 3.1432 | *0.0812* | 3714.5 | *80.25* | *2.4292* | *1.5769* |
| 20000 | 904.54 | 3099.9 | 6.5415 | 0.0501 | 24.25 | 1170.8 | 3.1129 | *0.0752* | 4438.5 | *95.8* | *2.5542* | *1.5589* |
| 25000 | 948.1 | 3107.6 | 6.5235 | 0.0501 | 24.32 | 1174.3 | 3.082 | *0.0721* | 5502.4 | *118.7* | *2.6556* | *1.545* |
| 30000 | 970.31 | 3050.6 | 6.6592 | 0.0501 | 23.83 | 1148.2 | 3.0742 | *0.0714* | 7022.3 | *151.4* | *2.7414* | *1.5338* |
| 35000 | 963.77 | 3129.2 | 6.4733 | 0.0465 | 23.36 | 1128.9 | 3.0595 | *0.0698* | 7389.9 | *159.3* | *2.8161* | *1.5244* |
| 40000 | 983.52 | 3123.4 | 6.4868 | 0.0465 | 23.31 | 1126.4 | 3.0523 | *0.0686* | 8718.8 | *187.9* | *2.8824* | *1.5163* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 892.25 | 4507.8 | 6.7712 | 0.047 | 39.3 | 1890.7 | 3.3852 | *0.093* | 1876.9 | *40.82* | | |
| 10000 | 1065 | 4553 | 6.6965 | 0.0462 | 39.22 | 1889 | 3.2304 | *0.0854* | 2716.4 | *58.83* | | |
| 15000 | 1222.3 | 4594.5 | 6.6293 | 0.0446 | 38.66 | 1863.6 | 3.1746 | *0.0783* | 3960.8 | *85.64* | | |
| 20000 | 1303.5 | 4606.5 | 6.61 | 0.0446 | 38.75 | 1868.5 | 3.1373 | *0.0754* | 4813.9 | *104* | | |
| 25000 | 1358.8 | 4653.7 | 6.5355 | 0.043 | 38.19 | 1843.5 | 3.1198 | *0.0729* | 5781.6 | *124.8* | | |
| 30000 | 1391.5 | 4659.2 | 6.5269 | 0.043 | 38.23 | 1845.7 | 3.0934 | *0.0706* | 6331.4 | *136.6* | | |
| 35000 | 1469.1 | 4695 | 6.4716 | 0.043 | 38.48 | 1859.8 | 3.0778 | *0.0697* | 7851.9 | *169.3* | | |
| 40000 | 1469.7 | 4697.7 | 6.4674 | 0.0414 | 37.57 | 1815.6 | 3.0659 | *0.0688* | 8673.1 | *187* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| 5000 | 692 | 3049.5 | 6.6619 | 0.0537 | 24.89 | 1199.4 | 2.9032 | *0.0995* | 1817 | *38.98* | | *1.6462* |
| 10000 | 793.88 | 3091.1 | 6.5622 | 0.0537 | 25.27 | 1219.5 | 2.7759 | *0.083* | 2529.8 | *54.07* | | *1.6007* |
| 15000 | 860.6 | 3112.7 | 6.5115 | 0.0501 | 24.36 | 1176.7 | 2.7058 | *0.0792* | 3569.6 | *76.14* | | *1.5748* |
| 20000 | 923.15 | 3152.1 | 6.4212 | 0.0501 | 24.7 | 1194.6 | 2.6643 | *0.076* | 4533.9 | *96.59* | | *1.5567* |
| 25000 | 981.9 | 3159.8 | 6.4037 | 0.0501 | 24.77 | 1198.2 | 2.6426 | *0.0737* | 6088.5 | *129.6* | | *1.5429* |
| 30000 | 1007.8 | 3170.1 | 6.3805 | 0.0501 | 24.86 | 1202.9 | 2.6289 | *0.0717* | 6968.7 | *148.3* | | *1.5317* |
| 35000 | 1032.3 | 3180.5 | 6.3574 | 0.0501 | 24.94 | 1207.6 | 2.616 | *0.0696* | 7985.3 | *169.9* | | *1.5222* |
| 40000 | 1050.4 | 3196 | 6.323 | 0.0501 | 25.08 | 1214.6 | 2.5999 | *0.0692* | 8737.8 | *185.8* | | *1.5141* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| 5000 | 921.2 | 4533.9 | 6.7279 | 0.0446 | 38.2 | 1838.9 | 2.9866 | *0.0946* | 2051.2 | *44.11* | | |
| 10000 | 1058.1 | 4616.4 | 6.5943 | 0.0446 | 38.82 | 1872.5 | 2.8118 | *0.077* | 2706.6 | *57.91* | | |
| 15000 | 1200.5 | 4642.1 | 6.5536 | 0.0446 | 39.01 | 1882.9 | 2.7473 | *0.0799* | 3691.8 | *78.84* | | |
| 20000 | 1347.8 | 4704.9 | 6.4564 | 0.043 | 38.56 | 1863.6 | 2.7126 | *0.0752* | 5444.1 | *116.1* | | |
| 25000 | 1373.3 | 4708.2 | 6.4514 | 0.0446 | 39.5 | 1909.6 | 2.6897 | *0.0742* | 5466.3 | *116.5* | | |
| 30000 | 1394.2 | 4732.5 | 6.4145 | 0.043 | 38.75 | 1874.5 | 2.6626 | *0.0728* | 6090.8 | *129.7* | | |
| 35000 | 1473.6 | 4748 | 6.3912 | 0.043 | 38.87 | 1880.5 | 2.6466 | *0.0707* | 7643 | *162.7* | | |
| 40000 | 1486.5 | 4741.9 | 6.4004 | 0.0414 | 37.88 | 1832.4 | 2.6317 | *0.0693* | 8858.1 | *188.5* | | |

**Table C-23:** Predicted Results ($Re_{s,c}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Tube-Side Heat Transfer Enhancement for Two Sizes of Inner Tube (Enhancement Status: : Wire Coil, e=1 mm, p= 40 mm).

| Re Inner tube | $U_o$ W/m².C | Annulus (smooth)† | | | | | Inner Tube (augmented) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Re_{s,c}$ | $Pr_c$ | $f_{s,o}$ | $Nu_s$ | $h_{s,o}$ W/m².C | $Pr_h$ | $f_a$ | $h_{a,i}$ W/m².C | $Nu_a$ | Augmentation†† | |
| | | | | | | | | | | | $f_a/f_s$ | $Nu_a/Nu_s$ |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| **5000** | 637.34 | 3242.2 | 6.7378 | 0.0474 | 26.28 | 1019.9 | 3.3069 | *0.0682* | 1937.3 | *33.04* | *1.6416* | *1.4427* |
| **10000** | 792.68 | 3237.5 | 6.7486 | 0.0474 | 26.24 | 1018.2 | 3.1713 | *0.0594* | 4096.2 | *69.59* | *1.8525* | *1.4035* |
| **15000** | 785.94 | 3275.4 | 6.6619 | 0.0474 | 26.56 | 1032.2 | 3.1124 | *0.055* | 3768.4 | *63.91* | *1.9883* | *1.3811* |
| **20000** | 844.35 | 3282 | 6.6469 | 0.0503 | 27.68 | 1075.7 | 3.0859 | *0.0499* | 4496.3 | *76.2* | *2.0906* | *1.3655* |
| **25000** | 883.68 | 3275.4 | 6.6619 | 0.0474 | 26.56 | 1032.2 | 3.083 | *0.0493* | 7066.3 | *119.7* | *2.1735* | *1.3536* |
| **30000** | 930.94 | 3315 | 6.5735 | 0.0503 | 27.97 | 1088.4 | 3.0517 | *0.0476* | 7408.4 | *125.4* | *2.2438* | *1.3439* |
| **35000** | 870.53 | 3298.5 | 6.61 | 0.0444 | 25.67 | 998.21 | 3.0402 | *0.0461* | 7841.3 | *132.7* | *2.3049* | *1.3357* |
| **40000** | 883.88 | 3298.9 | 6.6091 | 0.0444 | 25.67 | 998.35 | 3.0494 | *0.0445* | 8897.9 | *150.6* | *2.3592* | *1.3288* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| **5000** | 898.01 | 4846.4 | 6.7639 | 0.046 | 44.33 | 1719.9 | 3.3701 | *0.0654* | 2143.6 | *36.62* | | |
| **10000** | 1142.7 | 4889.6 | 6.6974 | 0.0474 | 45.49 | 1766.8 | 3.2399 | *0.0587* | 3700.1 | *62.98* | | |
| **15000** | 1188.7 | 4916 | 6.6575 | 0.0474 | 45.71 | 1776.2 | 3.1675 | *0.0544* | 4113.9 | *69.88* | | |
| **20000** | 1213.2 | 4930.1 | 6.6363 | 0.0447 | 44.16 | 1716.7 | 3.136 | *0.0526* | 4740.7 | *80.45* | | |
| **25000** | 1366.6 | 4946.6 | 6.6118 | 0.0473 | 45.95 | 1787 | 3.1124 | *0.0493* | 6678.7 | *113.3* | | |
| **30000** | 1347.6 | 4959.5 | 6.5926 | 0.0447 | 44.39 | 1726.7 | 3.1081 | *0.0475* | 7063.1 | *119.8* | | |
| **35000** | 1389.6 | 4953.6 | 6.6013 | 0.0447 | 44.34 | 1724.7 | 3.0804 | *0.0461* | 8247.3 | *139.7* | | |
| **40000** | 1414.5 | 4951.3 | 6.6048 | 0.0447 | 44.33 | 1723.9 | 3.082 | *0.0447* | 9101.2 | *154.2* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| **5000** | 622.39 | 3250 | 6.7198 | 0.0474 | 26.35 | 1022.8 | 2.8896 | *0.0712* | 1812.4 | *30.54* | | *1.441* |
| **10000** | 743.12 | 3307.5 | 6.59 | 0.0473 | 26.84 | 1044 | 2.7582 | *0.0601* | 2945.3 | *49.43* | | *1.4018* |
| **15000** | 801.58 | 3301.2 | 6.6039 | 0.0473 | 26.79 | 1041.7 | 2.6862 | *0.0555* | 3979.3 | *66.65* | | *1.3794* |
| **20000** | 846.65 | 3312.2 | 6.5795 | 0.0473 | 26.88 | 1045.8 | 2.6577 | *0.0523* | 5098.8 | *85.33* | | *1.3637* |
| **25000** | 881.77 | 3349.2 | 6.4987 | 0.0473 | 27.19 | 1059.3 | 2.6466 | *0.0497* | 6042.8 | *101.1* | | *1.3517* |
| **30000** | 897.28 | 3354.3 | 6.4877 | 0.0473 | 27.24 | 1061.2 | 2.6191 | *0.0482* | 6679.5 | *111.7* | | *1.342* |
| **35000** | 945.67 | 3358.7 | 6.4784 | 0.0473 | 27.27 | 1062.8 | 2.6028 | *0.0461* | 9924.9 | *165.8* | | *1.3338* |
| **40000** | 922.83 | 3340.5 | 6.5175 | 0.0473 | 27.12 | 1056.1 | 2.6227 | *0.045* | 8432.1 | *141* | | *1.3269* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| **5000** | 838.83 | 4848.7 | 6.7603 | 0.0447 | 43.53 | 1688.8 | 2.9715 | *0.0641* | 1900.3 | *32.1* | | |
| **10000** | 1052.2 | 4920.1 | 6.6513 | 0.0447 | 44.08 | 1713.3 | 2.8361 | *0.06* | 3116.2 | *52.42* | | |
| **15000** | 1225.3 | 4957.1 | 6.596 | 0.0447 | 44.37 | 1725.9 | 2.7679 | *0.0544* | 4842.3 | *81.3* | | |
| **20000** | 1272.1 | 5000.2 | 6.5329 | 0.0473 | 46.39 | 1806.1 | 2.709 | *0.0523* | 4931.6 | *82.66* | | |
| **25000** | 1394 | 4987.2 | 6.5519 | 0.0473 | 46.28 | 1801.5 | 2.6846 | *0.0493* | 7091.4 | *118.8* | | |
| **30000** | 1364.3 | 5000.2 | 6.5329 | 0.0447 | 44.7 | 1740.5 | 2.6601 | *0.0481* | 7265.8 | *121.6* | | |
| **35000** | 1383.3 | 5041.6 | 6.4733 | 0.0447 | 45.02 | 1754.5 | 2.6402 | *0.0461* | 7528.7 | *125.9* | | |
| **40000** | 1464 | 5059.9 | 6.4472 | 0.0447 | 45.16 | 1760.7 | 2.6388 | *0.0459* | 10049 | *168.1* | | |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| **5000** | 592.76 | 3042.9 | 6.6778 | 0.0537 | 24.83 | 1196.2 | 3.2592 | *0.0751* | 1303.9 | *28.26* | *1.5999* | *1.4886* |
| **10000** | 813.28 | 3089.3 | 6.5665 | 0.0573 | 26.31 | 1269.8 | 3.1883 | *0.0696* | 2515.9 | *54.42* | *1.8055* | *1.4479* |
| **15000** | 857.02 | 3086 | 6.5743 | 0.0537 | 25.22 | 1217 | 3.1309 | *0.0609* | 3226.2 | *69.67* | *1.9378* | *1.4245* |
| **20000** | 927.1 | 3114.9 | 6.5064 | 0.0537 | 25.49 | 1231 | 3.1055 | *0.0572* | 4189.3 | *90.41* | *2.0375* | *1.4082* |
| **25000** | 937.53 | 3115.7 | 6.5047 | 0.0501 | 24.39 | 1178 | 3.0698 | *0.0565* | 5130.9 | *110.6* | *2.1184* | *1.3957* |
| **30000** | 964.42 | 3134 | 6.4623 | 0.0501 | 24.55 | 1186.4 | 3.0713 | *0.0546* | 5765.2 | *124.3* | *2.1868* | *1.3856* |
| **35000** | 1000.5 | 3138.8 | 6.4514 | 0.0501 | 24.59 | 1188.6 | 3.0571 | *0.0533* | 7089.6 | *152.8* | *2.2464* | *1.3771* |
| **40000** | 969 | 3138.1 | 6.453 | 0.0465 | 23.43 | 1132.8 | 3.0423 | *0.052* | 7521.6 | *162* | *2.2993* | *1.3697* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| **5000** | 731.69 | 4518.7 | 6.7531 | 0.0462 | 38.96 | 1874.6 | 3.3156 | *0.0724* | 1331.9 | *28.91* | | |
| **10000** | 1007.3 | 4584.1 | 6.646 | 0.0462 | 39.46 | 1902 | 3.2265 | *0.0713* | 2380.9 | *51.56* | | |
| **15000** | 1145.1 | 4593.4 | 6.631 | 0.0462 | 39.54 | 1905.9 | 3.1743 | *0.0616* | 3194.3 | *69.07* | | |
| **20000** | 1274.8 | 4644.9 | 6.5493 | 0.0462 | 39.93 | 1927.3 | 3.1443 | *0.0576* | 4200.2 | *90.74* | | |
| **25000** | 1375 | 4633.4 | 6.5674 | 0.0446 | 38.95 | 1879.4 | 3.1198 | *0.0565* | 5730.8 | *123.7* | | |
| **30000** | 1406.6 | 4656.4 | 6.5312 | 0.0446 | 39.12 | 1888.7 | 3.1095 | *0.0549* | 6167.6 | *133.1* | | |
| **35000** | 1410.5 | 4672.9 | 6.5056 | 0.043 | 38.33 | 1851.1 | 3.0765 | *0.0537* | 6638.4 | *143.1* | | |
| **40000** | 1458.7 | 4675.7 | 6.5013 | 0.043 | 38.35 | 1852.2 | 3.0664 | *0.0524* | 7707.5 | *166.1* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.1 kg/s** | | | | | | | | | | | | |
| **5000** | 607.2 | 3037.9 | 6.6903 | 0.0537 | 24.79 | 1193.7 | 2.8732 | *0.0702* | 1371.6 | *29.4* | | *1.4869* |
| **10000** | 777.78 | 3106.9 | 6.5252 | 0.0537 | 25.41 | 1227.1 | 2.7523 | *0.0695* | 2361.7 | *50.44* | | *1.446* |
| **15000** | 874.07 | 3131.5 | 6.4682 | 0.0537 | 25.64 | 1238.9 | 2.7081 | *0.0617* | 3305.6 | *70.51* | | *1.4227* |
| **20000** | 933.47 | 3153.5 | 6.4178 | 0.0537 | 25.83 | 1249.5 | 2.6621 | *0.0599* | 4116.5 | *87.69* | | *1.4063* |
| **25000** | 938.96 | 3156.1 | 6.412 | 0.0501 | 24.74 | 1196.5 | 2.6435 | *0.0562* | 4872 | *103.7* | | *1.3938* |
| **30000** | 982.2 | 3161.3 | 6.4004 | 0.0501 | 24.78 | 1198.8 | 2.6304 | *0.0557* | 6083.4 | *129.5* | | *1.3837* |
| **35000** | 985.56 | 3144.7 | 6.4379 | 0.0501 | 24.64 | 1191.3 | 2.6213 | *0.0535* | 6390.8 | *136* | | *1.3752* |
| **40000** | 1025.5 | 3173.1 | 6.3738 | 0.0501 | 24.88 | 1204.2 | 2.6096 | *0.0529* | 7755.7 | *165* | | *1.3678* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Cold Water Mass Flowrate: 0.15 kg/s** | | | | | | | | | | | | |
| **5000** | 746.43 | 4563.3 | 6.6796 | 0.0446 | 38.42 | 1850.9 | 2.9054 | *0.0765* | 1388.4 | *29.79* | | |
| **10000** | 1073.1 | 4619.7 | 6.5891 | 0.0446 | 38.85 | 1873.8 | 2.8233 | *0.0644* | 2794.2 | *59.8* | | |
| **15000** | 1201 | 4680.1 | 6.4945 | 0.0446 | 39.3 | 1898.3 | 2.7645 | *0.0632* | 3643.3 | *77.84* | | |
| **20000** | 1304.9 | 4690.6 | 6.4784 | 0.0446 | 39.37 | 1902.5 | 2.7123 | *0.059* | 4637.4 | *98.93* | | |
| **25000** | 1320.5 | 4697.7 | 6.4674 | 0.0446 | 39.43 | 1905.4 | 2.6931 | *0.0565* | 4803.4 | *102.4* | | |
| **30000** | 1392.2 | 4720.4 | 6.4329 | 0.043 | 38.67 | 1869.7 | 2.6614 | *0.0555* | 6102 | *130* | | |
| **35000** | 1412.6 | 4732 | 6.4153 | 0.043 | 38.75 | 1874.2 | 2.6421 | *0.0535* | 6422.2 | *136.7* | | |
| **40000** | 1476.3 | 4750.2 | 6.3879 | 0.0414 | 37.93 | 1835.5 | 2.6309 | *0.0529* | 8478.9 | *180.5* | | |

**Table C-24:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu and empirical values of $f_{s,o}$, and $Nu_{s,o}$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Smooth Annulus).

| Re Annulus | $U_o$ W/m².C | Inner Tube (smooth)† | | | | | Annulus (smooth) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Re_{s,h}$ | $Pr_h$ | $f_{s,i}$ | $Nu_s$ | $h_{s,i}$ W/m².C | $Pr_c$ | $f_{s,o}$ | $h_{a,i}$ W/m².C | $Nu_{s,o}$ | Empirical $f_{s,o}$ | Empirical $Nu_{s,o}$ |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 1031.8 | 27334 | 3.068 | 0.0248 | 146.1 | 8623 | 6.4733 | 0.052 | 1197 | 30.72 | 0.0456 | 22.55 |
| 4000 | 1250.1 | 27043 | 3.1042 | 0.0248 | 145.2 | 8565.6 | 6.5132 | 0.0455 | 1503.2 | 38.6 | 0.0414 | 31.88 |
| 5000 | 1474.6 | 26976 | 3.1126 | 0.0248 | 145 | 8552.4 | 6.5381 | 0.042 | 1840.8 | 47.28 | 0.0386 | 40.64 |
| 6000 | 1639.4 | 26660 | 3.1532 | 0.0249 | 144.7 | 8519.4 | 6.6337 | 0.0391 | 2107.1 | 54.2 | 0.0365 | 49.23 |
| 7000 | 1820.5 | 26507 | 3.1732 | 0.025 | 144.7 | 8518.2 | 6.6223 | 0.0393 | 2416.1 | 62.14 | 0.0349 | 57.27 |
| 8000 | 1970.6 | 26433 | 3.1831 | 0.0251 | 145 | 8532.8 | 6.6021 | 0.0383 | 2686.2 | 69.07 | 0.0335 | 65.04 |
| 9000 | 2108.1 | 26416 | 3.1852 | 0.0251 | 145 | 8529.4 | 6.6707 | 0.0383 | 2948.7 | 75.9 | 0.0324 | 72.97 |
| 10000 | 2232.4 | 26348 | 3.1943 | 0.0252 | 145.3 | 8545 | 6.6389 | 0.039 | 3195.5 | 82.21 | 0.0315 | 80.34 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 1052 | 48851 | 3.0502 | 0.022 | 241 | 14235 | 6.5355 | 0.0475 | 1151.1 | 29.57 | 0.0456 | 22.63 |
| 4000 | 1289.7 | 48866 | 3.0492 | 0.022 | 241 | 14238 | 6.5022 | 0.0435 | 1441.8 | 37.01 | 0.0414 | 31.86 |
| 5000 | 1535 | 48631 | 3.0654 | 0.022 | 240.8 | 14216 | 6.5364 | 0.0394 | 1755.9 | 45.1 | 0.0386 | 40.64 |
| 6000 | 1779.3 | 48541 | 3.0716 | 0.022 | 240.5 | 14200 | 6.5372 | 0.042 | 2083.4 | 53.51 | 0.0365 | 48.97 |
| 7000 | 1960 | 48336 | 3.0859 | 0.022 | 240.1 | 14165 | 6.551 | 0.0394 | 2336.7 | 60.03 | 0.0349 | 57.04 |
| 8000 | 2173.3 | 48140 | 3.0997 | 0.022 | 239.6 | 14131 | 6.5579 | 0.0418 | 2647.6 | 68.03 | 0.0335 | 64.88 |
| 9000 | 2426.5 | 47813 | 3.123 | 0.0221 | 239.1 | 14093 | 6.557 | 0.0379 | 3035.2 | 77.99 | 0.0324 | 72.5 |
| 10000 | 2539.4 | 47881 | 3.1181 | 0.0221 | 239.2 | 14105 | 6.5997 | 0.0381 | 3213.2 | 82.61 | 0.0315 | 80.16 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 1078 | 31302 | 2.6461 | 0.0244 | 155.5 | 9297.4 | 6.4162 | 0.0528 | 1244.7 | 31.91 | 0.0456 | 22.49 |
| 4000 | 1267.3 | 31242 | 2.6517 | 0.0244 | 155.4 | 9286.7 | 6.4312 | 0.0423 | 1504.5 | 38.58 | 0.0414 | 31.73 |
| 5000 | 1463.6 | 30890 | 2.6844 | 0.0245 | 155.1 | 9258.3 | 6.5098 | 0.0397 | 1790.6 | 45.97 | 0.0386 | 40.58 |
| 6000 | 1638 | 30592 | 2.7128 | 0.0244 | 153.7 | 9171 | 6.5882 | 0.0378 | 2063.6 | 53.05 | 0.0365 | 49.1 |
| 7000 | 1819.2 | 30599 | 2.7121 | 0.0246 | 154.3 | 9205.9 | 6.5064 | 0.0365 | 2357.1 | 60.52 | 0.0349 | 56.9 |
| 8000 | 1961.9 | 30608 | 2.7112 | 0.0245 | 154.3 | 9207.6 | 6.5141 | 0.0392 | 2602.3 | 66.82 | 0.0335 | 64.72 |
| 9000 | 2097 | 30291 | 2.7421 | 0.0246 | 153.5 | 9150.2 | 6.6048 | 0.0366 | 2851.8 | 73.33 | 0.0324 | 72.7 |
| 10000 | 2234 | 30211 | 2.75 | 0.0246 | 153.3 | 9135.6 | 6.6025 | 0.0361 | 3113.1 | 80.04 | 0.0315 | 80.17 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 1162.4 | 56541 | 2.601 | 0.0218 | 257.9 | 15433 | 6.359 | 0.0537 | 1274.5 | 32.65 | 0.0456 | 22.42 |
| 4000 | 1394.6 | 56280 | 2.614 | 0.0218 | 257.3 | 15393 | 6.4162 | 0.0424 | 1559.5 | 39.98 | 0.0414 | 31.71 |
| 5000 | 1643.7 | 56187 | 2.6187 | 0.0218 | 257.1 | 15379 | 6.4062 | 0.0395 | 1877.9 | 48.14 | 0.0386 | 40.34 |
| 6000 | 1827.3 | 55739 | 2.6415 | 0.0218 | 256.4 | 15331 | 6.4329 | 0.0376 | 2122.6 | 54.43 | 0.0365 | 48.68 |
| 7000 | 2005 | 55717 | 2.6426 | 0.0218 | 256.4 | 15327 | 6.4724 | 0.0368 | 2366.2 | 60.72 | 0.0349 | 56.79 |
| 8000 | 2207.1 | 55468 | 2.6555 | 0.0219 | 256.2 | 15309 | 6.4741 | 0.0376 | 2653.6 | 68.09 | 0.0335 | 64.57 |
| 9000 | 2347 | 55399 | 2.659 | 0.0219 | 256 | 15299 | 6.4843 | 0.037 | 2859 | 73.38 | 0.0324 | 72.19 |
| 10000 | 2531.3 | 55098 | 2.6748 | 0.0219 | 255.7 | 15272 | 6.5332 | 0.0362 | 3138.5 | 80.61 | 0.0315 | 79.85 |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 1043.7 | 21291 | 3.0974 | 0.0274 | 123.3 | 5713.8 | 6.4145 | 0.0515 | 1311.7 | 27.12 | 0.0456 | 21.57 |
| 4000 | 1242.7 | 21140 | 3.1216 | 0.0275 | 122.8 | 5687.3 | 6.4547 | 0.0485 | 1644.5 | 34.02 | 0.0414 | 30.49 |
| 5000 | 1472.1 | 21037 | 3.1384 | 0.0275 | 122.5 | 5669.2 | 6.4716 | 0.0449 | 2074.5 | 42.93 | 0.0386 | 38.85 |
| 6000 | 1642.2 | 20908 | 3.1597 | 0.0275 | 122 | 5646.4 | 6.5141 | 0.0414 | 2433.8 | 50.4 | 0.0365 | 46.93 |
| 7000 | 1762.8 | 20845 | 3.1702 | 0.0277 | 122.5 | 5664.7 | 6.5553 | 0.0385 | 2703.9 | 56.03 | 0.0349 | 54.75 |
| 8000 | 1926.1 | 20754 | 3.1855 | 0.0278 | 122.8 | 5677.9 | 6.5709 | 0.0352 | 3103.6 | 64.32 | 0.0335 | 62.3 |
| 9000 | 2115 | 20608 | 3.2103 | 0.0282 | 123.6 | 5709.8 | 6.5943 | 0.0341 | 3611.1 | 74.87 | 0.0324 | 69.72 |
| 10000 | 2166.8 | 20541 | 3.2218 | 0.0284 | 124 | 5726.5 | 6.6114 | 0.0327 | 3756.8 | 77.91 | 0.0315 | 76.97 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 1218.2 | 38374 | 3.051 | 0.0232 | 198.2 | 9199.1 | 6.3426 | 0.0525 | 1431.5 | 29.56 | 0.0456 | 21.49 |
| 4000 | 1391.8 | 38222 | 3.0643 | 0.0232 | 197.4 | 9158.7 | 6.4145 | 0.049 | 1678.9 | 34.71 | 0.0414 | 30.42 |
| 5000 | 1688.7 | 37923 | 3.0908 | 0.0232 | 196.6 | 9115.7 | 6.4187 | 0.0441 | 2133.4 | 44.11 | 0.0386 | 38.74 |
| 6000 | 1903.5 | 37862 | 3.0963 | 0.0233 | 197.3 | 9143.3 | 6.4354 | 0.0428 | 2485.9 | 51.41 | 0.0365 | 46.72 |
| 7000 | 2098 | 37661 | 3.1145 | 0.0234 | 197.5 | 9150.3 | 6.4716 | 0.0387 | 2827.5 | 58.51 | 0.0349 | 54.49 |
| 8000 | 2303.6 | 37573 | 3.1224 | 0.0235 | 197.7 | 9155.5 | 6.5804 | 0.034 | 3213.5 | 66.61 | 0.0335 | 62.34 |
| 9000 | 2532.5 | 37350 | 3.143 | 0.0236 | 197.5 | 9140.5 | 6.5039 | 0.0335 | 3679.9 | 76.19 | 0.0324 | 69.36 |
| 10000 | 2588.4 | 37339 | 3.144 | 0.0236 | 197.4 | 9138.8 | 6.5509 | 0.0319 | 3799.3 | 78.72 | 0.0315 | 76.7 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 1091.3 | 24566 | 2.6495 | 0.0266 | 130.4 | 6123.7 | 6.2671 | 0.0537 | 1363.2 | 28.12 | 0.0456 | 21.4 |
| 4000 | 1257 | 24407 | 2.6681 | 0.0268 | 130.7 | 6133.4 | 6.345 | 0.0522 | 1631.1 | 33.69 | 0.0414 | 30.31 |
| 5000 | 1462.1 | 24154 | 2.6985 | 0.0266 | 129.2 | 6059.7 | 6.3805 | 0.0461 | 2003 | 41.39 | 0.0386 | 38.66 |
| 6000 | 1635.5 | 23920 | 2.7272 | 0.0271 | 130.7 | 6123.8 | 6.4212 | 0.04 | 2332.8 | 48.24 | 0.0365 | 46.68 |
| 7000 | 1769.4 | 23874 | 2.7328 | 0.027 | 129.8 | 6083 | 6.4547 | 0.0381 | 2623.5 | 54.27 | 0.0349 | 54.44 |
| 8000 | 1938.7 | 23709 | 2.7536 | 0.0273 | 130.8 | 6122.9 | 6.4902 | 0.0344 | 3003 | 62.16 | 0.0335 | 62.02 |
| 9000 | 2114 | 23598 | 2.7677 | 0.0273 | 130.4 | 6104.8 | 6.4945 | 0.0331 | 3451.8 | 71.46 | 0.0324 | 69.32 |
| 10000 | 2226.6 | 23508 | 2.7792 | 0.0274 | 130.2 | 6090.1 | 6.5131 | 0.0312 | 3768.9 | 78.04 | 0.0315 | 76.53 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 1211.2 | 44435 | 2.6003 | 0.0229 | 211.8 | 9962.4 | 6.1907 | 0.0506 | 1403.5 | 28.91 | 0.0456 | 21.31 |
| 4000 | 1428.1 | 44030 | 2.6262 | 0.023 | 210.9 | 9910.4 | 6.2607 | 0.0488 | 1704.9 | 35.16 | 0.0414 | 30.17 |
| 5000 | 1839.3 | 43579 | 2.6557 | 0.0231 | 210.7 | 9893 | 6.2615 | 0.0461 | 2326.8 | 47.99 | 0.0386 | 38.4 |
| 6000 | 1872 | 43501 | 2.6608 | 0.0231 | 211 | 9903.4 | 6.3401 | 0.0455 | 2378.6 | 49.12 | 0.0365 | 46.47 |
| 7000 | 2137.3 | 43248 | 2.6777 | 0.0231 | 210.3 | 9870.1 | 6.3524 | 0.0377 | 2827 | 58.39 | 0.0349 | 54.12 |
| 8000 | 2336.2 | 43215 | 2.6799 | 0.0232 | 210.7 | 9886 | 6.3846 | 0.0359 | 3184 | 65.8 | 0.0335 | 61.64 |
| 9000 | 2556.1 | 42761 | 2.7108 | 0.0233 | 210.5 | 9866.1 | 6.4028 | 0.0335 | 3610 | 74.62 | 0.0324 | 68.95 |
| 10000 | 2633.3 | 42785 | 2.7091 | 0.0233 | 210.5 | 9869.3 | 6.4418 | 0.0311 | 3765.2 | 77.88 | 0.0315 | 76.21 |

†Predicted values of smooth inner tube are used to complete calculations only.

**Table C-25:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: : Wire Coil, e=1 mm, p= 10 mm).

| Re Annulus | $U_o$ W/m².C | Inner Tube (smooth)† $Re_{s,h}$ | $Pr_h$ | $f_{s,i}$ | $Nu_{s,i}$ | $h_{s,i}$ W/m².C | Annulus (augmented) $Pr_c$ | $f_a$ | $h_{a,o}$ W/m².C | $Nu_a$ | Augmentation†† $f_a/f_s$ | $Nu_a/Nu_s$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2153.4 | 26548 | 3.1678 | 0.0257 | 147.9 | 8704.4 | 6.1726 | *0.1537* | 3013.7 | *76.96* | *2.6291* | *3.2276* |
| 4000 | 2479.8 | 26391 | 3.1885 | 0.0257 | 147.4 | 8671.6 | 6.1914 | *0.1357* | 3701 | *94.54* | *2.7003* | *2.961* |
| 5000 | 2738 | 26261 | 3.2059 | 0.0259 | 148 | 8702.8 | 6.2873 | *0.1239* | 4298.5 | *110* | *2.7568* | *2.7669* |
| 6000 | 2948.2 | 25893 | 3.256 | 0.0259 | 146.9 | 8624.6 | 6.3524 | *0.1104* | 4868.1 | *124.7* | *2.8038* | *2.6168* |
| 7000 | 3122.1 | 26000 | 3.2413 | 0.0262 | 148.2 | 8705.1 | 6.4212 | *0.1024* | 5326.5 | *136.6* | *2.8442* | *2.4975* |
| 8000 | 3287.4 | 25699 | 3.2832 | 0.0262 | 147.2 | 8640.1 | 6.4463 | *0.0958* | 5859.6 | *150.3* | *2.8797* | *2.399* |
| 9000 | 3492.1 | 25733 | 3.2783 | 0.0263 | 147.8 | 8676.2 | 6.5631 | *0.0942* | 6520.2 | *167.5* | *2.9113* | *2.3116* |
| 10000 | 3597.9 | 25572 | 3.3011 | 0.0263 | 147.3 | 8641.1 | 6.5393 | *0.0939* | 6924.1 | *177.9* | *2.9399* | *2.2411* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2401 | 47932 | 3.1145 | 0.0224 | 242.1 | 14274 | 6.0887 | *0.1492* | 2986.2 | *76.15* | | |
| 4000 | 2866 | 47691 | 3.1317 | 0.0224 | 241.5 | 14232 | 6.1522 | *0.1327* | 3744.6 | *95.6* | | |
| 5000 | 3200.1 | 47617 | 3.1371 | 0.0224 | 241.9 | 14254 | 6.1978 | *0.1243* | 4333.6 | *110.7* | | |
| 6000 | 3430.8 | 47414 | 3.1518 | 0.0225 | 241.4 | 14218 | 6.2808 | *0.1156* | 4772.4 | *122.1* | | |
| 7000 | 3666.6 | 47252 | 3.1637 | 0.0225 | 241.6 | 14224 | 6.2986 | *0.1117* | 5240.3 | *134.1* | | |
| 8000 | 3861.7 | 47135 | 3.1724 | 0.0225 | 241.3 | 14203 | 6.3311 | *0.1022* | 5651.9 | *144.7* | | |
| 9000 | 4063.2 | 47094 | 3.1754 | 0.0225 | 241.2 | 14196 | 6.4062 | *0.0958* | 6095.7 | *156.3* | | |
| 10000 | 4229.1 | 47013 | 3.1814 | 0.0226 | 241.3 | 14199 | 6.412 | *0.0979* | 6476.2 | *166* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2145.8 | 30511 | 2.7207 | 0.0254 | 158.6 | 9457.1 | 5.9758 | *0.1542* | 2908.2 | *74.03* | | *3.2461* |
| 4000 | 2540.1 | 30255 | 2.7457 | 0.0256 | 158.7 | 9458.3 | 5.9953 | *0.1294* | 3682.8 | *93.77* | | *2.9785* |
| 5000 | 2802.4 | 29780 | 2.7933 | 0.0257 | 157.7 | 9383.6 | 6.1071 | *0.1187* | 4278.5 | *109.1* | | *2.7800* |
| 6000 | 3045 | 29789 | 2.7924 | 0.0258 | 158.2 | 9417.8 | 6.2287 | *0.1054* | 4860.7 | *124.2* | | *2.6277* |
| 7000 | 3227.6 | 29632 | 2.8085 | 0.0258 | 157.8 | 9387.3 | 6.2921 | *0.1091* | 5354.4 | *137* | | *2.5074* |
| 8000 | 3448.9 | 29443 | 2.8282 | 0.0258 | 157.3 | 9350.4 | 6.3475 | *0.0941* | 6009.4 | *153.9* | | *2.4068* |
| 9000 | 3583.4 | 29317 | 2.8415 | 0.026 | 158 | 9389.6 | 6.453 | *0.0913* | 6409.2 | *164.4* | | *2.3204* |
| 10000 | 3773.7 | 29056 | 2.8694 | 0.0261 | 157.2 | 9337.6 | 6.4359 | *0.0932* | 7078 | *181.5* | | *2.2468* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2458.5 | 55575 | 2.6499 | 0.0221 | 258.4 | 15446 | 5.8251 | *0.1525* | 3019.7 | *76.67* | | |
| 4000 | 2891.5 | 54853 | 2.6877 | 0.0222 | 257.5 | 15373 | 5.8727 | *0.1442* | 3704.9 | *94.14* | | |
| 5000 | 3333.1 | 54832 | 2.6888 | 0.0222 | 257.4 | 15370 | 5.9915 | *0.1228* | 4462.9 | *113.6* | | |
| 6000 | 3618.7 | 54548 | 2.7041 | 0.0222 | 257.3 | 15354 | 6.0611 | *0.1191* | 4992 | *127.3* | | |
| 7000 | 3849.4 | 54122 | 2.7272 | 0.0223 | 256.8 | 15316 | 6.0956 | *0.1033* | 5447.4 | *138.9* | | |
| 8000 | 4082.8 | 53591 | 2.7566 | 0.0223 | 255.6 | 15230 | 6.1569 | *0.0971* | 5941.6 | *151.7* | | |
| 9000 | 4297.8 | 53790 | 2.7455 | 0.0223 | 256.2 | 15272 | 6.1938 | *0.092* | 6399.8 | *163.5* | | |
| 10000 | 4431.2 | 53452 | 2.7644 | 0.0224 | 255.9 | 15246 | 6.2959 | *0.0948* | 6705.7 | *171.6* | | |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2147.5 | 20676 | 3.1987 | 0.028 | 123.2 | 5693.1 | 6.0398 | *0.1587* | 3714.6 | *76.33* | *3.3652* | *3.125* |
| 4000 | 2385.1 | 20580 | 3.215 | 0.028 | 122.9 | 5675.6 | 6.1358 | *0.1423* | 4500.3 | *92.63* | *3.4563* | *2.9024* |
| 5000 | 2556.5 | 20438 | 3.2396 | 0.0282 | 123 | 5678.5 | 6.2543 | *0.1342* | 5149.2 | *106.2* | *3.5286* | *2.7388* |
| 6000 | 2748.8 | 20308 | 3.2626 | 0.0282 | 122.6 | 5654.3 | 6.314 | *0.1252* | 6024.2 | *124.4* | *3.5888* | *2.6127* |
| 7000 | 2930.3 | 20224 | 3.2774 | 0.0282 | 122.3 | 5638.7 | 6.3681 | *0.1253* | 6996.7 | *144.5* | *3.6405* | *2.5117* |
| 8000 | 3042 | 20096 | 3.3004 | 0.0286 | 123.1 | 5671.7 | 6.4281 | *0.1259* | 7602.6 | *157.2* | *3.6859* | *2.4261* |
| 9000 | 3159 | 20026 | 3.3132 | 0.029 | 124.1 | 5714.7 | 6.4651 | *0.1228* | 8275.8 | *171.2* | *3.7264* | *2.3541* |
| 10000 | 3265.5 | 19962 | 3.3249 | 0.029 | 123.8 | 5702.4 | 6.4964 | *0.1202* | 9083.7 | *188* | *3.763* | *2.2916* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2576 | 37620 | 3.1182 | 0.0233 | 196.6 | 9108 | 5.8373 | *0.164* | 3778.6 | *77.38* | | |
| 4000 | 2976.3 | 37335 | 3.1443 | 0.0233 | 195.9 | 9066.2 | 5.9498 | *0.1452* | 4719.5 | *96.84* | | |
| 5000 | 3270.3 | 37121 | 3.1643 | 0.0233 | 195.3 | 9034.7 | 6.0527 | *0.1392* | 5517.2 | *113.4* | | |
| 6000 | 3555 | 36925 | 3.1828 | 0.0233 | 194.8 | 9005.6 | 6.1545 | *0.1279* | 6395.3 | *131.7* | | |
| 7000 | 3757.2 | 36769 | 3.1976 | 0.0233 | 194.4 | 8982.5 | 6.2033 | *0.1235* | 7096.7 | *146.2* | | |
| 8000 | 3944.9 | 36605 | 3.2134 | 0.0235 | 194.7 | 8993.5 | 6.2769 | *0.1256* | 7788 | *160.7* | | |
| 9000 | 4113.7 | 36495 | 3.224 | 0.0235 | 194.4 | 8977.1 | 6.3207 | *0.1229* | 8491 | *175.3* | | |
| 10000 | 4266.8 | 36389 | 3.2343 | 0.0236 | 194.9 | 8996.4 | 6.36 | *0.1205* | 9148.1 | *189* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2130 | 23746 | 2.7489 | 0.0277 | 132.3 | 6195.4 | 5.7703 | *0.1531* | 3462.7 | *70.83* | | *3.1467* |
| 4000 | 2413.7 | 23394 | 2.794 | 0.0281 | 132.6 | 6202 | 5.9565 | *0.1399* | 4277.3 | *87.77* | | *2.9159* |
| 5000 | 2650.2 | 23314 | 2.8044 | 0.0281 | 132.4 | 6188.5 | 6.0764 | *0.1382* | 5090.4 | *104.7* | | *2.7517* |
| 6000 | 2814.4 | 23151 | 2.8259 | 0.0281 | 131.9 | 6160.8 | 6.1851 | *0.1257* | 5759.5 | *118.6* | | *2.6231* |
| 7000 | 2963.4 | 23021 | 2.8434 | 0.0285 | 132.8 | 6202.5 | 6.2279 | *0.1227* | 6371.1 | *131.3* | | *2.5201* |
| 8000 | 3125.4 | 22884 | 2.8619 | 0.0285 | 132.4 | 6178.8 | 6.2945 | *0.1163* | 7205.6 | *148.7* | | *2.4348* |
| 9000 | 3205.8 | 22841 | 2.8678 | 0.0285 | 132.3 | 6171.2 | 6.3279 | *0.1177* | 7660.1 | *158.2* | | *2.3624* |
| 10000 | 3366.2 | 22635 | 2.8964 | 0.0289 | 132.9 | 6198 | 6.3894 | *0.1202* | 8587.3 | *177.5* | | *2.298* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2520 | 43298 | 2.6744 | 0.0232 | 210.9 | 9897 | 5.5703 | *0.158* | 3534 | *72.03* | | |
| 4000 | 2945.7 | 42872 | 2.7032 | 0.0231 | 209 | 9800.2 | 5.7618 | *0.1511* | 4454.1 | *91.1* | | |
| 5000 | 3234.4 | 42534 | 2.7265 | 0.0232 | 209.1 | 9795.5 | 5.8503 | *0.1344* | 5150.2 | *105.5* | | |
| 6000 | 3517.7 | 42155 | 2.7532 | 0.0232 | 208.1 | 9744.7 | 5.9587 | *0.1299* | 5928.6 | *121.7* | | |
| 7000 | 3742.4 | 42031 | 2.762 | 0.0233 | 208.7 | 9767.6 | 6.0672 | *0.1245* | 6584.4 | *135.4* | | |
| 8000 | 3894.4 | 41951 | 2.7677 | 0.0234 | 208.5 | 9756.8 | 6.1126 | *0.1184* | 7076.2 | *145.6* | | |
| 9000 | 4122.6 | 41765 | 2.7812 | 0.0234 | 208 | 9731.4 | 6.1616 | *0.1182* | 7885.9 | *162.4* | | |
| 10000 | 4263.1 | 41676 | 2.7876 | 0.0235 | 208.6 | 9758.8 | 6.2295 | *0.1183* | 8394.2 | *173* | | |

†Predicted values of smooth inner tube are used to complete calculations only.

††Augmentation values are predicted by using the proposed correlations and not experimental results.

**Table C-26:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e=1 mm, p= 20 mm).

| Re Annulus | $U_o$ W/m².C | Inner Tube (smooth)† | | | | | Annulus (augmented) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Augmentation†† | |
| | | $Re_{s,h}$ | $Pr_h$ | $f_{s,i}$ | $Nu_{s,i}$ | $h_{s,i}$ W/m².C | $Pr_c$ | $f_a$ | $h_{a,o}$ W/m².C | $Nu_a$ | $f_a/f_s$ | $Nu_a/Nu_s$ |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 2050 | 26492 | 3.1751 | 0.0258 | 148.2 | 8722.2 | 6.1836 | *0.129* | 2812.9 | *71.85* | *1.876* | *2.8991* |
| **4000** | 2382.7 | 26298 | 3.2009 | 0.0257 | 147.1 | 8652.2 | 6.2727 | *0.1149* | 3492.3 | *89.33* | *1.9267* | *2.7025* |
| **5000** | 2648.9 | 26140 | 3.2223 | 0.0258 | 147.1 | 8648 | 6.3434 | *0.1054* | 4096.6 | *104.9* | *1.967* | *2.5594* |
| **6000** | 2810.9 | 26060 | 3.2332 | 0.0259 | 147.4 | 8660 | 6.4262 | *0.0997* | 4494 | *115.2* | *2.0006* | *2.4439* |
| **7000** | 3082.7 | 25889 | 3.2566 | 0.0263 | 148.3 | 8709.9 | 6.4371 | *0.0965* | 5210.7 | *133.6* | *2.0294* | *2.3562* |
| **8000** | 3181.3 | 25789 | 3.2706 | 0.0259 | 146.5 | 8602.3 | 6.4826 | *0.0886* | 5548.5 | *142.4* | *2.0547* | *2.2808* |
| **9000** | 3384 | 25699 | 3.2832 | 0.0263 | 147.7 | 8668.6 | 6.5398 | *0.0859* | 6157.4 | *158.2* | *2.0773* | *2.2151* |
| **10000** | 3492.4 | 25641 | 3.2912 | 0.0263 | 147.5 | 8656.2 | 6.5415 | *0.0859* | 6533.9 | *167.8* | *2.0977* | *2.1595* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2341.6 | 48050 | 3.106 | 0.0224 | 243 | 14331 | 6.0725 | *0.1249* | 2892.3 | *73.74* | | |
| **4000** | 2768 | 47839 | 3.1211 | 0.0224 | 242.5 | 14293 | 6.1459 | *0.1146* | 3574.5 | *91.24* | | |
| **5000** | 3154.9 | 47636 | 3.1357 | 0.0224 | 241.4 | 14222 | 6.1962 | *0.107* | 4254.3 | *108.7* | | |
| **6000** | 3287.3 | 47352 | 3.1564 | 0.0225 | 241.2 | 14207 | 6.3598 | *0.0997* | 4500.3 | *115.3* | | |
| **7000** | 3581.8 | 47433 | 3.1505 | 0.0225 | 242 | 14257 | 6.3459 | *0.0961* | 5064 | *129.7* | | |
| **8000** | 3707.2 | 47138 | 3.1721 | 0.0225 | 241.3 | 14204 | 6.3722 | *0.0892* | 5326.8 | *136.5* | | |
| **9000** | 4001.5 | 46984 | 3.1836 | 0.0226 | 241.2 | 14194 | 6.4237 | *0.087* | 5958.4 | *152.8* | | |
| **10000** | 4108.4 | 46811 | 3.1965 | 0.0226 | 240.8 | 14162 | 6.4581 | *0.0866* | 6205.3 | *159.2* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 2141.8 | 30543 | 2.7175 | 0.0252 | 157.5 | 9396.7 | 5.9594 | *0.1206* | 2907.4 | *73.99* | | *2.9198* |
| **4000** | 2505.3 | 30257 | 2.7455 | 0.0252 | 156.8 | 9343.2 | 6.0239 | *0.1140* | 3629.5 | *92.46* | | *2.7212* |
| **5000** | 2761.8 | 29997 | 2.7714 | 0.0254 | 156.6 | 9327.1 | 6.1639 | *0.1051* | 4197.4 | *107.2* | | *2.5732* |
| **6000** | 3050.6 | 29814 | 2.7899 | 0.0254 | 156.1 | 9292.4 | 6.2191 | *0.0997* | 4914 | *125.6* | | *2.4584* |
| **7000** | 3228.2 | 29635 | 2.8083 | 0.0254 | 155.6 | 9258.2 | 6.3116 | *0.0942* | 5404.9 | *138.3* | | *2.3662* |
| **8000** | 3522.6 | 29348 | 2.8382 | 0.0255 | 155.4 | 9235.4 | 6.2752 | *0.0883* | 6296.3 | *161.1* | | *2.2919* |
| **9000** | 3646.8 | 29297 | 2.8436 | 0.0255 | 155.2 | 9225.6 | 6.3271 | *0.0860* | 6710.3 | *171.8* | | *2.2259* |
| **10000** | 3791.1 | 29099 | 2.8647 | 0.0256 | 155.2 | 9219 | 6.4321 | *0.0852* | 7220.3 | *185.2* | | *2.1672* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2613.6 | 55391 | 2.6595 | 0.0221 | 258 | 15418 | 5.7309 | *0.1200* | 3258.5 | *82.59* | | |
| **4000** | 3008.7 | 54673 | 2.6973 | 0.0221 | 256.4 | 15305 | 5.8359 | *0.1106* | 3904.6 | *99.15* | | |
| **5000** | 3342.9 | 54531 | 2.7049 | 0.0222 | 256.8 | 15322 | 5.9328 | *0.1063* | 4485 | *114.1* | | |
| **6000** | 3563.6 | 53953 | 2.7364 | 0.0222 | 255.5 | 15230 | 6.0703 | *0.0958* | 4902.3 | *125* | | |
| **7000** | 3821.6 | 54056 | 2.7308 | 0.0222 | 256.4 | 15285 | 6.1141 | *0.0937* | 5396.2 | *137.7* | | |
| **8000** | 4057.2 | 53713 | 2.7498 | 0.0223 | 255.9 | 15250 | 6.1686 | *0.0888* | 5884.3 | *150.3* | | |
| **9000** | 4209.9 | 53558 | 2.7584 | 0.0223 | 255.5 | 15225 | 6.2223 | *0.0841* | 6215.7 | *158.9* | | |
| **10000** | 4400.2 | 53461 | 2.7638 | 0.0223 | 255.3 | 15209 | 6.2631 | *0.0830* | 6643.2 | *169.9* | | |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 2114.9 | 20759 | 3.1847 | 0.0278 | 122.8 | 5678.8 | 6.0043 | *0.1292* | 3624.7 | *74.44* | *2.4011* | *2.7663* |
| **4000** | 2397.5 | 20569 | 3.217 | 0.028 | 122.8 | 5673.5 | 6.1459 | *0.125* | 4546 | *93.58* | *2.4661* | *2.6153* |
| **5000** | 2571.8 | 20449 | 3.2377 | 0.0282 | 123.1 | 5680.6 | 6.2519 | *0.1239* | 5209.9 | *107.4* | *2.5177* | *2.5036* |
| **6000** | 2673.3 | 20346 | 3.2558 | 0.0282 | 122.7 | 5661.4 | 6.3254 | *0.1208* | 5665 | *117* | *2.5607* | *2.4168* |
| **7000** | 2922.9 | 20176 | 3.286 | 0.0286 | 123.4 | 5686.8 | 6.3962 | *0.1213* | 6875.3 | *142.1* | *2.5975* | *2.3451* |
| **8000** | 2937.2 | 20208 | 3.2803 | 0.0286 | 123.5 | 5692.8 | 6.4262 | *0.1166* | 6945 | *143.6* | *2.6299* | *2.2862* |
| **9000** | 3012.6 | 20156 | 3.2895 | 0.0286 | 123.3 | 5683.1 | 6.4581 | *0.1148* | 7399.6 | *153.1* | *2.6588* | *2.2351* |
| **10000** | 3161.2 | 20024 | 3.3135 | 0.029 | 124 | 5714.4 | 6.5079 | *0.1132* | 8291.8 | *171.7* | *2.685* | *2.1898* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2559.6 | 37637 | 3.1166 | 0.0232 | 195.9 | 9074.2 | 5.8438 | *0.131* | 3749.6 | *76.8* | | |
| **4000** | 2922.8 | 37335 | 3.1443 | 0.0232 | 195.1 | 9030.1 | 5.9639 | *0.1269* | 4596.7 | *94.34* | | |
| **5000** | 3241.3 | 37141 | 3.1624 | 0.0233 | 195.4 | 9037.7 | 6.0741 | *0.1257* | 5433.9 | *111.7* | | |
| **6000** | 3437.9 | 37023 | 3.1735 | 0.0232 | 194.3 | 8984.3 | 6.1498 | *0.1206* | 6036.6 | *124.3* | | |
| **7000** | 3613.6 | 36714 | 3.2028 | 0.0233 | 194.2 | 8974.3 | 6.2279 | *0.1188* | 6605.9 | *136.2* | | |
| **8000** | 3798.4 | 36654 | 3.2087 | 0.0235 | 194.8 | 9000.8 | 6.276 | *0.1164* | 7231.8 | *149.2* | | |
| **9000** | 3940.6 | 36590 | 3.2148 | 0.0235 | 194.6 | 8991.3 | 6.3262 | *0.1132* | 7773.1 | *160.5* | | |
| **10000** | 4073.1 | 36378 | 3.2354 | 0.0235 | 194.1 | 8959.4 | 6.3714 | *0.1133* | 8336.6 | *172.2* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 2197.9 | 23655 | 2.7604 | 0.0277 | 132 | 6180.2 | 5.7443 | *0.1302* | 3651.6 | *74.66* | | *2.7869* |
| **4000** | 2425.9 | 23415 | 2.7913 | 0.0277 | 131.3 | 6140.3 | 5.9498 | *0.1274* | 4349.3 | *89.24* | | *2.6306* |
| **5000** | 2605.2 | 23262 | 2.8113 | 0.0281 | 132.2 | 6179.6 | 6.0596 | *0.1215* | 4933.6 | *101.4* | | *2.5172* |
| **6000** | 2734.9 | 23132 | 2.8284 | 0.0281 | 131.8 | 6157.5 | 6.1624 | *0.1212* | 5439.3 | *112* | | *2.4281* |
| **7000** | 2879.4 | 23092 | 2.8338 | 0.0285 | 133.1 | 6214.9 | 6.2343 | *0.1186* | 5982.3 | *123.3* | | *2.3555* |
| **8000** | 2959.4 | 22981 | 2.8488 | 0.0285 | 132.7 | 6195.6 | 6.3091 | *0.1164* | 6360.6 | *131.3* | | *2.2924* |
| **9000** | 3066 | 22933 | 2.8553 | 0.0285 | 132.6 | 6187.2 | 6.3549 | *0.1163* | 6885.5 | *142.2* | | *2.2405* |
| **10000** | 3084.6 | 22905 | 2.8591 | 0.0287 | 133.1 | 6214.2 | 6.3962 | *0.1132* | 6942.6 | *143.5* | | *2.1945* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2627.2 | 43155 | 2.6839 | 0.0231 | 209.7 | 9837.5 | 5.5317 | *0.129* | 3757.9 | *76.54* | | |
| **4000** | 2994.1 | 42947 | 2.698 | 0.0231 | 209.2 | 9810.2 | 5.6989 | *0.1293* | 4563.3 | *93.23* | | |
| **5000** | 3291.8 | 42592 | 2.7225 | 0.0232 | 209.2 | 9803.3 | 5.8294 | *0.1235* | 5294.9 | *108.4* | | |
| **6000** | 3546.6 | 42434 | 2.7335 | 0.0232 | 208.8 | 9782.1 | 5.9298 | *0.1208* | 5995.4 | *123* | | |
| **7000** | 3700.5 | 42251 | 2.7464 | 0.0233 | 209.2 | 9797.4 | 6.0224 | *0.1189* | 6441.5 | *132.3* | | |
| **8000** | 3808.7 | 41761 | 2.7814 | 0.0234 | 208 | 9731 | 6.1671 | *0.1165* | 6812.2 | *140.3* | | |
| **9000** | 3934 | 41837 | 2.7759 | 0.0234 | 208.2 | 9741.3 | 6.2247 | *0.1128* | 7217.6 | *148.8* | | |
| **10000** | 4080.3 | 41595 | 2.7936 | 0.0234 | 207.6 | 9708.2 | 6.3018 | *0.1133* | 7749 | *159.9* | | |

**Table C-27:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e=1 mm, p= 30 mm).

| Re Annulus | $U_o$ W/m².C | Inner Tube (smooth)† $Re_{s,h}$ | $Pr_h$ | $f_{s,i}$ | $Nu_{s,i}$ | $h_{s,i}$ W/m².C | Annulus (augmented) $Pr_c$ | $f_a$ | $h_{a,o}$ W/m².C | $Nu_a$ | Augmentation†† $f_a/f_s$ | $Nu_a/Nu_s$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 1974.2 | 26644 | 3.1553 | 0.0256 | 147.6 | 8694.6 | 6.2375 | *0.0913* | 2675 | *68.39* | *1.5398* | *2.5303* |
| 4000 | 2253 | 26232 | 3.2098 | 0.0256 | 146.4 | 8609.1 | 6.3871 | *0.0834* | 3227.4 | *82.71* | *1.5815* | *2.3815* |
| 5000 | 2513.4 | 26164 | 3.2189 | 0.0257 | 146.7 | 8624.1 | 6.4237 | *0.0813* | 3786.6 | *97.09* | *1.6145* | *2.2751* |
| 6000 | 2703.4 | 26189 | 3.2156 | 0.0257 | 146.8 | 8629.3 | 6.4178 | *0.0754* | 4233.5 | *108.5* | *1.6421* | *2.194* |
| 7000 | 2894.3 | 26131 | 3.2234 | 0.0256 | 146.1 | 8588 | 6.417 | *0.0734* | 4735.3 | *121.4* | *1.6658* | *2.1264* |
| 8000 | 3016.2 | 26037 | 3.2363 | 0.0257 | 146.3 | 8597.3 | 6.4885 | *0.0692* | 5067.2 | *130.1* | *1.6865* | *2.0687* |
| 9000 | 3203.8 | 25908 | 3.254 | 0.0258 | 146.4 | 8598.8 | 6.5813 | *0.0665* | 5619.1 | *144.4* | *1.7051* | *2.0169* |
| 10000 | 3350.3 | 25838 | 3.2637 | 0.0259 | 146.7 | 8612.8 | 6.545 | *0.0669* | 6078 | *156.1* | *1.7218* | *1.9758* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2254.7 | 47928 | 3.1147 | 0.0224 | 241.9 | 14265 | 6.1718 | *0.089* | 2763.6 | *70.57* | | |
| 4000 | 2617.6 | 47569 | 3.1406 | 0.0224 | 241.2 | 14210 | 6.2792 | *0.0838* | 3332.8 | *85.26* | | |
| 5000 | 2909.2 | 47359 | 3.1559 | 0.0224 | 240.7 | 14173 | 6.336 | *0.0806* | 3823.4 | *97.9* | | |
| 6000 | 3209.5 | 47241 | 3.1645 | 0.0224 | 240.4 | 14152 | 6.3295 | *0.0754* | 4361.8 | *111.7* | | |
| 7000 | 3463.1 | 47429 | 3.1508 | 0.0224 | 241.1 | 14203 | 6.3681 | *0.073* | 4837 | *123.9* | | |
| 8000 | 3631 | 47282 | 3.1616 | 0.0224 | 240.8 | 14177 | 6.3689 | *0.0699* | 5175.1 | *132.6* | | |
| 9000 | 3884.9 | 47142 | 3.1719 | 0.0225 | 240.7 | 14169 | 6.4287 | *0.0677* | 5708 | *146.4* | | |
| 10000 | 4028.4 | 47068 | 3.1773 | 0.0225 | 240.5 | 14156 | 6.427 | *0.0677* | 6025.9 | *154.5* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 1999 | 30497 | 2.722 | 0.025 | 156.3 | 9321.3 | 6.0787 | *0.0873* | 2657.3 | *67.76* | | *2.5447* |
| 4000 | 2266 | 30388 | 2.7326 | 0.0252 | 157.1 | 9367.7 | 6.1048 | *0.0835* | 3144.8 | *80.22* | | *2.3981* |
| 5000 | 2491.7 | 30004 | 2.7707 | 0.0252 | 156.1 | 9295.6 | 6.2112 | *0.0777* | 3609.2 | *92.23* | | *2.2863* |
| 6000 | 2703.7 | 29879 | 2.7832 | 0.0252 | 155.7 | 9272.1 | 6.2671 | *0.0748* | 4076.7 | *104.3* | | *2.2015* |
| 7000 | 2828.9 | 29812 | 2.7901 | 0.0252 | 155.6 | 9259.3 | 6.3246 | *0.0697* | 4371.5 | *111.9* | | *2.1326* |
| 8000 | 3011.6 | 29700 | 2.8016 | 0.0254 | 155.8 | 9270.6 | 6.4103 | *0.0675* | 4820.1 | *123.6* | | *2.074* |
| 9000 | 3158.7 | 29528 | 2.8194 | 0.0254 | 155.3 | 9237.7 | 6.4004 | *0.0657* | 5220.4 | *133.8* | | *2.0249* |
| 10000 | 3309.7 | 29443 | 2.8282 | 0.0254 | 155.1 | 9221.5 | 6.422 | *0.0644* | 5652.8 | *144.9* | | *1.9816* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2362.2 | 55246 | 2.667 | 0.0219 | 256.4 | 15315 | 5.872 | *0.0884* | 2880.8 | *73.2* | | |
| 4000 | 2729.8 | 55064 | 2.6766 | 0.0219 | 256 | 15286 | 5.9893 | *0.084* | 3448.6 | *87.8* | | |
| 5000 | 3045.9 | 54627 | 2.6998 | 0.022 | 255.3 | 15238 | 6.1389 | *0.0794* | 3972.7 | *101.4* | | |
| 6000 | 3313.2 | 54419 | 2.711 | 0.0221 | 255.5 | 15245 | 6.1922 | *0.0764* | 4439.1 | *113.4* | | |
| 7000 | 3512.2 | 54510 | 2.7061 | 0.0221 | 256.4 | 15299 | 6.2152 | *0.0704* | 4797.7 | *122.6* | | |
| 8000 | 3744.4 | 54287 | 2.7182 | 0.0222 | 256.2 | 15283 | 6.2287 | *0.0683* | 5243.9 | *134* | | |
| 9000 | 3948.7 | 54076 | 2.7297 | 0.0222 | 255.7 | 15249 | 6.2727 | *0.0677* | 5658.9 | *144.7* | | |
| 10000 | 4143.8 | 53953 | 2.7364 | 0.0222 | 255.8 | 15249 | 6.297 | *0.0653* | 6068.3 | *155.3* | | |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 1862.4 | 20827 | 3.1732 | 0.0278 | 123.1 | 5691.1 | 6.0894 | *0.0999* | 2937.6 | *60.42* | *1.9709* | *2.3641* |
| 4000 | 2074.1 | 20608 | 3.2103 | 0.0279 | 122.3 | 5651.4 | 6.2223 | *0.0929* | 3518 | *72.51* | *2.0242* | *2.2604* |
| 5000 | 2238.1 | 20521 | 3.2253 | 0.0279 | 122 | 5635.6 | 6.3124 | *0.0822* | 4026.2 | *83.11* | *2.0666* | *2.1867* |
| 6000 | 2371.6 | 20519 | 3.2256 | 0.0282 | 123.3 | 5693.4 | 6.3763 | *0.079* | 4440.3 | *91.75* | *2.1018* | *2.1267* |
| 7000 | 2509.1 | 20353 | 3.2546 | 0.0282 | 122.7 | 5662.6 | 6.4818 | *0.0735* | 4973.9 | *102.9* | *2.1321* | *2.076* |
| 8000 | 2588.3 | 20327 | 3.2592 | 0.0282 | 122.6 | 5657.9 | 6.4775 | *0.0744* | 5299.9 | *109.7* | *2.1587* | *2.0355* |
| 9000 | 2685.6 | 20242 | 3.2743 | 0.0282 | 122.3 | 5642 | 6.5562 | *0.069* | 5742.5 | *119* | *2.1824* | *1.9993* |
| 10000 | 2798.9 | 20149 | 3.2908 | 0.0282 | 122 | 5624.8 | 6.5541 | *0.0669* | 6310.5 | *130.8* | *2.2038* | *1.9683* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2158.7 | 37614 | 3.1187 | 0.0232 | 195.8 | 9070.8 | 5.9706 | *0.0945* | 2948 | *60.51* | | |
| 4000 | 2355.9 | 37457 | 3.1331 | 0.0233 | 195.8 | 9066.1 | 6.1397 | *0.0843* | 3329.4 | *68.53* | | |
| 5000 | 2804.8 | 37289 | 3.1486 | 0.0233 | 195.7 | 9059.4 | 6.1522 | *0.0829* | 4304 | *88.61* | | |
| 6000 | 3032.2 | 37182 | 3.1586 | 0.0233 | 195.5 | 9043.6 | 6.2311 | *0.0772* | 4868.9 | *100.4* | | |
| 7000 | 3236.5 | 37060 | 3.17 | 0.0233 | 195.1 | 9025.7 | 6.301 | *0.0721* | 5425.2 | *112* | | |
| 8000 | 3271.7 | 36841 | 3.1907 | 0.0235 | 195.3 | 9028.8 | 6.3598 | *0.0684* | 5523.7 | *114.1* | | |
| 9000 | 3490.2 | 36861 | 3.1888 | 0.0235 | 195.4 | 9031.8 | 6.3722 | *0.0708* | 6174.8 | *127.6* | | |
| 10000 | 3642.6 | 36649 | 3.2091 | 0.0235 | 194.8 | 9000.1 | 6.422 | *0.0676* | 6687.7 | *138.3* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 1827.3 | 23958 | 2.7225 | 0.0275 | 132.2 | 6196.9 | 5.8975 | *0.092* | 2727.8 | *55.92* | | *2.3773* |
| 4000 | 2105.1 | 23750 | 2.7484 | 0.0277 | 132.3 | 6196 | 6.0504 | *0.0828* | 3397.2 | *69.82* | | *2.2736* |
| 5000 | 2290.4 | 23585 | 2.7693 | 0.0277 | 131.8 | 6168.7 | 6.1444 | *0.0801* | 3919.6 | *80.69* | | *2.1958* |
| 6000 | 2448 | 23394 | 2.794 | 0.0277 | 131.2 | 6136.7 | 6.2615 | *0.0755* | 4422.8 | *91.22* | | *2.1334* |
| 7000 | 2541.2 | 23309 | 2.8051 | 0.0277 | 131 | 6122.6 | 6.2913 | *0.0704* | 4746.1 | *97.93* | | *2.084* |
| 8000 | 2638 | 23211 | 2.818 | 0.0277 | 130.7 | 6106.1 | 6.3656 | *0.0655* | 5107.9 | *105.5* | | *2.0417* |
| 9000 | 2779.1 | 23064 | 2.8376 | 0.0277 | 130.2 | 6081.3 | 6.4121 | *0.0643* | 5688.8 | *117.6* | | *2.0053* |
| 10000 | 2875.9 | 22979 | 2.8491 | 0.0277 | 130 | 6067 | 6.4481 | *0.0635* | 6125.9 | *126.7* | | *1.9735* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2163.2 | 43481 | 2.6621 | 0.023 | 210 | 9859.8 | 5.7226 | *0.0971* | 2873.6 | *58.73* | | |
| 4000 | 2538.8 | 43162 | 2.6835 | 0.0231 | 209.7 | 9838.4 | 5.8409 | *0.0843* | 3579.5 | *73.31* | | |
| 5000 | 2825.4 | 42882 | 2.7025 | 0.0231 | 209 | 9801.5 | 5.978 | *0.0808* | 4184.3 | *85.9* | | |
| 6000 | 3069.4 | 42502 | 2.7288 | 0.0231 | 208.1 | 9751.1 | 6.084 | *0.0729* | 4755.8 | *97.8* | | |
| 7000 | 3248.6 | 42308 | 2.7423 | 0.0232 | 208.5 | 9765.3 | 6.171 | *0.0701* | 5195.7 | *107* | | |
| 8000 | 3440.4 | 42144 | 2.7539 | 0.0232 | 208.1 | 9743.2 | 6.2123 | *0.066* | 5713 | *117.7* | | |
| 9000 | 3596.5 | 41991 | 2.7649 | 0.0232 | 207.7 | 9722.6 | 6.2626 | *0.0643* | 6165.6 | *127.2* | | |
| 10000 | 3738.2 | 41855 | 2.7747 | 0.0232 | 207.4 | 9704.2 | 6.3054 | *0.0632* | 6603.6 | *136.3* | | |

**Table C-28:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e=1 mm, p= 40 mm).

| Re Annulus | $U_o$ W/m².C | Inner Tube (smooth)† | | | | | Annulus (augmented) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Re_{s,h}$ | $Pr_h$ | $f_{s,i}$ | $Nu_{s,i}$ | $h_{s,i}$ W/m².C | $Pr_c$ | $f_a$ | $h_{a,o}$ W/m².C | $Nu_a$ | Augmentation†† $f_a/f_s$ | $Nu_a/Nu_s$ |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 1769.3 | 26669 | 3.1521 | 0.0253 | 146.7 | 8640.3 | 6.3108 | *0.0855* | 2316.7 | *59.29* | *1.2752* | *2.1997* |
| **4000** | 2053.9 | 26464 | 3.179 | 0.0254 | 146.1 | 8598.2 | 6.3979 | *0.0725* | 2835.2 | *72.67* | *1.3097* | *2.0894* |
| **5000** | 2255.6 | 26284 | 3.2028 | 0.0256 | 146.6 | 8619.8 | 6.5073 | *0.0662* | 3231.1 | *82.96* | *1.3371* | *2.0068* |
| **6000** | 2411.5 | 26329 | 3.1968 | 0.0257 | 147.2 | 8658.7 | 6.4287 | *0.0658* | 3553.3 | *91.12* | *1.3599* | *1.947* |
| **7000** | 2542.5 | 26307 | 3.1998 | 0.0258 | 147.6 | 8683.2 | 6.5381 | *0.0603* | 3839.9 | *98.63* | *1.3795* | *1.8931* |
| **8000** | 2722.4 | 26154 | 3.2203 | 0.0257 | 146.7 | 8621.9 | 6.5004 | *0.0581* | 4282.5 | *109.9* | *1.3967* | *1.8495* |
| **9000** | 2860.9 | 26033 | 3.2368 | 0.0258 | 146.8 | 8625.4 | 6.5226 | *0.0537* | 4634.4 | *119* | *1.4121* | *1.8121* |
| **10000** | 2982 | 25969 | 3.2456 | 0.0259 | 147.1 | 8640.8 | 6.6805 | *0.0518* | 4954.8 | *127.5* | *1.4259* | *1.7748* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 1990.2 | 48136 | 3.1 | 0.0221 | 240.2 | 14167 | 6.2343 | *0.0794* | 2379.6 | *60.83* | | |
| **4000** | 2359.5 | 47813 | 3.123 | 0.0222 | 240.3 | 14164 | 6.3091 | *0.0700* | 2927.6 | *74.93* | | |
| **5000** | 2616.4 | 47773 | 3.1259 | 0.0224 | 242.3 | 14282 | 6.3648 | *0.0661* | 3326.4 | *85.21* | | |
| **6000** | 2865.4 | 47529 | 3.1435 | 0.0225 | 241.7 | 14238 | 6.35 | *0.0634* | 3743 | *95.86* | | |
| **7000** | 3239.5 | 47370 | 3.1551 | 0.0225 | 241.3 | 14210 | 6.3738 | *0.0617* | 4410.9 | *113* | | |
| **8000** | 3301.4 | 47569 | 3.1406 | 0.0225 | 242.4 | 14281 | 6.4379 | *0.057* | 4518.5 | *115.9* | | |
| **9000** | 3458.7 | 47407 | 3.1524 | 0.0225 | 242 | 14252 | 6.4312 | *0.0543* | 4822 | *123.7* | | |
| **10000** | 3706.9 | 47263 | 3.1629 | 0.0225 | 241.6 | 14226 | 6.5056 | *0.0537* | 5322.6 | *136.6* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 1688.8 | 30808 | 2.6922 | 0.0247 | 155.4 | 9277.3 | 6.171 | *0.0809* | 2138.4 | *54.61* | | *2.2083* |
| **4000** | 2056.5 | 30559 | 2.7159 | 0.0249 | 155.9 | 9299.4 | 6.1907 | *0.0679* | 2762 | *70.55* | | *2.0993* |
| **5000** | 2164.1 | 30172 | 2.7539 | 0.0252 | 156.5 | 9327.3 | 6.3871 | *0.063* | 2956.6 | *75.76* | | *2.014* |
| **6000** | 2323.4 | 29988 | 2.7723 | 0.0252 | 156 | 9292.6 | 6.4128 | *0.0604* | 3266.8 | *83.75* | | *1.9506* |
| **7000** | 2512.6 | 30042 | 2.7668 | 0.0252 | 156.2 | 9302.9 | 6.3987 | *0.0585* | 3651.9 | *93.6* | | *1.8968* |
| **8000** | 2657.5 | 29758 | 2.7956 | 0.0256 | 157.1 | 9346.8 | 6.4254 | *0.0561* | 3957.2 | *101.5* | | *1.8546* |
| **9000** | 2773 | 29738 | 2.7977 | 0.0255 | 156.5 | 9310.4 | 6.4657 | *0.0529* | 4227.3 | *108.5* | | *1.8155* |
| **10000** | 2804.2 | 29886 | 2.7826 | 0.0258 | 158.5 | 9436.6 | 6.4767 | *0.0521* | 4270.4 | *109.6* | | *1.7805* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 1990 | 55653 | 2.6459 | 0.0218 | 255.6 | 15277 | 6.0542 | *0.0753* | 2346.8 | *59.82* | | |
| **4000** | 2374.5 | 54903 | 2.685 | 0.0218 | 254.6 | 15202 | 6.1226 | *0.0692* | 2903.8 | *74.1* | | |
| **5000** | 2621 | 54811 | 2.69 | 0.0218 | 254.4 | 15187 | 6.1812 | *0.0639* | 3281.9 | *83.82* | | |
| **6000** | 2907.5 | 55165 | 2.6712 | 0.0219 | 255.9 | 15282 | 6.2104 | *0.062* | 3737.4 | *95.5* | | |
| **7000** | 2971.4 | 54773 | 2.692 | 0.022 | 255.7 | 15261 | 6.345 | *0.058* | 3845.2 | *98.47* | | |
| **8000** | 3308.3 | 54299 | 2.7175 | 0.022 | 254.6 | 15186 | 6.2776 | *0.0574* | 4435.9 | *113.5* | | |
| **9000** | 3469.1 | 54134 | 2.7265 | 0.022 | 254.2 | 15160 | 6.323 | *0.0542* | 4732.9 | *121.2* | | |
| **10000** | 3731.1 | 54307 | 2.7171 | 0.022 | 254.6 | 15188 | 6.4287 | *0.0521* | 5230.6 | *134.1* | | |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 1841.2 | 20803 | 3.1773 | 0.0282 | 124.2 | 5745.5 | 6.1218 | *0.0818* | 2869.9 | *59.06* | *1.7132* | *2.0267* |
| **4000** | 2008 | 20728 | 3.1899 | 0.0282 | 124 | 5731.8 | 6.2327 | *0.0703* | 3301.9 | *68.07* | *1.7596* | *1.9562* |
| **5000** | 2170.1 | 20652 | 3.2028 | 0.0282 | 123.7 | 5717.8 | 6.323 | *0.0644* | 3770.9 | *77.85* | *1.7964* | *1.9022* |
| **6000** | 2281.1 | 20561 | 3.2184 | 0.0282 | 123.4 | 5701.2 | 6.3962 | *0.0597* | 4128.8 | *85.34* | *1.827* | *1.8612* |
| **7000** | 2399.9 | 20459 | 3.236 | 0.0286 | 124.3 | 5740.1 | 6.4455 | *0.0555* | 4508.3 | *93.25* | *1.8534* | *1.8264* |
| **8000** | 2473.4 | 20375 | 3.2507 | 0.0288 | 124.7 | 5753 | 6.4919 | *0.0523* | 4764.8 | *98.63* | *1.8765* | *1.7977* |
| **9000** | 2586.9 | 20324 | 3.2597 | 0.029 | 125.1 | 5771.8 | 6.5201 | *0.0500* | 5187.8 | *107.4* | *1.8971* | *1.7722* |
| **10000** | 2634.2 | 20309 | 3.2623 | 0.029 | 125.1 | 5769.1 | 6.5553 | *0.0476* | 5384.3 | *111.6* | *1.9157* | *1.7498* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2182.1 | 37751 | 3.1063 | 0.0232 | 196.2 | 9090.7 | 5.9439 | *0.0817* | 2989.6 | *61.34* | | |
| **4000** | 2471.6 | 37512 | 3.128 | 0.0232 | 195.6 | 9056 | 6.0748 | *0.0712* | 3566.8 | *73.34* | | |
| **5000** | 2670.1 | 37382 | 3.14 | 0.0233 | 196 | 9073.1 | 6.2191 | *0.0648* | 3991.8 | *82.27* | | |
| **6000** | 2882 | 37188 | 3.158 | 0.0233 | 195.5 | 9044.5 | 6.2479 | *0.0591* | 4492.7 | *92.64* | | |
| **7000** | 3023.5 | 37202 | 3.1567 | 0.0234 | 196.3 | 9082.6 | 6.3295 | *0.0559* | 4834.3 | *99.81* | | |
| **8000** | 3178.4 | 37060 | 3.17 | 0.0235 | 195.9 | 9061.5 | 6.3508 | *0.0527* | 5250.5 | *108.4* | | |
| **9000** | 3288.2 | 36890 | 3.1861 | 0.0235 | 195.5 | 9036.2 | 6.4087 | *0.0498* | 5567.6 | *115.1* | | |
| **10000** | 3403.2 | 36890 | 3.1861 | 0.0236 | 196.2 | 9071.8 | 6.4455 | *0.0477* | 5889 | *121.8* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 1818.3 | 24002 | 2.7171 | 0.027 | 130.2 | 6103.3 | 5.8975 | *0.0828* | 2727.8 | *55.92* | | *2.038* |
| **4000** | 2092.2 | 23761 | 2.7471 | 0.027 | 129.5 | 6064.8 | 6.0405 | *0.0719* | 3408.1 | *70.04* | | *1.9659* |
| **5000** | 2242.4 | 23525 | 2.7771 | 0.027 | 128.8 | 6026.7 | 6.2088 | *0.0635* | 3842.5 | *79.18* | | *1.9101* |
| **6000** | 2360.4 | 23369 | 2.7972 | 0.0274 | 129.8 | 6067.2 | 6.3189 | *0.059* | 4180.7 | *86.3* | | *1.867* |
| **7000** | 2496.5 | 23323 | 2.8032 | 0.0274 | 129.6 | 6059.6 | 6.4004 | *0.0555* | 4632.6 | *95.76* | | *1.8314* |
| **8000** | 2580.9 | 23190 | 2.8208 | 0.0277 | 130.6 | 6102.6 | 6.3615 | *0.0526* | 4900.8 | *101.2* | | *1.8034* |
| **9000** | 2664.2 | 23209 | 2.8182 | 0.0277 | 130.7 | 6105.8 | 6.4153 | *0.0493* | 5207.4 | *107.7* | | *1.7745* |
| **10000** | 2751.4 | 23130 | 2.8287 | 0.0279 | 131.1 | 6125 | 6.4371 | *0.0475* | 5533.7 | *114.4* | | *1.7524* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2147.2 | 43181 | 2.6821 | 0.0227 | 207.2 | 9718.7 | 5.7302 | *0.0824* | 2858.7 | *58.43* | | |
| **4000** | 2496.5 | 43072 | 2.6895 | 0.0227 | 206.9 | 9704.6 | 5.8684 | *0.0705* | 3515 | *72.02* | | |
| **5000** | 2718.1 | 42875 | 2.7029 | 0.0227 | 206.4 | 9679.1 | 5.99 | *0.0644* | 3975.7 | *81.63* | | |
| **6000** | 2957.7 | 42602 | 2.7218 | 0.0228 | 206.2 | 9663.7 | 6.0695 | *0.059* | 4513.8 | *92.8* | | |
| **7000** | 3103.7 | 42437 | 2.7333 | 0.0229 | 206.3 | 9662.2 | 6.1444 | *0.0558* | 4863.1 | *100.1* | | |
| **8000** | 3242.3 | 42238 | 2.7473 | 0.0229 | 205.8 | 9635.9 | 6.2104 | *0.0525* | 5220.9 | *107.6* | | |
| **9000** | 3350.6 | 42031 | 2.762 | 0.023 | 206.1 | 9648.3 | 6.4004 | *0.0499* | 5503 | *113.7* | | |
| **10000** | 3434.9 | 42129 | 2.755 | 0.023 | 206.4 | 9661.5 | 6.4371 | *0.0475* | 5729.1 | *118.5* | | |

**Table C-29:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e=2.2 mm, p= 10 mm).

| Re Annulus | $U_o$ W/m².C | Inner Tube (smooth)† | | | | | Annulus (augmented) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Re_{s,h}$ | $Pr_h$ | $f_{s,i}$ | $Nu_{s,i}$ | $h_{s,i}$ W/m².C | $Pr_c$ | $f_a$ | $h_{a,o}$ W/m².C | $Nu_a$ | Augmentation†† $f_a/f_s$ | $Nu_a/Nu_s$ |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2184.6 | 26480 | 3.1768 | 0.0248 | 143.6 | 8453.3 | 6.1624 | *0.3082* | 3112.3 | *79.47* | *5.8418* | *2.8705* |
| 4000 | 2479.9 | 26257 | 3.2064 | 0.025 | 144 | 8467.5 | 6.3165 | *0.2706* | 3745 | *95.86* | *5.9999* | *2.7203* |
| 5000 | 2724.3 | 26099 | 3.2279 | 0.0249 | 143 | 8405.7 | 6.3631 | *0.2647* | 4350.3 | *111.4* | *6.1254* | *2.6096* |
| 6000 | 2924.5 | 26010 | 3.2399 | 0.0248 | 142.3 | 8358.4 | 6.4581 | *0.2424* | 4902.5 | *125.8* | *6.2299* | *2.5215* |
| 7000 | 3076.7 | 25852 | 3.2617 | 0.025 | 142.8 | 8384.5 | 6.4379 | *0.2452* | 5333.9 | *136.8* | *6.3197* | *2.4522* |
| 8000 | 3275.8 | 25762 | 3.2743 | 0.025 | 142.5 | 8365.9 | 6.4472 | *0.2188* | 5972.8 | *153.2* | *6.3985* | *2.3931* |
| 9000 | 3446.1 | 25809 | 3.2677 | 0.0253 | 143.7 | 8433.6 | 6.475 | *0.2244* | 6517.7 | *167.3* | *6.4688* | *2.3411* |
| 10000 | 3547.8 | 25721 | 3.28 | 0.0253 | 143.6 | 8429.7 | 6.4953 | *0.206* | 6894.4 | *177* | *6.5324* | *2.2939* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2492.8 | 47961 | 3.1124 | 0.0221 | 240 | 14154 | 6.0573 | *0.2927* | 3136.1 | *79.94* | | |
| 4000 | 2920.7 | 47924 | 3.115 | 0.0221 | 240.1 | 14157 | 6.0894 | *0.2703* | 3844.7 | *98.05* | | |
| 5000 | 3311.5 | 47580 | 3.1398 | 0.0222 | 239.4 | 14106 | 6.1773 | *0.2529* | 4557.8 | *116.4* | | |
| 6000 | 3601.6 | 47101 | 3.1749 | 0.0222 | 238.5 | 14039 | 6.2271 | *0.2547* | 5136.2 | *131.3* | | |
| 7000 | 3876.3 | 47065 | 3.1776 | 0.0222 | 238.6 | 14041 | 6.2719 | *0.2353* | 5713.2 | *146.1* | | |
| 8000 | 4154.2 | 46819 | 3.1959 | 0.0223 | 238.4 | 14024 | 6.3091 | *0.2264* | 6342.2 | *162.3* | | |
| 9000 | 4313.6 | 46416 | 3.2265 | 0.0223 | 237.4 | 13952 | 6.3574 | *0.2225* | 6740.1 | *172.6* | | |
| 10000 | 4537.4 | 46753 | 3.2009 | 0.0223 | 238.5 | 14030 | 6.4648 | *0.2057* | 7279.1 | *186.8* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2128.5 | 30393 | 2.7321 | 0.0244 | 153.2 | 9135.1 | 5.9624 | *0.3011* | 2911.9 | *74.1* | | *2.8868* |
| 4000 | 2435 | 30255 | 2.7457 | 0.0245 | 153.1 | 9126.9 | 6.0649 | *0.2676* | 3519.2 | *89.71* | | *2.7344* |
| 5000 | 2707.2 | 30045 | 2.7666 | 0.0246 | 152.9 | 9105.2 | 6.1087 | *0.261* | 4122.6 | *105.2* | | *2.6246* |
| 6000 | 2973.2 | 29597 | 2.8122 | 0.0247 | 152.2 | 9055.6 | 6.2073 | *0.2502* | 4788.5 | *122.4* | | *2.5358* |
| 7000 | 3063.4 | 29706 | 2.8009 | 0.0249 | 153.6 | 9141.4 | 6.2953 | *0.2438* | 4997.2 | *127.9* | | *2.4603* |
| 8000 | 3280.1 | 29586 | 2.8134 | 0.025 | 153.9 | 9151.3 | 6.3238 | *0.2243* | 5596.4 | *143.3* | | *2.4006* |
| 9000 | 3400 | 29452 | 2.8273 | 0.0251 | 153.8 | 9142.3 | 6.3722 | *0.219* | 5959.3 | *152.7* | | *2.3487* |
| 10000 | 3546.8 | 29253 | 2.8483 | 0.0253 | 154 | 9152.8 | 6.4145 | *0.2052* | 6419.6 | *164.6* | | *2.3024* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2402.4 | 55799 | 2.6384 | 0.0219 | 257.3 | 15380 | 5.8051 | *0.2978* | 2938.2 | *74.57* | | |
| 4000 | 2886.3 | 55123 | 2.6735 | 0.0219 | 256 | 15290 | 5.9202 | *0.2745* | 3701.9 | *94.14* | | |
| 5000 | 3213.6 | 54962 | 2.6819 | 0.022 | 256.1 | 15293 | 5.9624 | *0.2602* | 4257.8 | *108.4* | | |
| 6000 | 3720.5 | 54171 | 2.7245 | 0.022 | 254.3 | 15166 | 6.0103 | *0.2481* | 5212.7 | *132.8* | | |
| 7000 | 4076.3 | 54081 | 2.7294 | 0.022 | 254.4 | 15171 | 6.1397 | *0.2354* | 5938 | *151.6* | | |
| 8000 | 4264.6 | 53790 | 2.7455 | 0.0221 | 254.1 | 15145 | 6.1686 | *0.2266* | 6351.6 | *162.2* | | |
| 9000 | 4534.3 | 53457 | 2.7641 | 0.0221 | 253.8 | 15121 | 6.1836 | *0.2096* | 6974.7 | *178.1* | | |
| 10000 | 4707.2 | 53518 | 2.7607 | 0.0221 | 254.1 | 15140 | 6.2311 | *0.2133* | 7387 | *188.8* | | |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2091.8 | 20653 | 3.2026 | 0.0294 | 127.5 | 5892.1 | 6.0994 | *0.3531* | 3470.1 | *71.38* | *7.5635* | *2.4688* |
| 4000 | 2245.5 | 20559 | 3.2187 | 0.0294 | 127.2 | 5874.1 | 6.2407 | *0.3392* | 3923.5 | *80.89* | *7.7681* | *2.3763* |
| 5000 | 2352.8 | 20477 | 3.2329 | 0.0294 | 126.9 | 5858.3 | 6.301 | *0.3311* | 4272.7 | *88.18* | *7.9307* | *2.3091* |
| 6000 | 2442.6 | 20430 | 3.2411 | 0.0297 | 128 | 5906.2 | 6.3656 | *0.3211* | 4546.4 | *93.92* | *8.066* | *2.2532* |
| 7000 | 2518.2 | 20403 | 3.2458 | 0.0299 | 128.5 | 5929.2 | 6.4615 | *0.3159* | 4798.5 | *99.28* | *8.1822* | *2.2085* |
| 8000 | 2594 | 20354 | 3.2543 | 0.0297 | 127.7 | 5891.4 | 6.5226 | *0.3137* | 5112.7 | *105.9* | *8.2842* | *2.1703* |
| 9000 | 2653.7 | 20197 | 3.2823 | 0.0298 | 127.1 | 5860.5 | 6.5141 | *0.306* | 5378.4 | *111.4* | *8.3753* | *2.1397* |
| 10000 | 2713 | 20176 | 3.286 | 0.0298 | 127 | 5856.5 | 6.5865 | *0.2991* | 5631.9 | *116.8* | *8.4576* | *2.1086* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2674.9 | 37008 | 3.1749 | 0.0237 | 197.3 | 9125.2 | 5.8895 | *0.3621* | 3991.5 | *81.82* | | |
| 4000 | 2883.1 | 37107 | 3.1656 | 0.0234 | 196 | 9068.4 | 6.0405 | *0.3472* | 4489 | *92.25* | | |
| 5000 | 3040.1 | 36904 | 3.1847 | 0.0235 | 195.5 | 9038.3 | 6.1374 | *0.3378* | 4891.2 | *100.7* | | |
| 6000 | 3179.7 | 36818 | 3.1929 | 0.0235 | 195.3 | 9025.4 | 6.2889 | *0.32* | 5267.6 | *108.7* | | |
| 7000 | 3281.4 | 36567 | 3.217 | 0.0237 | 196.1 | 9058.6 | 6.3238 | *0.3171* | 5538.8 | *114.3* | | |
| 8000 | 3360.7 | 36579 | 3.2159 | 0.0236 | 195.4 | 9025 | 6.3805 | *0.3204* | 5783.7 | *119.5* | | |
| 9000 | 3439.4 | 36769 | 3.1976 | 0.0235 | 195.1 | 9018.1 | 6.3945 | *0.3101* | 6024.3 | *124.5* | | |
| 10000 | 3437 | 36488 | 3.2246 | 0.0236 | 195.1 | 9011.4 | 6.494 | *0.3008* | 6020.3 | *124.6* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2098.3 | 23676 | 2.7577 | 0.0288 | 136.3 | 6380.8 | 5.8575 | *0.3493* | 3321.5 | *68.05* | | *2.4816* |
| 4000 | 2303.7 | 23466 | 2.7846 | 0.0292 | 137 | 6409 | 6.0542 | *0.331* | 3855.9 | *79.26* | | *2.388* |
| 5000 | 2458.9 | 23413 | 2.7915 | 0.0289 | 135.5 | 6335.1 | 6.1164 | *0.3321* | 4349.1 | *89.49* | | *2.3204* |
| 6000 | 2549.4 | 23318 | 2.8039 | 0.0289 | 135.2 | 6318.5 | 6.3541 | *0.3262* | 4650.4 | *96.06* | | *2.2591* |
| 7000 | 2666.2 | 23216 | 2.8173 | 0.0292 | 136.2 | 6364.7 | 6.3262 | *0.3116* | 5022 | *103.7* | | *2.2183* |
| 8000 | 2784.1 | 23141 | 2.8273 | 0.0296 | 137.3 | 6415 | 6.3369 | *0.313* | 5416.9 | *111.9* | | *2.1821* |
| 9000 | 2870.3 | 23070 | 2.8368 | 0.0296 | 137.1 | 6402.1 | 6.4078 | *0.3063* | 5764.7 | *119.2* | | *2.1478* |
| 10000 | 2983.6 | 22822 | 2.8704 | 0.0298 | 136.9 | 6388.6 | 6.4741 | *0.3032* | 6254.7 | *129.4* | | *2.1162* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2441.3 | 43152 | 2.6842 | 0.0233 | 211 | 9898 | 5.7261 | *0.3493* | 3380.9 | *69.1* | | |
| 4000 | 2934.8 | 42771 | 2.7101 | 0.0232 | 209.6 | 9827.1 | 5.8323 | *0.3432* | 4423.1 | *90.57* | | |
| 5000 | 3213.1 | 42312 | 2.7421 | 0.0233 | 209.4 | 9805.7 | 5.9247 | *0.3303* | 5093.4 | *104.5* | | |
| 6000 | 3515.4 | 42091 | 2.7577 | 0.0233 | 208.8 | 9775.8 | 6.081 | *0.3322* | 5909.4 | *121.5* | | |
| 7000 | 3610.6 | 42283 | 2.7441 | 0.0232 | 208.4 | 9761.9 | 6.0864 | *0.3259* | 6189.7 | *127.3* | | |
| 8000 | 3785.7 | 42117 | 2.7559 | 0.0233 | 208.9 | 9779.3 | 6.1087 | *0.3251* | 6713.7 | *138.1* | | |
| 9000 | 3962.7 | 41844 | 2.7755 | 0.0234 | 208.2 | 9742.2 | 6.1796 | *0.3198* | 7314.2 | *150.7* | | |
| 10000 | 4108.3 | 41580 | 2.7947 | 0.0234 | 207.6 | 9706.1 | 6.297 | *0.3113* | 7852 | *162* | | |

**Table C-30:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e=2.2 mm, p= 20 mm).

| Re Annulus | $U_o$ W/m².C | Inner Tube (smooth)† | | | | | Annulus (augmented) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Re_{s,h}$ | $Pr_h$ | $f_{s,i}$ | $Nu_{s,i}$ | $h_{s,i}$ W/m².C | $Pr_c$ | $f_a$ | $h_{a,o}$ W/m².C | $Nu_a$ | Augmentation†† $f_a/f_s$ | $Nu_a/Nu_s$ |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 2348.4 | 26435 | 3.1828 | 0.0251 | 145 | 8533.2 | 6.1288 | *0.2293* | 3440.8 | *87.81* | *4.1683* | *2.8552* |
| **4000** | 2626.6 | 26152 | 3.2206 | 0.0252 | 144.7 | 8504.7 | 6.2889 | *0.2068* | 4080.1 | *104.4* | *4.2811* | *2.7595* |
| **5000** | 2892.3 | 26008 | 3.2402 | 0.0253 | 144.3 | 8474.9 | 6.2591 | *0.2016* | 4769.8 | *122* | *4.3707* | *2.6949* |
| **6000** | 3133.7 | 25967 | 3.2458 | 0.0254 | 144.6 | 8495.5 | 6.3124 | *0.1884* | 5454.3 | *139.6* | *4.4453* | *2.6389* |
| **7000** | 3280.8 | 25750 | 3.276 | 0.0254 | 144 | 8450.1 | 6.3714 | *0.1881* | 5941.2 | *152.2* | *4.5093* | *2.5917* |
| **8000** | 3522 | 25701 | 3.2829 | 0.0255 | 144.6 | 8483 | 6.4153 | *0.1773* | 6758.5 | *173.3* | *4.5655* | *2.5519* |
| **9000** | 3653.5 | 25538 | 3.3059 | 0.0256 | 144.3 | 8462.9 | 6.4898 | *0.1766* | 7277 | *186.8* | *4.6157* | *2.5154* |
| **10000** | 3723.8 | 25434 | 3.3208 | 0.0256 | 144 | 8440.8 | 6.5209 | *0.1814* | 7581.3 | *194.7* | *4.6611* | *2.4852* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2698.5 | 47876 | 3.1185 | 0.0222 | 240.4 | 14175 | 6.0103 | *0.229* | 3467.5 | *88.31* | | |
| **4000** | 3096.2 | 47470 | 3.1478 | 0.0222 | 239.7 | 14122 | 6.1118 | *0.2084* | 4158.1 | *106.1* | | |
| **5000** | 3440.4 | 47308 | 3.1597 | 0.0222 | 239.3 | 14093 | 6.1172 | *0.1982* | 4807.3 | *122.7* | | |
| **6000** | 3770 | 46973 | 3.1844 | 0.0223 | 239.1 | 14069 | 6.1828 | *0.1915* | 5480.4 | *140* | | |
| **7000** | 3998.8 | 47135 | 3.1724 | 0.0224 | 239.8 | 14115 | 6.2471 | *0.1905* | 5968.1 | *152.6* | | |
| **8000** | 4227.6 | 46815 | 3.1962 | 0.0224 | 239 | 14058 | 6.2986 | *0.1788* | 6506.4 | *166.5* | | |
| **9000** | 4460.7 | 46563 | 3.2152 | 0.0224 | 238.8 | 14039 | 6.3744 | *0.1781* | 7080.7 | *181.4* | | |
| **10000** | 4638.9 | 46446 | 3.2241 | 0.0225 | 238.9 | 14044 | 6.4084 | *0.1831* | 7539.1 | *193.3* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 2388.1 | 30033 | 2.7677 | 0.0247 | 153.4 | 9136.3 | 5.9483 | *0.2246* | 3420.5 | *87.03* | | *2.8719* |
| **4000** | 2693.2 | 29864 | 2.7848 | 0.0249 | 154 | 9170.8 | 6.0398 | *0.2034* | 4075.2 | *103.8* | | *2.7757* |
| **5000** | 2948.1 | 29592 | 2.8127 | 0.025 | 153.9 | 9152.6 | 6.1726 | *0.1892* | 4694 | *119.9* | | *2.7042* |
| **6000** | 3202.7 | 29673 | 2.8044 | 0.025 | 154.1 | 9167.7 | 6.2311 | *0.1849* | 5368.4 | *137.2* | | *2.6474* |
| **7000** | 3388.8 | 29512 | 2.821 | 0.025 | 153.7 | 9137.5 | 6.2359 | *0.1896* | 5927.2 | *151.5* | | *2.602* |
| **8000** | 3563.7 | 29137 | 2.8607 | 0.025 | 152.6 | 9066.2 | 6.3664 | *0.1722* | 6525.3 | *167.2* | | *2.5589* |
| **9000** | 3714 | 28997 | 2.8758 | 0.025 | 152.2 | 9039.5 | 6.4176 | *0.1718* | 7065.8 | *181.2* | | *2.5217* |
| **10000** | 3852.2 | 28861 | 2.8906 | 0.0251 | 151.9 | 9013.5 | 6.464 | *0.1756* | 7604.1 | *195.1* | | *2.4906* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2801.3 | 55161 | 2.6715 | 0.0221 | 257.2 | 15362 | 5.7275 | *0.2219* | 3558.9 | *90.2* | | |
| **4000** | 3180.6 | 54656 | 2.6982 | 0.0221 | 256.2 | 15292 | 5.8858 | *0.213* | 4200.1 | *106.7* | | |
| **5000** | 3527 | 54163 | 2.7249 | 0.0221 | 255.3 | 15224 | 5.9247 | *0.2005* | 4834 | *122.9* | | |
| **6000** | 3795.3 | 54444 | 2.7097 | 0.0221 | 256.2 | 15288 | 5.9975 | *0.1958* | 5343.6 | *136.1* | | |
| **7000** | 4073.2 | 54163 | 2.7249 | 0.0222 | 255.9 | 15263 | 6.0527 | *0.1938* | 5915.6 | *150.8* | | |
| **8000** | 4335.1 | 53778 | 2.7461 | 0.0222 | 255.1 | 15201 | 6.1195 | *0.1813* | 6497.5 | *165.8* | | |
| **9000** | 4442.3 | 53501 | 2.7616 | 0.0222 | 254.9 | 15186 | 6.2336 | *0.1783* | 6744.7 | *172.4* | | |
| **10000** | 4606.3 | 53331 | 2.7712 | 0.0223 | 254.7 | 15168 | 6.2809 | *0.182* | 7134.5 | *182.5* | | |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 2051.2 | 20553 | 3.2198 | 0.0292 | 126.5 | 5844.1 | 6.1343 | *0.3045* | 3377.4 | *69.51* | *5.3966* | *2.4381* |
| **4000** | 2212 | 20456 | 3.2366 | 0.0294 | 126.8 | 5854.2 | 6.2144 | *0.2805* | 3831.8 | *78.97* | *5.5426* | *2.3998* |
| **5000** | 2362.9 | 20327 | 3.2592 | 0.0294 | 126.3 | 5829.4 | 6.2953 | *0.2639* | 4323.6 | *89.22* | *5.6586* | *2.372* |
| **6000** | 2478.3 | 20375 | 3.2507 | 0.0301 | 129 | 5952.1 | 6.3664 | *0.2518* | 4640.2 | *95.86* | *5.7552* | *2.3505* |
| **7000** | 2569.4 | 20161 | 3.2886 | 0.029 | 124.5 | 5740.8 | 6.4741 | *0.2375* | 5145.4 | *106.5* | *5.8381* | *2.3309* |
| **8000** | 2701 | 20274 | 3.2686 | 0.0297 | 127.4 | 5875.6 | 6.4987 | *0.2138* | 5561.2 | *115.1* | *5.9109* | *2.3167* |
| **9000** | 2721 | 20131 | 3.2941 | 0.029 | 124.4 | 5734.9 | 6.497 | *0.2086* | 5798.2 | *120* | *5.9758* | *2.3029* |
| **10000** | 2812.8 | 20091 | 3.3012 | 0.0294 | 125.5 | 5783.7 | 6.5555 | *0.2033* | 6168.8 | *127.8* | *6.0345* | *2.2901* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2484.5 | 37518 | 3.1275 | 0.0233 | 196.4 | 9093.1 | 5.8735 | *0.3152* | 3587.4 | *73.51* | | |
| **4000** | 2793.6 | 37199 | 3.157 | 0.0233 | 195.5 | 9046.2 | 6.0902 | *0.2835* | 4281 | *88.05* | | |
| **5000** | 2966.6 | 36971 | 3.1784 | 0.0233 | 194.9 | 9012.4 | 6.1914 | *0.2718* | 4711.3 | *97.06* | | |
| **6000** | 3149.3 | 36939 | 3.1814 | 0.0235 | 195.6 | 9043.5 | 6.2359 | *0.2561* | 5178.1 | *106.8* | | |
| **7000** | 3297.4 | 36631 | 3.2109 | 0.0235 | 194.8 | 8997.4 | 6.2856 | *0.2421* | 5610.8 | *115.8* | | |
| **8000** | 3422 | 36429 | 3.2304 | 0.0237 | 195.7 | 9037.7 | 6.301 | *0.2185* | 5961.7 | *123* | | |
| **9000** | 3575.4 | 36572 | 3.2165 | 0.0236 | 195.4 | 9024 | 6.3879 | *0.2083* | 6451 | *133.3* | | |
| **10000** | 3678.8 | 36500 | 3.2235 | 0.0236 | 195.2 | 9013.2 | 6.4254 | *0.2032* | 6802.4 | *140.7* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 2158 | 23589 | 2.7689 | 0.0281 | 133.2 | 6235 | 5.8575 | *0.3167* | 3523.1 | *72.17* | | *2.4526* |
| **4000** | 2359 | 23459 | 2.7855 | 0.0281 | 132.8 | 6213.1 | 6.0367 | *0.2855* | 4103 | *84.31* | | *2.4142* |
| **5000** | 2545.2 | 23276 | 2.8095 | 0.0281 | 132.3 | 6182 | 6.1343 | *0.2671* | 4721.1 | *97.17* | | *2.3846* |
| **6000** | 2639.8 | 23132 | 2.8284 | 0.0285 | 133.2 | 6221.9 | 6.2615 | *0.2491* | 5028 | *103.7* | | *2.3602* |
| **7000** | 2745.6 | 23059 | 2.8382 | 0.0285 | 133 | 6209.2 | 6.3369 | *0.2341* | 5437.2 | *112.3* | | *2.34* |
| **8000** | 2815.9 | 23004 | 2.8457 | 0.0285 | 132.8 | 6199.5 | 6.4037 | *0.2111* | 5729 | *118.4* | | *2.3238* |
| **9000** | 2923.7 | 22795 | 2.8742 | 0.0281 | 130.7 | 6099.6 | 6.3829 | *0.2077* | 6307.6 | *130.3* | | *2.3107* |
| **10000** | 2995.5 | 22789 | 2.875 | 0.0287 | 132.8 | 6193.7 | 6.486 | *0.1956* | 6531.7 | *135.2* | | *2.2961* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2586.4 | 42667 | 2.7173 | 0.0231 | 208.5 | 9773 | 5.6851 | *0.3292* | 3685 | *75.27* | | |
| **4000** | 2997.3 | 42589 | 2.7227 | 0.0231 | 208.3 | 9762.7 | 5.788 | *0.2998* | 4582.2 | *93.76* | | |
| **5000** | 3238 | 42398 | 2.736 | 0.0231 | 207.9 | 9737.3 | 5.9188 | *0.2798* | 5177.6 | *106.2* | | |
| **6000** | 3509.8 | 42206 | 2.7495 | 0.0232 | 208.3 | 9751.5 | 6.0013 | *0.2609* | 5903.3 | *121.2* | | |
| **7000** | 3706.3 | 41996 | 2.7645 | 0.0232 | 207.7 | 9723.2 | 6.0971 | *0.2445* | 6495.3 | *133.6* | | |
| **8000** | 3863.3 | 41882 | 2.7727 | 0.0233 | 207.9 | 9727.6 | 6.1382 | *0.2229* | 6990.7 | *143.9* | | |
| **9000** | 3958.1 | 41802 | 2.7784 | 0.0234 | 208.1 | 9736.6 | 6.2144 | *0.2128* | 7302 | *150.5* | | |
| **10000** | 4167.7 | 41532 | 2.7982 | 0.0234 | 207.4 | 9699.6 | 6.2679 | *0.2024* | 8076.8 | *166.6* | | |

**Table C-31:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e=2.2 mm, p= 30 mm).

| Re Annulus | $U_o$ W/m².C | Inner Tube (smooth)† | | | | | Annulus (augmented) | | | | Augmentation†† | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Re_{s,h}$ | $Pr_h$ | $f_{s,i}$ | $Nu_{s,i}$ | $h_{s,i}$ W/m².C | $Pr_c$ | $f_a$ | $h_{a,o}$ W/m².C | $Nu_a$ | $f_a/f_s$ | $Nu_a/Nu_s$ |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2274.1 | 26501 | 3.174 | 0.025 | 144.7 | 8517 | 6.1126 | 0.1893 | 3286.3 | 83.84 | 3.4214 | 2.6641 |
| 4000 | 2474.9 | 26393 | 3.1883 | 0.025 | 144.4 | 8495.2 | 6.2335 | 0.1609 | 3727.4 | 95.28 | 3.5139 | 2.6096 |
| 5000 | 2685 | 26222 | 3.2111 | 0.0252 | 144.9 | 8519.1 | 6.3238 | 0.1394 | 4218.7 | 108 | 3.5875 | 2.5667 |
| 6000 | 2833.1 | 26129 | 3.2237 | 0.0252 | 144.6 | 8500 | 6.3623 | 0.1302 | 4602.6 | 117.9 | 3.6487 | 2.5337 |
| 7000 | 3043.4 | 25928 | 3.2512 | 0.0254 | 144.5 | 8487.4 | 6.4287 | 0.134 | 5190 | 133.1 | 3.7013 | 2.5083 |
| 8000 | 3196.6 | 25862 | 3.2603 | 0.0254 | 144.3 | 8473.7 | 6.4455 | 0.121 | 5658.9 | 145.1 | 3.7474 | 2.484 |
| 9000 | 3298.1 | 25778 | 3.272 | 0.0255 | 144.6 | 8485 | 6.6004 | 0.1156 | 5978.5 | 153.7 | 3.7886 | 2.46 |
| 10000 | 3402.4 | 25733 | 3.2784 | 0.0256 | 144.9 | 8504.2 | 6.5466 | 0.1146 | 6318 | 162.3 | 3.8258 | 2.4447 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2738 | 47795 | 3.1243 | 0.0222 | 240.2 | 14161 | 5.9602 | 0.1894 | 3534 | 89.93 | | |
| 4000 | 3128.4 | 47311 | 3.1594 | 0.0222 | 239.3 | 14094 | 6.068 | 0.1595 | 4219.2 | 107.6 | | |
| 5000 | 3344.2 | 47544 | 3.1424 | 0.0223 | 240.2 | 14149 | 6.2033 | 0.1443 | 4614.6 | 117.9 | | |
| 6000 | 3540.3 | 47363 | 3.1556 | 0.0223 | 239.8 | 14121 | 6.3018 | 0.1325 | 5000.6 | 128 | | |
| 7000 | 3760.8 | 47285 | 3.1613 | 0.0223 | 239.6 | 14107 | 6.2752 | 0.1298 | 5454.5 | 139.5 | | |
| 8000 | 3894.6 | 47028 | 3.1803 | 0.0223 | 239.4 | 14088 | 6.3829 | 0.1178 | 5744.3 | 147.2 | | |
| 9000 | 3981.1 | 47065 | 3.1776 | 0.0224 | 239.6 | 14103 | 6.4346 | 0.1159 | 5931.2 | 152.1 | | |
| 10000 | 4165.9 | 46819 | 3.1959 | 0.0224 | 239 | 14059 | 6.4634 | 0.1106 | 6361.2 | 163.2 | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2292.5 | 30506 | 2.7211 | 0.0247 | 154.6 | 9222.7 | 5.9151 | 0.1745 | 3215.7 | 81.77 | | 2.678 |
| 4000 | 2613.6 | 30015 | 2.7695 | 0.0247 | 153.3 | 9132.9 | 5.9803 | 0.1492 | 3903.6 | 99.37 | | 2.6258 |
| 5000 | 2840.2 | 29956 | 2.7755 | 0.025 | 154.6 | 9204.5 | 6.1164 | 0.1361 | 4412.8 | 112.6 | | 2.5813 |
| 6000 | 3024 | 29834 | 2.7878 | 0.0251 | 154.8 | 9214.5 | 6.2239 | 0.1275 | 4869.7 | 124.5 | | 2.5472 |
| 7000 | 3221.3 | 29559 | 2.8162 | 0.0252 | 154.6 | 9195 | 6.3254 | 0.1265 | 5410.2 | 138.5 | | 2.5178 |
| 8000 | 3342.9 | 29465 | 2.8259 | 0.0253 | 154.6 | 9193.4 | 6.3385 | 0.115 | 5762.8 | 147.6 | | 2.4948 |
| 9000 | 3491.3 | 29297 | 2.8436 | 0.0253 | 154.2 | 9161.2 | 6.3995 | 0.1095 | 6235.3 | 159.8 | | 2.4721 |
| 10000 | 3615 | 29167 | 2.8574 | 0.0253 | 154.1 | 9152.3 | 6.4455 | 0.1064 | 6646.8 | 170.5 | | 2.4533 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2653.4 | 55220 | 2.6683 | 0.0219 | 256.2 | 15305 | 5.7471 | 0.1654 | 3326.5 | 84.34 | | |
| 4000 | 3028.3 | 55102 | 2.6746 | 0.022 | 256.2 | 15302 | 5.8222 | 0.1464 | 3937.8 | 99.97 | | |
| 5000 | 3372.1 | 54048 | 2.7312 | 0.022 | 254.4 | 15166 | 5.9446 | 0.1339 | 4553.4 | 115.8 | | |
| 6000 | 3741.8 | 54291 | 2.718 | 0.022 | 254.9 | 15205 | 5.9983 | 0.1277 | 5249.4 | 133.7 | | |
| 7000 | 4003.5 | 54134 | 2.7265 | 0.0221 | 254.9 | 15200 | 6.0634 | 0.1257 | 5780.1 | 147.3 | | |
| 8000 | 4249.5 | 53941 | 2.7371 | 0.0221 | 254.4 | 15169 | 6.1257 | 0.1141 | 6313.3 | 161.1 | | |
| 9000 | 4402.3 | 53491 | 2.7622 | 0.0221 | 253.7 | 15116 | 6.2158 | 0.1083 | 6668.1 | 170.4 | | |
| 10000 | 4627.1 | 53233 | 2.7768 | 0.0222 | 253.5 | 15094 | 6.2622 | 0.1064 | 7203.6 | 184.2 | | |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2124.6 | 20647 | 3.2037 | 0.029 | 126.2 | 5833.1 | 6.0733 | 0.227 | 3585.6 | 73.72 | 4.4296 | 2.2419 |
| 4000 | 2354.1 | 20504 | 3.2281 | 0.0294 | 127 | 5863.6 | 6.1452 | 0.2164 | 4273.7 | 87.98 | 4.5495 | 2.242 |
| 5000 | 2505 | 20235 | 3.2754 | 0.0297 | 127.2 | 5868.1 | 6.2575 | 0.2056 | 4795.3 | 98.89 | 4.6446 | 2.2379 |
| 6000 | 2691.4 | 20364 | 3.2526 | 0.0294 | 126.5 | 5836.5 | 6.3254 | 0.201 | 5559.2 | 114.8 | 4.7239 | 2.2376 |
| 7000 | 2795.3 | 20218 | 3.2786 | 0.0298 | 127.2 | 5864.6 | 6.3854 | 0.1921 | 5988.9 | 123.8 | 4.792 | 2.2374 |
| 8000 | 2935.5 | 20187 | 3.284 | 0.0298 | 127.1 | 5858.6 | 6.4589 | 0.1842 | 6680.4 | 138.2 | 4.8517 | 2.2361 |
| 9000 | 2979.4 | 20037 | 3.311 | 0.0298 | 126.5 | 5829.2 | 6.5016 | 0.1799 | 6958.1 | 144.1 | 4.905 | 2.2358 |
| 10000 | 3067.9 | 19980 | 3.3215 | 0.0298 | 126.3 | 5817.8 | 6.5332 | 0.1759 | 7481.1 | 155 | 4.9532 | 2.2346 |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2549.8 | 37623 | 3.1179 | 0.0233 | 196.6 | 9108.4 | 5.8735 | 0.2318 | 3722.4 | 76.28 | | |
| 4000 | 2940.1 | 37147 | 3.1618 | 0.0234 | 196.1 | 9074.4 | 5.9587 | 0.216 | 4626.7 | 94.95 | | |
| 5000 | 3216.7 | 37159 | 3.1607 | 0.0233 | 195.4 | 9040.2 | 6.1226 | 0.2107 | 5364.2 | 110.4 | | |
| 6000 | 3474.8 | 36841 | 3.1907 | 0.0233 | 194.5 | 8993.2 | 6.1733 | 0.2067 | 6146.8 | 126.6 | | |
| 7000 | 3634.3 | 36760 | 3.1984 | 0.0235 | 195.1 | 9016.8 | 6.2136 | 0.2002 | 6649.9 | 137 | | |
| 8000 | 3806.7 | 36636 | 3.2103 | 0.0235 | 194.8 | 8998.2 | 6.2679 | 0.1915 | 7263.9 | 149.8 | | |
| 9000 | 3966.8 | 36507 | 3.2228 | 0.0232 | 192.9 | 8908 | 6.3051 | 0.1815 | 7948.1 | 164 | | |
| 10000 | 4145.4 | 36357 | 3.2375 | 0.0235 | 194 | 8956.3 | 6.3827 | 0.1805 | 8648.4 | 178.7 | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2179.6 | 23734 | 2.7505 | 0.0288 | 136.5 | 6390.7 | 5.7916 | 0.2282 | 3526.5 | 72.16 | | 2.2587 |
| 4000 | 2431.3 | 23509 | 2.7791 | 0.0288 | 135.8 | 6351.7 | 5.9736 | 0.21 | 4255.2 | 87.34 | | 2.2543 |
| 5000 | 2623.2 | 23265 | 2.8108 | 0.0292 | 136.4 | 6373.4 | 6.1273 | 0.2058 | 4866 | 100.1 | | 2.2497 |
| 6000 | 2755 | 23083 | 2.835 | 0.0296 | 137.1 | 6404.6 | 6.2073 | 0.2016 | 5315.6 | 109.5 | | 2.2457 |
| 7000 | 2869.2 | 23030 | 2.8422 | 0.0292 | 135.6 | 6331.5 | 6.2623 | 0.1936 | 5824.8 | 120.1 | | 2.2438 |
| 8000 | 2987.4 | 22941 | 2.8541 | 0.0296 | 136.7 | 6378.9 | 6.3075 | 0.1899 | 6281.9 | 129.7 | | 2.2422 |
| 9000 | 3079.6 | 22915 | 2.8577 | 0.03 | 137.9 | 6437 | 6.3459 | 0.1884 | 6634.3 | 137 | | 2.2441 |
| 10000 | 3180.2 | 22737 | 2.8822 | 0.03 | 137.3 | 6404.1 | 6.4336 | 0.1765 | 7164.4 | 148.2 | | 2.2407 |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2619.1 | 43288 | 2.675 | 0.0231 | 210 | 9854.9 | 5.5756 | 0.2289 | 3738.6 | 76.21 | | |
| 4000 | 3024.1 | 42830 | 2.7061 | 0.0231 | 208.9 | 9794.6 | 5.6962 | 0.2121 | 4637.2 | 94.73 | | |
| 5000 | 3307.8 | 42498 | 2.729 | 0.0231 | 208.1 | 9750.6 | 5.8294 | 0.2114 | 5353.7 | 109.6 | | |
| 6000 | 3512.3 | 41863 | 2.7741 | 0.0231 | 206.6 | 9665.5 | 5.996 | 0.201 | 5946.1 | 122.1 | | |
| 7000 | 3688.2 | 42091 | 2.7577 | 0.0232 | 208 | 9736.1 | 6.0987 | 0.2014 | 6433.6 | 132.3 | | |
| 8000 | 3879.5 | 41989 | 2.765 | 0.0232 | 207.7 | 9722.3 | 6.1891 | 0.1917 | 7047 | 145.2 | | |
| 9000 | 4110.1 | 41604 | 2.7929 | 0.0234 | 207.6 | 9709.5 | 6.1483 | 0.1875 | 7856.3 | 161.7 | | |
| 10000 | 4207.5 | 41506 | 2.8001 | 0.0233 | 207 | 9676.4 | 6.2525 | 0.1828 | 8246.2 | 170.1 | | |

**Table C-32:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Wire Coil, e=2.2 mm, p= 40 mm).

| Re Annulus | $U_o$ W/m$^2$.C | Inner Tube (smooth)† | | | | | Annulus (augmented) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Re_{s,h}$ | $Pr_h$ | $f_{s,i}$ | $Nu_{s,i}$ | $h_{s,i}$ W/m$^2$.C | $Pr_c$ | $f_a$ | $h_{a,o}$ W/m$^2$.C | $Nu_a$ | Augmentation†† | |
| | | | | | | | | | | | $f_a/f_s$ | $Nu_a/Nu_s$ |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2168.2 | 26459 | 3.1795 | 0.0247 | 143.1 | 8419.4 | 6.094 | *0.1489* | 3084.2 | *78.66* | *2.8334* | *2.4321* |
| 4000 | 2452.1 | 26352 | 3.1937 | 0.0248 | 143.3 | 8427.6 | 6.2009 | *0.1354* | 3690.5 | *94.29* | *2.9101* | *2.4053* |
| 5000 | 2670 | 26286 | 3.2026 | 0.0248 | 143.1 | 8414.3 | 6.3598 | *0.1269* | 4211.2 | *107.9* | *2.971* | *2.3849* |
| 6000 | 2822 | 26107 | 3.2267 | 0.0249 | 143 | 8407.4 | 6.3747 | *0.1241* | 4604.5 | *118* | *3.0217* | *2.3702* |
| 7000 | 3049.6 | 26047 | 3.2349 | 0.025 | 143.4 | 8424.5 | 6.4195 | *0.1177* | 5235.3 | *134.2* | *3.0652* | *2.3567* |
| 8000 | 3122.3 | 25953 | 3.2478 | 0.025 | 143.1 | 8405.2 | 6.4708 | *0.1129* | 5462.7 | *140.2* | *3.1035* | *2.346* |
| 9000 | 3313.4 | 25760 | 3.2746 | 0.0253 | 143.5 | 8423.4 | 6.4902 | *0.1076* | 6064.7 | *155.7* | *3.1376* | *2.3368* |
| 10000 | 3426.6 | 25748 | 3.2763 | 0.0253 | 143.5 | 8420.8 | 6.5338 | *0.1052* | 6456.8 | *165.8* | *3.1684* | *2.3272* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2486.4 | 48251 | 3.0919 | 0.0221 | 240.5 | 14187 | 6.0239 | *0.1394* | 3124.2 | *79.59* | | |
| 4000 | 2760.1 | 47647 | 3.1349 | 0.0221 | 239 | 14082 | 6.1577 | *0.1279* | 3576.7 | *91.32* | | |
| 5000 | 3095.8 | 47773 | 3.1259 | 0.0221 | 239.6 | 14121 | 6.1851 | *0.1218* | 4157.4 | *106.2* | | |
| 6000 | 3315.3 | 47540 | 3.1427 | 0.0222 | 239.6 | 14116 | 6.2583 | *0.1183* | 4563.8 | *116.7* | | |
| 7000 | 3593.5 | 47315 | 3.1591 | 0.0222 | 239.1 | 14077 | 6.3254 | *0.1081* | 5113.9 | *130.9* | | |
| 8000 | 3850 | 47215 | 3.1664 | 0.0222 | 238.8 | 14059 | 6.3418 | *0.1116* | 5653 | *144.8* | | |
| 9000 | 4056.3 | 47028 | 3.1803 | 0.0222 | 238.6 | 14044 | 6.3738 | *0.1069* | 6112.4 | *156.6* | | |
| 10000 | 4315.3 | 46855 | 3.1932 | 0.0222 | 238.2 | 14013 | 6.4295 | *0.1015* | 6728.2 | *172.5* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2134 | 30386 | 2.7328 | 0.0244 | 153.2 | 9133.9 | 5.9736 | *0.1329* | 2922.5 | *74.39* | | *2.4415* |
| 4000 | 2388.8 | 30287 | 2.7425 | 0.0245 | 153.2 | 9132.7 | 6.1102 | *0.1228* | 3422.5 | *87.31* | | *2.4135* |
| 5000 | 2606.4 | 30045 | 2.7666 | 0.0246 | 152.9 | 9105.2 | 6.1978 | *0.1142* | 3893.3 | *99.47* | | *2.3944* |
| 6000 | 2730.8 | 29970 | 2.7741 | 0.0247 | 153.2 | 9124.6 | 6.2495 | *0.1117* | 4172.8 | *106.7* | | *2.3783* |
| 7000 | 2927.4 | 29769 | 2.7945 | 0.0247 | 152.7 | 9087.5 | 6.2897 | *0.1048* | 4661.1 | *119.3* | | *2.3648* |
| 8000 | 3126.1 | 29568 | 2.8152 | 0.0249 | 153.3 | 9115.4 | 6.3492 | *0.0995* | 5175.8 | *132.6* | | *2.3526* |
| 9000 | 3189.2 | 29528 | 2.8194 | 0.025 | 153.7 | 9140.4 | 6.5047 | *0.0957* | 5341.4 | *137.1* | | *2.3384* |
| 10000 | 3310.3 | 29481 | 2.8243 | 0.025 | 153.6 | 9131.6 | 6.4463 | *0.095* | 5693.7 | *146* | | *2.332* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2433.8 | 55043 | 2.6777 | 0.0217 | 253.9 | 15163 | 5.838 | *0.134* | 2994.8 | *76.05* | | |
| 4000 | 2728.4 | 54866 | 2.6871 | 0.0217 | 253.5 | 15136 | 5.9721 | *0.1206* | 3455.1 | *87.94* | | |
| 5000 | 3001.3 | 55005 | 2.6797 | 0.0217 | 253.8 | 15157 | 6.0193 | *0.1127* | 3903.2 | *99.43* | | |
| 6000 | 3230 | 54874 | 2.6866 | 0.0218 | 254.2 | 15177 | 6.0987 | *0.1095* | 4297.2 | *109.6* | | |
| 7000 | 3593.3 | 54415 | 2.7112 | 0.0218 | 253.2 | 15105 | 6.1671 | *0.1071* | 4973.8 | *127* | | |
| 8000 | 3828.5 | 54295 | 2.7177 | 0.0218 | 253.1 | 15097 | 6.2247 | *0.1008* | 5437.4 | *139* | | |
| 9000 | 3931.8 | 53865 | 2.7413 | 0.0219 | 252.6 | 15059 | 6.3025 | *0.0996* | 5654.2 | *144.7* | | |
| 10000 | 4130.6 | 53666 | 2.7524 | 0.0219 | 252.2 | 15027 | 6.3392 | *0.0951* | 6080.4 | *155.7* | | |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2065.2 | 20564 | 3.2178 | 0.0282 | 123.4 | 5701.8 | 6.1796 | *0.182* | 3471.5 | *71.5* | *3.8505* | *2.0195* |
| 4000 | 2271.6 | 20451 | 3.2374 | 0.0282 | 123.1 | 5680.9 | 6.2065 | *0.1748* | 4109.6 | *84.68* | *3.9547* | *2.0417* |
| 5000 | 2429.7 | 20213 | 3.2794 | 0.0282 | 122.2 | 5636.6 | 6.2953 | *0.1621* | 4691.1 | *96.81* | *4.0375* | *2.0569* |
| 6000 | 2510.8 | 20211 | 3.2797 | 0.0286 | 123.5 | 5693.4 | 6.3755 | *0.1561* | 4954.5 | *102.4* | *4.1063* | *2.069* |
| 7000 | 2651 | 20174 | 3.2863 | 0.0286 | 123.3 | 5686.4 | 6.4187 | *0.1467* | 5539.2 | *114.5* | *4.1655* | *2.0807* |
| 8000 | 2792 | 20232 | 3.276 | 0.029 | 124.8 | 5754.3 | 6.448 | *0.1434* | 6106.1 | *126.3* | *4.2174* | *2.0906* |
| 9000 | 2826.8 | 20020 | 3.3142 | 0.029 | 124 | 5713.7 | 6.5124 | *0.137* | 6328.9 | *131.1* | *4.2638* | *2.1017* |
| 10000 | 2900.7 | 19997 | 3.3183 | 0.0292 | 124.6 | 5737.4 | 6.5329 | *0.1362* | 6676.3 | *138.3* | *4.3057* | *2.1082* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2445.8 | 37347 | 3.1432 | 0.0232 | 195.1 | 9031.8 | 5.9758 | *0.1843* | 3517.5 | *72.21* | | |
| 4000 | 2693.9 | 37185 | 3.1583 | 0.0232 | 194.7 | 9008.1 | 6.0894 | *0.1711* | 4059.7 | *83.5* | | |
| 5000 | 2963.1 | 36884 | 3.1866 | 0.0233 | 194.7 | 8999.6 | 6.1938 | *0.1593* | 4706.5 | *96.96* | | |
| 6000 | 3178.1 | 36587 | 3.215 | 0.0235 | 194.6 | 8990.9 | 6.2945 | *0.1577* | 5276.4 | *108.9* | | |
| 7000 | 3372.7 | 36582 | 3.2156 | 0.0235 | 194.6 | 8990.1 | 6.3459 | *0.152* | 5835.7 | *120.5* | | |
| 8000 | 3537 | 36530 | 3.2206 | 0.0235 | 194.5 | 8982.3 | 6.4137 | *0.1415* | 6350.2 | *131.3* | | |
| 9000 | 3727.4 | 36226 | 3.2504 | 0.0236 | 194.4 | 8971.6 | 6.3377 | *0.1421* | 6998.4 | *144.5* | | |
| 10000 | 3901 | 36355 | 3.2377 | 0.0236 | 194.8 | 8991.2 | 6.4485 | *0.1373* | 7620.9 | *157.6* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2110.5 | 23615 | 2.7654 | 0.0279 | 132.6 | 6206.6 | 5.8909 | *0.1844* | 3407.7 | *69.85* | | *2.0343* |
| 4000 | 2318 | 23376 | 2.7963 | 0.0277 | 131.2 | 6133.8 | 5.9923 | *0.1736* | 4017.3 | *82.49* | | *2.0546* |
| 5000 | 2485 | 23118 | 2.8303 | 0.0279 | 131.1 | 6122.9 | 6.1133 | *0.1631* | 4553.5 | *93.69* | | *2.068* |
| 6000 | 2654.6 | 22981 | 2.8488 | 0.0281 | 131.3 | 6131.6 | 6.1946 | *0.158* | 5150.4 | *106.1* | | *2.0800* |
| 7000 | 2769.4 | 22860 | 2.8652 | 0.0281 | 131 | 6110.9 | 6.2679 | *0.1516* | 5620.4 | *115.9* | | *2.091* |
| 8000 | 2874.4 | 22802 | 2.8732 | 0.0283 | 131.4 | 6132.6 | 6.3238 | *0.1457* | 6046.8 | *124.8* | | *2.0999* |
| 9000 | 2946.7 | 22728 | 2.8834 | 0.0289 | 133.2 | 6214.5 | 6.3966 | *0.1371* | 6280.4 | *129.8* | | *2.1064* |
| 10000 | 3035 | 22643 | 2.8953 | 0.0289 | 133 | 6199.3 | 6.4375 | *0.1363* | 6715.5 | *138.9* | | *2.1147* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2470.2 | 42761 | 2.7108 | 0.023 | 207.9 | 9745.1 | 5.6865 | *0.1866* | 3457.5 | *70.62* | | |
| 4000 | 2830.1 | 42402 | 2.7358 | 0.0229 | 206.2 | 9657.5 | 5.7951 | *0.1656* | 4224.4 | *86.45* | | |
| 5000 | 3094.3 | 42492 | 2.7294 | 0.0229 | 206.4 | 9669.4 | 5.9365 | *0.1604* | 4838.3 | *99.25* | | |
| 6000 | 3335 | 42248 | 2.7466 | 0.023 | 206.7 | 9677.2 | 6.0337 | *0.1601* | 5451 | *112* | | |
| 7000 | 3459.1 | 42395 | 2.7362 | 0.023 | 207 | 9696.8 | 6.0833 | *0.1503* | 5782.8 | *118.9* | | |
| 8000 | 3695.9 | 42148 | 2.7536 | 0.0231 | 207.3 | 9703.9 | 6.16 | *0.1443* | 6472.8 | *133.3* | | |
| 9000 | 3857.9 | 41999 | 2.7643 | 0.0231 | 206.9 | 9683.9 | 6.2631 | *0.1382* | 6998.3 | *144.3* | | |
| 10000 | 4029 | 41568 | 2.7955 | 0.0231 | 205.9 | 9625.8 | 6.2791 | *0.1403* | 7622.1 | *157.2* | | |

**Table C-33:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Circular Ribs, e=2.2 mm, p= 10 mm).

| Re Annulus | $U_o$ W/m$^2$.C | Inner Tube (smooth)$^{\dagger}$ | | | | | Annulus (augmented) | | | | Augmentation$^{\dagger\dagger}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Re_{s,h}$ | $Pr_h$ | $f_{s,i}$ | $Nu_{s,i}$ | $h_{s,i}$ W/m$^2$.C | $Pr_c$ | $f_a$ | $h_{a,o}$ W/m$^2$.C | $Nu_a$ | $f_a/f_s$ | $Nu_a/Nu_s$ |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2077.3 | 26397 | 3.1877 | 0.024 | 141.9 | 8347.5 | 6.2391 | *0.4272* | 2913.3 | *74.48* | *8.6658* | *2.5661* |
| 4000 | 2396.5 | 26294 | 3.2015 | 0.025 | 142.1 | 8356.7 | 6.2832 | *0.3966* | 3580.7 | *91.61* | *8.8494* | *2.5652* |
| 5000 | 2602.4 | 26224 | 3.2109 | 0.025 | 141.9 | 8342.7 | 6.3401 | *0.3719* | 4064.5 | *104.1* | *8.9946* | *2.566* |
| 6000 | 2821.3 | 26117 | 3.2253 | 0.025 | 142.1 | 8350.7 | 6.3995 | *0.3563* | 4622.1 | *118.5* | *9.1149* | *2.5645* |
| 7000 | 2966.9 | 25967 | 3.2458 | 0.025 | 141.9 | 8335 | 6.4775 | *0.342* | 5032.7 | *129.2* | *9.2179* | *2.5628* |
| 8000 | 3114 | 25883 | 3.2575 | 0.025 | 141.9 | 8332.5 | 6.4877 | *0.3298* | 5472.3 | *140.5* | *9.3081* | *2.5633* |
| 9000 | 3272 | 25764 | 3.274 | 0.025 | 142 | 8337.3 | 6.5149 | *0.319* | 5976.8 | *153.5* | *9.3884* | *2.5625* |
| 10000 | 3382.1 | 25781 | 3.2717 | 0.025 | 142.8 | 8384.2 | 6.5467 | *0.3112* | 6324 | *162.5* | *9.4607* | *2.5607* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2405.5 | 47991 | 3.1103 | 0.022 | 238.8 | 14082 | 6.0413 | *0.4286* | 3002.9 | *76.52* | | |
| 4000 | 2830.4 | 47617 | 3.1371 | 0.022 | 238.1 | 14032 | 6.1491 | *0.3939* | 3699.5 | *94.44* | | |
| 5000 | 3178.6 | 47710 | 3.1304 | 0.022 | 238.8 | 14075 | 6.1678 | *0.3732* | 4313.1 | *110.1* | | |
| 6000 | 3508 | 47370 | 3.1551 | 0.022 | 238.3 | 14033 | 6.2359 | *0.3553* | 4948.6 | *126.5* | | |
| 7000 | 3795.7 | 47234 | 3.1651 | 0.022 | 238 | 14009 | 6.2808 | *0.3413* | 5545.4 | *141.9* | | |
| 8000 | 4024.1 | 47109 | 3.1743 | 0.022 | 237.6 | 13987 | 6.3148 | *0.3297* | 6051.6 | *154.9* | | |
| 9000 | 4200.6 | 46907 | 3.1894 | 0.022 | 237.3 | 13964 | 6.3681 | *0.3187* | 6465.4 | *165.6* | | |
| 10000 | 4320.5 | 46661 | 3.2078 | 0.022 | 236.7 | 13921 | 6.4413 | *0.3102* | 6765.4 | *173.5* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2074.9 | 30432 | 2.7283 | 0.024 | 151.3 | 9024.6 | 5.9788 | *0.4281* | 2824.7 | *71.9* | | *2.5804* |
| 4000 | 2388.9 | 30177 | 2.7534 | 0.024 | 151 | 8996 | 6.1265 | *0.3965* | 3445.1 | *87.91* | | *2.5784* |
| 5000 | 2677 | 30056 | 2.7654 | 0.024 | 150.7 | 8974.4 | 6.1538 | *0.3718* | 4082.9 | *104.2* | | *2.5786* |
| 6000 | 2826.6 | 29864 | 2.7848 | 0.024 | 150.2 | 8939.8 | 6.2375 | *0.3532* | 4451.1 | *113.8* | | *2.5763* |
| 7000 | 3044.6 | 29664 | 2.8053 | 0.024 | 150.2 | 8936.7 | 6.2962 | *0.3412* | 5018 | *128.4* | | *2.5737* |
| 8000 | 3183.2 | 29530 | 2.8192 | 0.024 | 149.9 | 8912.3 | 6.3508 | *0.3296* | 5416.1 | *138.7* | | *2.573* |
| 9000 | 3348.4 | 29481 | 2.8243 | 0.024 | 150.3 | 8936.1 | 6.3681 | *0.3195* | 5900.7 | *151.2* | | *2.573* |
| 10000 | 3460.4 | 29341 | 2.8389 | 0.024 | 149.9 | 8910.4 | 6.4112 | *0.3094* | 6272 | *160.8* | | *2.5714* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2294.3 | 55429 | 2.6575 | 0.022 | 254.9 | 15233 | 5.8815 | *0.4232* | 2783.6 | *70.74* | | |
| 4000 | 2845.5 | 55250 | 2.6668 | 0.022 | 254.6 | 15209 | 5.9151 | *0.3976* | 3640.3 | *92.56* | | |
| 5000 | 3291.3 | 54836 | 2.6886 | 0.022 | 253.8 | 15151 | 5.9758 | *0.3733* | 4408.8 | *112.2* | | |
| 6000 | 3707 | 54402 | 2.7119 | 0.022 | 252.8 | 15084 | 6.0413 | *0.3572* | 5197.3 | *132.4* | | |
| 7000 | 3952.8 | 54011 | 2.7333 | 0.022 | 252.5 | 15054 | 6.1273 | *0.3416* | 5698.5 | *145.4* | | |
| 8000 | 4171.9 | 53908 | 2.7389 | 0.022 | 252.4 | 15046 | 6.153 | *0.3305* | 6166.9 | *157.4* | | |
| 9000 | 4449.7 | 53713 | 2.7498 | 0.022 | 252.3 | 15034 | 6.1883 | *0.3202* | 6796.5 | *173.6* | | |
| 10000 | 4620.3 | 53546 | 2.7591 | 0.022 | 251.9 | 15008 | 6.2423 | *0.3089* | 7209.6 | *184.3* | | |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2015.7 | 20700 | 3.1946 | 0.029 | 126.4 | 5843.2 | 6.0994 | *0.6239* | 3282.4 | *67.52* | *12.2557* | *2.2648* |
| 4000 | 2138.2 | 20588 | 3.2136 | 0.0292 | 126.7 | 5850.9 | 6.2776 | *0.5787* | 3617.1 | *74.62* | *12.5154* | *2.1991* |
| 5000 | 2231.6 | 20511 | 3.227 | 0.0294 | 127 | 5864.8 | 6.3385 | *0.549* | 3885.9 | *80.24* | *12.7207* | *2.1527* |
| 6000 | 2337.8 | 20477 | 3.2329 | 0.0297 | 128.1 | 5915.3 | 6.3929 | *0.5209* | 4191.2 | *86.62* | *12.8909* | *2.1139* |
| 7000 | 2353.7 | 20461 | 3.2357 | 0.0297 | 128.1 | 5912.2 | 6.4928 | *0.4996* | 4244.1 | *87.85* | *13.0366* | *2.0821* |
| 8000 | 2447.4 | 20404 | 3.2456 | 0.0297 | 127.9 | 5901.2 | 6.5415 | *0.4796* | 4566.3 | *94.6* | *13.1641* | *2.055* |
| 9000 | 2552.7 | 20277 | 3.268 | 0.0297 | 127.4 | 5876.3 | 6.5278 | *0.4682* | 4966.7 | *102.9* | *13.2776* | *2.0348* |
| 10000 | 2568.6 | 20274 | 3.2685 | 0.0299 | 128 | 5903.9 | 6.5949 | *0.4554* | 5004.9 | *103.8* | *13.38* | *2.0128* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2015.7 | 20700 | 3.1946 | 0.029 | 126.4 | 5843.2 | 6.0994 | *0.6239* | 3762.1 | *77.15* | | |
| 4000 | 2138.2 | 20588 | 3.2136 | 0.0292 | 126.7 | 5850.9 | 6.2776 | *0.5787* | 4077.5 | *83.85* | | |
| 5000 | 2231.6 | 20511 | 3.227 | 0.0294 | 127 | 5864.8 | 6.3385 | *0.549* | 4472.5 | *92.12* | | |
| 6000 | 2337.8 | 20477 | 3.2329 | 0.0297 | 128.1 | 5915.3 | 6.3929 | *0.5209* | 4761.8 | *98.3* | | |
| 7000 | 2353.7 | 20461 | 3.2357 | 0.0297 | 128.1 | 5912.2 | 6.4928 | *0.4996* | 5045 | *104.2* | | |
| 8000 | 2447.4 | 20404 | 3.2456 | 0.0297 | 127.9 | 5901.2 | 6.5415 | *0.4796* | 5187.7 | *107.3* | | |
| 9000 | 2552.7 | 20277 | 3.268 | 0.0297 | 127.4 | 5876.3 | 6.5278 | *0.4682* | 5470.8 | *113.1* | | |
| 10000 | 2568.6 | 20274 | 3.2685 | 0.0299 | 128 | 5903.9 | 6.5949 | *0.4554* | 5710.2 | *118.2* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2039.3 | 23732 | 2.7507 | 0.0281 | 133.7 | 6259.1 | 5.8727 | *0.6166* | 3210.3 | *65.79* | | *2.2781* |
| 4000 | 2206.3 | 23489 | 2.7816 | 0.0281 | 132.9 | 6218.2 | 6.1211 | *0.5885* | 3660.2 | *75.32* | | *2.2108* |
| 5000 | 2389.6 | 23422 | 2.7903 | 0.0285 | 134.1 | 6271.8 | 6.1428 | *0.5514* | 4167.2 | *85.78* | | *2.1649* |
| 6000 | 2480.6 | 23328 | 2.8025 | 0.0285 | 133.8 | 6255.7 | 6.3623 | *0.5203* | 4461 | *92.15* | | *2.1203* |
| 7000 | 2564.1 | 23202 | 2.8192 | 0.0289 | 134.8 | 6298.2 | 6.3483 | *0.4964* | 4711.8 | *97.32* | | *2.0928* |
| 8000 | 2686.8 | 23148 | 2.8264 | 0.0289 | 134.6 | 6288.7 | 6.3738 | *0.4787* | 5150.6 | *106.4* | | *2.0672* |
| 9000 | 2774.1 | 23075 | 2.8361 | 0.0292 | 135.7 | 6339.6 | 6.4388 | *0.4698* | 5439.3 | *112.5* | | *2.0428* |
| 10000 | 2884.4 | 22955 | 2.8523 | 0.0292 | 135.3 | 6318.2 | 6.4892 | *0.458* | 5900.5 | *122.1* | | *2.0205* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2429.7 | 43168 | 2.683 | 0.0231 | 209.7 | 9839.3 | 5.7107 | *0.6239* | 3366.3 | *68.79* | | |
| 4000 | 2862.8 | 42843 | 2.7052 | 0.0231 | 208.9 | 9796.3 | 5.8373 | *0.5694* | 4267.9 | *87.4* | | |
| 5000 | 3154.7 | 42386 | 2.7369 | 0.0233 | 209.6 | 9815.6 | 5.9431 | *0.5425* | 4945.4 | *101.5* | | |
| 6000 | 3356.6 | 42216 | 2.7489 | 0.0231 | 207.4 | 9712.9 | 6.111 | *0.529* | 5496.1 | *113.1* | | |
| 7000 | 3535.9 | 42244 | 2.7468 | 0.0232 | 208.4 | 9756.7 | 6.1025 | *0.4985* | 5975.4 | *122.9* | | |
| 8000 | 3734.8 | 42117 | 2.7559 | 0.0233 | 208.5 | 9759.4 | 6.1366 | *0.4942* | 6565 | *135.1* | | |
| 9000 | 3910.3 | 41793 | 2.7791 | 0.0234 | 208.1 | 9735.3 | 6.2025 | *0.4625* | 7141.7 | *147.2* | | |
| 10000 | 4028 | 41652 | 2.7894 | 0.0234 | 207.7 | 9716 | 6.2997 | *0.4424* | 7557.3 | *156* | | |

**Table C-34:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Circular Ribs, e=2.2 mm, p= 20 mm).

| Re Annulus | $U_o$ W/m².C | Inner Tube (smooth)† | | | | | Annulus (augmented) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Re_{s,h}$ | $Pr_h$ | $f_{s,i}$ | $Nu_{s,i}$ | $h_{s,i}$ W/m².C | $Pr_c$ | $f_a$ | $h_{a,o}$ W/m².C | $Nu_a$ | Augmentation†† $f_a/f_s$ | $Nu_a/Nu_s$ |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2348.5 | 26311 | 3.1993 | 0.0251 | 144.6 | 8507.9 | 6.1203 | *0.3531* | 3445.7 | *87.92* | *6.2044* | *2.612* |
| 4000 | 2662.8 | 26144 | 3.2217 | 0.0252 | 144.7 | 8503 | 6.2136 | *0.3192* | 4168.5 | *106.5* | *6.3359* | *2.5814* |
| 5000 | 2921.5 | 26060 | 3.2332 | 0.0254 | 144.9 | 8514.7 | 6.2776 | *0.3107* | 4835.1 | *123.7* | *6.4398* | *2.5606* |
| 6000 | 3120.1 | 25916 | 3.2529 | 0.0254 | 144.5 | 8484.8 | 6.3747 | *0.2958* | 5418.4 | *138.8* | *6.5259* | *2.5396* |
| 7000 | 3326.1 | 25756 | 3.2751 | 0.0255 | 144.5 | 8480.3 | 6.3854 | *0.2824* | 6074.1 | *155.6* | *6.5997* | *2.5254* |
| 8000 | 3455.7 | 25695 | 3.2837 | 0.0255 | 144.5 | 8481.7 | 6.4522 | *0.2732* | 6519.5 | *167.2* | *6.6642* | *2.5101* |
| 9000 | 3615 | 25529 | 3.3072 | 0.0257 | 144.8 | 8489.5 | 6.4801 | *0.2644* | 7104.4 | *182.3* | *6.7217* | *2.4992* |
| 10000 | 3726.5 | 25458 | 3.3174 | 0.0258 | 145 | 8502.7 | 6.5278 | *0.2575* | 7536.6 | *193.6* | *6.7735* | *2.4884* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2667.5 | 47799 | 3.124 | 0.0222 | 240.3 | 14162 | 5.9803 | *0.3509* | 3417.3 | *86.99* | | |
| 4000 | 3125.1 | 47355 | 3.1562 | 0.0223 | 239.8 | 14119 | 6.0987 | *0.33* | 4210.7 | *107.4* | | |
| 5000 | 3458.1 | 47514 | 3.1446 | 0.0223 | 240.3 | 14158 | 6.1172 | *0.3107* | 4833.3 | *123.3* | | |
| 6000 | 3778.8 | 47153 | 3.1711 | 0.0223 | 239.5 | 14101 | 6.2152 | *0.2956* | 5493.4 | *140.4* | | |
| 7000 | 4014.2 | 46987 | 3.1833 | 0.0224 | 239.7 | 14107 | 6.2663 | *0.2834* | 6004.2 | *153.6* | | |
| 8000 | 4203.9 | 46672 | 3.207 | 0.0224 | 238.6 | 14033 | 6.3483 | *0.2736* | 6456.6 | *165.4* | | |
| 9000 | 4436.9 | 46533 | 3.2175 | 0.0224 | 238.6 | 14025 | 6.3738 | *0.2647* | 7025.1 | *180* | | |
| 10000 | 4610.6 | 46493 | 3.2206 | 0.0225 | 239.1 | 14053 | 6.4078 | *0.2573* | 7461.8 | *191.3* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2370.4 | 30161 | 2.755 | 0.025 | 155.1 | 9242.5 | 5.9357 | *0.3469* | 3368 | *85.67* | | *2.6281* |
| 4000 | 2732 | 29877 | 2.7835 | 0.0251 | 154.9 | 9222.5 | 6.0535 | *0.3297* | 4152.7 | *105.8* | | *2.5957* |
| 5000 | 2957.1 | 29684 | 2.8032 | 0.0251 | 154.7 | 9202.5 | 6.1616 | *0.3096* | 4702.1 | *120.1* | | *2.5708* |
| 6000 | 3248.8 | 29397 | 2.8331 | 0.0251 | 153.9 | 9148 | 6.2239 | *0.2948* | 5507.3 | *140.8* | | *2.5502* |
| 7000 | 3412.2 | 29350 | 2.838 | 0.0251 | 153.8 | 9139.1 | 6.28 | *0.2837* | 5998.5 | *153.5* | | *2.5339* |
| 8000 | 3575 | 29218 | 2.852 | 0.0252 | 153.4 | 9113.8 | 6.336 | *0.2735* | 6534.9 | *167.3* | | *2.5209* |
| 9000 | 3704.6 | 29077 | 2.8671 | 0.0252 | 153.3 | 9102.9 | 6.397 | *0.2647* | 6988.6 | *179.1* | | *2.5063* |
| 10000 | 3877.4 | 28933 | 2.8827 | 0.0252 | 152.9 | 9075.1 | 6.448 | *0.2558* | 7652.6 | *196.3* | | *2.4961* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2789.7 | 54996 | 2.6801 | 0.0221 | 257.6 | 15380 | 5.7107 | *0.3531* | 3539 | *89.67* | | |
| 4000 | 3173.5 | 54794 | 2.6909 | 0.0221 | 257.2 | 15354 | 5.8402 | *0.3264* | 4182.6 | *106.2* | | |
| 5000 | 3542.1 | 54569 | 2.7029 | 0.0222 | 256.9 | 15328 | 5.9291 | *0.3097* | 4850.5 | *123.4* | | |
| 6000 | 3853.9 | 53912 | 2.7387 | 0.0222 | 255.4 | 15223 | 6.0436 | *0.296* | 5469.9 | *139.4* | | |
| 7000 | 4085.2 | 53843 | 2.7425 | 0.0222 | 255.2 | 15212 | 6.1079 | *0.283* | 5949.8 | *151.8* | | |
| 8000 | 4313.6 | 53753 | 2.7475 | 0.0222 | 255.3 | 15217 | 6.1273 | *0.2719* | 6445.9 | *164.5* | | |
| 9000 | 4417 | 53599 | 2.7561 | 0.0222 | 255.1 | 15202 | 6.2295 | *0.2661* | 6683.1 | *170.8* | | |
| 10000 | 4623.4 | 53554 | 2.7586 | 0.0223 | 255.2 | 15204 | 6.2423 | *0.2575* | 7166.5 | *183.2* | | |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2028.4 | 20595 | 3.2126 | 0.029 | 126.1 | 5823.3 | 6.128 | *0.4839* | 3323.6 | *68.4* | *8.7743* | *2.3766* |
| 4000 | 2203.2 | 20490 | 3.2307 | 0.0294 | 126.9 | 5860.8 | 6.2215 | *0.4493* | 3802.5 | *78.37* | *8.9602* | *2.2873* |
| 5000 | 2359.1 | 20370 | 3.2516 | 0.0296 | 127.1 | 5866.1 | 6.3067 | *0.4232* | 4288.8 | *88.52* | *9.1072* | *2.2217* |
| 6000 | 2479.6 | 20360 | 3.2534 | 0.0294 | 126.5 | 5835.7 | 6.3689 | *0.4031* | 4726.3 | *97.64* | *9.229* | *2.1712* |
| 7000 | 2560.9 | 20224 | 3.2774 | 0.0297 | 127.2 | 5865.9 | 6.4733 | *0.3792* | 5006 | *103.6* | *9.3333* | *2.1271* |
| 8000 | 2643.1 | 20207 | 3.2804 | 0.0301 | 128.4 | 5918.7 | 6.5321 | *0.3735* | 5282.6 | *109.4* | *9.4246* | *2.0906* |
| 9000 | 2781.7 | 20044 | 3.3099 | 0.0301 | 127.8 | 5886.1 | 6.5484 | *0.3621* | 5902.9 | *122.3* | *9.5059* | *2.0591* |
| 10000 | 2793 | 20062 | 3.3066 | 0.0298 | 126.6 | 5834 | 6.5794 | *0.3559* | 6014.1 | *124.7* | *9.5792* | *2.0317* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2510.7 | 37495 | 3.1296 | 0.0232 | 195.5 | 9053.4 | 5.8887 | *0.4983* | 3649.5 | *74.8* | | |
| 4000 | 2755.4 | 37250 | 3.1522 | 0.0232 | 194.9 | 9017.7 | 6.0902 | *0.4594* | 4198.9 | *86.36* | | |
| 5000 | 2938.7 | 37071 | 3.169 | 0.0233 | 194.8 | 9009.3 | 6.1938 | *0.4295* | 4642.3 | *95.64* | | |
| 6000 | 3153.6 | 36904 | 3.1847 | 0.0233 | 194.7 | 9002.5 | 6.2247 | *0.4074* | 5204.8 | *107.3* | | |
| 7000 | 3313.9 | 36677 | 3.2064 | 0.0233 | 194.1 | 8968.8 | 6.2848 | *0.3847* | 5671.3 | *117* | | |
| 8000 | 3496 | 36431 | 3.2302 | 0.0233 | 193.4 | 8932.1 | 6.3344 | *0.3759* | 6245.9 | *129* | | |
| 9000 | 3563.2 | 36576 | 3.2162 | 0.0235 | 194.6 | 8989.2 | 6.407 | *0.3637* | 6431.2 | *132.9* | | |
| 10000 | 3652.4 | 36563 | 3.2174 | 0.0235 | 194.6 | 8987.3 | 6.4379 | *0.3544* | 6728.8 | *139.2* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2183.3 | 23578 | 2.7703 | 0.0281 | 133.2 | 6233.1 | 5.8546 | *0.4802* | 3591.7 | *73.58* | | *2.3928* |
| 4000 | 2382.2 | 23406 | 2.7924 | 0.0284 | 133.6 | 6249.6 | 6.0352 | *0.4396* | 4155.6 | *85.39* | | *2.3022* |
| 5000 | 2540.5 | 23296 | 2.8068 | 0.0281 | 132.3 | 6185.4 | 6.1405 | *0.4007* | 4702.7 | *96.8* | | *2.2346* |
| 6000 | 2635.8 | 23116 | 2.8307 | 0.0285 | 133.1 | 6219 | 6.2551 | *0.3987* | 5015.5 | *103.4* | | *2.1807* |
| 7000 | 2733.4 | 23059 | 2.8382 | 0.0289 | 134.3 | 6273.1 | 6.3492 | *0.3904* | 5336.9 | *110.2* | | *2.1357* |
| 8000 | 2808.6 | 22989 | 2.8477 | 0.0289 | 134.1 | 6260.8 | 6.3929 | *0.3714* | 5642.5 | *116.6* | | *2.0998* |
| 9000 | 2976.5 | 22768 | 2.878 | 0.0285 | 132 | 6158.3 | 6.392 | *0.3551* | 6485 | *134* | | *2.0685* |
| 10000 | 2981.4 | 22796 | 2.874 | 0.0285 | 132.1 | 6163.3 | 6.4876 | *0.344* | 6502.4 | *134.6* | | *2.0385* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2588.7 | 42821 | 2.7066 | 0.0232 | 209.3 | 9813.7 | 5.6624 | *0.4652* | 3683.4 | *75.2* | | |
| 4000 | 3021 | 42539 | 2.7262 | 0.0231 | 208.2 | 9756 | 5.788 | *0.4336* | 4639.3 | *94.93* | | |
| 5000 | 3255.8 | 42364 | 2.7384 | 0.0232 | 208.6 | 9772.7 | 5.9144 | *0.4153* | 5211.9 | *106.9* | | |
| 6000 | 3507.6 | 42231 | 2.7478 | 0.0233 | 209.2 | 9794.8 | 5.9983 | *0.4074* | 5879.7 | *120.7* | | |
| 7000 | 3722.7 | 42047 | 2.7609 | 0.0233 | 208.7 | 9769.8 | 6.091 | *0.4005* | 6522.6 | *134.2* | | |
| 8000 | 3919.6 | 41865 | 2.7739 | 0.0233 | 207.9 | 9725.4 | 6.1242 | *0.3823* | 7178.6 | *147.7* | | |
| 9000 | 4046.8 | 41743 | 2.7827 | 0.0234 | 208 | 9728.5 | 6.1985 | *0.3597* | 7615.1 | *156.9* | | |
| 10000 | 4208.5 | 41525 | 2.7987 | 0.0234 | 207.4 | 9698.6 | 6.2607 | *0.3495* | 8232.2 | *169.8* | | |

**Table C-35:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Circular Ribs, e=2.2 mm, p= 30 mm).

| **Re** Annulus | **$U_o$** $W/m^2.C$ | **Inner Tube (smooth)**† | | | | | **Annulus (augmented)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **$Re_{s,h}$** | **$Pr_h$** | **$f_{s,i}$** | **$Nu_{s,i}$** | **$h_{s,i}$** $W/m^2.C$ | **$Pr_c$** | **$f_a$** | **$h_{a,o}$** $W/m^2.C$ | **$Nu_a$** | **Augmentation**†† $f_a/f_s$ | **Augmentation**†† $Nu_a/Nu_s$ |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 2274 | 26518 | 3.1718 | 0.0248 | 143.7 | 8460.9 | 6.0794 | *0.2626* | 3295.6 | *84.03* | *5.1027* | *2.6578* |
| **4000** | 2520.2 | 26357 | 3.1931 | 0.0249 | 143.8 | 8458.1 | 6.2367 | *0.2456* | 3839.9 | *98.16* | *5.2108* | *2.6069* |
| **5000** | 2729.2 | 26200 | 3.2141 | 0.0248 | 142.8 | 8396.9 | 6.3173 | *0.2262* | 4365.6 | *111.7* | *5.2963* | *2.5717* |
| **6000** | 2893.6 | 26064 | 3.2326 | 0.0252 | 144.4 | 8486.5 | 6.4112 | *0.2173* | 4769.4 | *122.3* | *5.3671* | *2.5414* |
| **7000** | 3065.5 | 25973 | 3.2451 | 0.0253 | 144.1 | 8467.6 | 6.4203 | *0.2063* | 5263.3 | *134.9* | *5.4278* | *2.5178* |
| **8000** | 3218.9 | 25826 | 3.2653 | 0.0253 | 143.7 | 8437.2 | 6.4741 | *0.2026* | 5748.1 | *147.5* | *5.4809* | *2.4969* |
| **9000** | 3315.5 | 25810 | 3.2676 | 0.0254 | 144.2 | 8462.6 | 6.5022 | *0.1965* | 6048.9 | *155.3* | *5.5282* | *2.4795* |
| **10000** | 3445.2 | 25675 | 3.2865 | 0.0255 | 144.2 | 8463.2 | 6.5484 | *0.1899* | 6494.6 | *166.8* | *5.5708* | *2.4627* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2825.2 | 47978 | 3.1112 | 0.0222 | 240.7 | 14193 | 5.9041 | *0.2627* | 3678.2 | *93.51* | | |
| **4000** | 3171.5 | 47672 | 3.1332 | 0.0222 | 239.6 | 14122 | 6.071 | *0.2437* | 4295 | *109.5* | | |
| **5000** | 3440.1 | 47532 | 3.1433 | 0.0222 | 239.6 | 14115 | 6.1405 | *0.2292* | 4803.8 | *122.6* | | |
| **6000** | 3668.6 | 47372 | 3.1549 | 0.0222 | 239.5 | 14104 | 6.2271 | *0.2169* | 5263 | *134.5* | | |
| **7000** | 3839.7 | 47078 | 3.1766 | 0.0222 | 238.8 | 14052 | 6.3156 | *0.2096* | 5632 | *144.2* | | |
| **8000** | 3981.5 | 47031 | 3.1801 | 0.0223 | 238.9 | 14062 | 6.3697 | *0.2021* | 5940.5 | *152.2* | | |
| **9000** | 4102.8 | 46919 | 3.1884 | 0.0223 | 239 | 14059 | 6.4087 | *0.1949* | 6215.2 | *159.3* | | |
| **10000** | 4258 | 46731 | 3.2026 | 0.0224 | 238.8 | 14043 | 6.4665 | *0.1895* | 6582.4 | *168.9* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 2385.6 | 30397 | 2.7317 | 0.0249 | 155.5 | 9269.6 | 5.8366 | *0.2503* | 3394.7 | *86.2* | | *2.6744* |
| **4000** | 2675.9 | 30067 | 2.7643 | 0.0249 | 154.6 | 9208.6 | 6.0156 | *0.2382* | 4027.6 | *102.6* | | *2.6231* |
| **5000** | 2925.3 | 29774 | 2.7939 | 0.0249 | 153.8 | 9154.1 | 6.1452 | *0.226* | 4636.2 | *118.3* | | *2.5855* |
| **6000** | 3096.3 | 29452 | 2.8273 | 0.0249 | 152.9 | 9093.7 | 6.2808 | *0.2175* | 5102.2 | *130.5* | | *2.5524* |
| **7000** | 3273 | 29535 | 2.8187 | 0.0249 | 153.2 | 9109.2 | 6.2873 | *0.2084* | 5593.9 | *143.1* | | *2.5292* |
| **8000** | 3449.2 | 29386 | 2.8343 | 0.0251 | 153.9 | 9145.8 | 6.3336 | *0.202* | 6110.1 | *156.4* | | *2.5093* |
| **9000** | 3580.4 | 29254 | 2.8482 | 0.0253 | 154 | 9152.9 | 6.3763 | *0.1942* | 6530.3 | *167.3* | | *2.4911* |
| **10000** | 3711.6 | 29140 | 2.8604 | 0.0254 | 154.3 | 9163 | 6.4187 | *0.1893* | 6973.6 | *178.8* | | *2.474* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2730.6 | 55068 | 2.6764 | 0.0219 | 255.3 | 15247 | 5.6913 | *0.2711* | 3452.1 | *87.44* | | |
| **4000** | 3202.6 | 54653 | 2.6984 | 0.0218 | 254 | 15160 | 5.8258 | *0.2421* | 4250.3 | *107.9* | | |
| **5000** | 3562.2 | 54506 | 2.7063 | 0.0219 | 254.1 | 15159 | 5.9012 | *0.2335* | 4907.9 | *124.8* | | |
| **6000** | 3944.6 | 53872 | 2.741 | 0.0219 | 252.6 | 15059 | 6.0201 | *0.222* | 5680.6 | *144.7* | | |
| **7000** | 4183 | 53693 | 2.7509 | 0.0219 | 252.6 | 15051 | 6.094 | *0.2128* | 6190.1 | *157.9* | | |
| **8000** | 4399.1 | 53664 | 2.7525 | 0.022 | 253.2 | 15085 | 6.1195 | *0.2033* | 6667.6 | *170.1* | | |
| **9000** | 4625.7 | 53493 | 2.7621 | 0.022 | 253.1 | 15078 | 6.1647 | *0.1954* | 7204.5 | *184* | | |
| **10000** | 4790.9 | 53231 | 2.7769 | 0.0221 | 253.2 | 15074 | 6.2287 | *0.1618* | 7614.3 | *194.6* | | |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 2168.8 | 20597 | 3.2122 | 0.0294 | 127.3 | 5881.4 | 6.0618 | *0.3839* | 3692 | *75.9* | *7.2164* | *2.462* |
| **4000** | 2414.3 | 20422 | 3.2425 | 0.0294 | 126.7 | 5847.7 | 6.1561 | *0.3548* | 4486.8 | *92.38* | *7.3693* | *2.3605* |
| **5000** | 2622.2 | 20194 | 3.2828 | 0.0298 | 127.1 | 5859.9 | 6.2567 | *0.3353* | 5251.1 | *108.3* | *7.4902* | *2.2811* |
| **6000** | 2748.7 | 20291 | 3.2655 | 0.0297 | 127.4 | 5879 | 6.3271 | *0.3186* | 5763.8 | *119* | *7.5904* | *2.2206* |
| **7000** | 2875.8 | 20153 | 3.2901 | 0.0298 | 126.9 | 5851.9 | 6.3887 | *0.3062* | 6387.9 | *132* | *7.6762* | *2.1711* |
| **8000** | 2958.4 | 20123 | 3.2955 | 0.0298 | 126.8 | 5846.1 | 6.4514 | *0.3004* | 6819.1 | *141.1* | *7.7512* | *2.1281* |
| **9000** | 3062 | 20016 | 3.315 | 0.0298 | 126.4 | 5824.9 | 6.5141 | *0.2863* | 7433.8 | *153.9* | *7.8181* | *2.0908* |
| **10000** | 3142.9 | 19936 | 3.3296 | 0.0301 | 127.4 | 5864.6 | 6.5631 | *0.2743* | 7849 | *162.7* | *7.8784* | *2.0579* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2629.1 | 37491 | 3.13 | 0.0234 | 197.1 | 9125.3 | 5.8793 | *0.3933* | 3890.4 | *79.73* | | |
| **4000** | 3043.6 | 37066 | 3.1694 | 0.0235 | 195.9 | 9062.4 | 5.9617 | *0.3605* | 4892.3 | *100.4* | | |
| **5000** | 3283.4 | 37097 | 3.1665 | 0.0234 | 196 | 9067 | 6.1187 | *0.3428* | 5541.1 | *114* | | |
| **6000** | 3535.4 | 36768 | 3.1977 | 0.0235 | 195.5 | 9035.7 | 6.1757 | *0.321* | 6315.6 | *130.1* | | |
| **7000** | 3788.3 | 36576 | 3.2162 | 0.0236 | 195.4 | 9024.6 | 6.212 | *0.3081* | 7178.5 | *147.9* | | |
| **8000** | 3925.4 | 36553 | 3.2184 | 0.0236 | 195.3 | 9021.1 | 6.2727 | *0.2927* | 7690.1 | *158.6* | | |
| **9000** | 4106.2 | 36390 | 3.2342 | 0.0236 | 194.9 | 8996.5 | 6.3222 | *0.2912* | 8439.9 | *174.2* | | |
| **10000** | 4253.6 | 36306 | 3.2424 | 0.0236 | 194.6 | 8983.8 | 6.3763 | *0.2791* | 9101.4 | *188.1* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| **3000** | 2291.3 | 23568 | 2.7715 | 0.0288 | 136 | 6362 | 5.7887 | *0.3711* | 3840.1 | *78.57* | | *2.4816* |
| **4000** | 2504 | 23417 | 2.7909 | 0.0289 | 135.5 | 6335.8 | 5.9609 | *0.3479* | 4491.7 | *92.18* | | *2.3751* |
| **5000** | 2707 | 23168 | 2.8236 | 0.0289 | 134.7 | 6292.3 | 6.1218 | *0.3115* | 5222.7 | *107.5* | | *2.2938* |
| **6000** | 2868.7 | 22964 | 2.8511 | 0.0289 | 134 | 6256.3 | 6.1875 | *0.3115* | 5894.7 | *121.4* | | *2.2327* |
| **7000** | 2973.8 | 22917 | 2.8574 | 0.0293 | 135.2 | 6311.4 | 6.2695 | *0.3038* | 6294.5 | *129.8* | | *2.1796* |
| **8000** | 3116.7 | 22790 | 2.8748 | 0.0296 | 136.1 | 6351.4 | 6.31 | *0.2925* | 6917.8 | *142.8* | | *2.1337* |
| **9000** | 3228.2 | 22758 | 2.8792 | 0.0296 | 136 | 6345.6 | 6.3508 | *0.2889* | 7501.6 | *154.9* | | *2.0995* |
| **10000** | 3312.3 | 22650 | 2.8942 | 0.0296 | 135.7 | 6325.8 | 6.4194 | *0.2708* | 8006.4 | *165.5* | | *2.065* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| **3000** | 2717.4 | 43106 | 2.6872 | 0.023 | 208.7 | 9790.4 | 5.5763 | *0.3865* | 3953.7 | *80.6* | | |
| **4000** | 3128.2 | 42678 | 2.7165 | 0.023 | 207.7 | 9734.2 | 5.6969 | *0.3717* | 4903.1 | *100.2* | | |
| **5000** | 3443.9 | 42295 | 2.7432 | 0.0231 | 207.6 | 9723.6 | 5.8294 | *0.3298* | 5729.9 | *117.3* | | |
| **6000** | 3813.7 | 41821 | 2.7771 | 0.0231 | 206.5 | 9660 | 5.8997 | *0.3219* | 6867.3 | *140.8* | | |
| **7000** | 3952.2 | 41977 | 2.7658 | 0.0231 | 206.9 | 9681 | 6.0277 | *0.3089* | 7316.6 | *150.3* | | |
| **8000** | 4037.3 | 41681 | 2.7873 | 0.0232 | 207 | 9680.5 | 6.2041 | *0.2837* | 7614.2 | *156.9* | | |
| **9000** | 4320.5 | 41321 | 2.8138 | 0.0232 | 206.1 | 9631.5 | 6.1569 | *0.2949* | 8732.5 | *179.8* | | |
| **10000** | 4365.1 | 41339 | 2.8124 | 0.0232 | 206.1 | 9634 | 6.2443 | *0.2655* | 8913.9 | *183.8* | | |

**Table C-36:** Predicted Results ($Re_{s,h}$, Pr, $f$, h, Nu, $f_a/f_s$ and $Nu_a/Nu_s$) for Annulus-Side Heat Transfer Enhancement for Two Annulus Sizes (Enhancement Status: Circular Ribs, e=2.2 mm, p= 40 mm).

| Re Annulus | $U_o$ W/m².C | Inner Tube (smooth)† $Re_{s,h}$ | $Pr_h$ | $f_{s,i}$ | $Nu_{s,i}$ | $h_{s,i}$ W/m².C | Annulus (augmented) $Pr_c$ | $f_a$ | $h_{a,o}$ W/m².C | $Nu_a$ | Augmentation†† $f_a/f_s$ | $Nu_a/Nu_s$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2232 | 26539 | 3.169 | 0.0247 | 143.5 | 8450.3 | 6.0917 | *0.2236* | 3209.8 | *81.86* | *4.2339* | *2.6937* |
| 4000 | 2532.7 | 26278 | 3.2037 | 0.0248 | 143 | 8412.6 | 6.2367 | *0.192* | 3879.9 | *99.19* | *4.3236* | *2.6327* |
| 5000 | 2773 | 26190 | 3.2155 | 0.0248 | 142.8 | 8394.8 | 6.2792 | *0.1751* | 4479.4 | *114.6* | *4.3945* | *2.5905* |
| 6000 | 2988.8 | 25956 | 3.2473 | 0.0253 | 144.1 | 8464.2 | 6.3937 | *0.1614* | 5042.5 | *129.2* | *4.4533* | *2.5523* |
| 7000 | 3128.9 | 25942 | 3.2494 | 0.0251 | 143.6 | 8432 | 6.3979 | *0.1546* | 5470 | *140.2* | *4.5036* | *2.5236* |
| 8000 | 3352.4 | 25705 | 3.2823 | 0.0253 | 143.3 | 8411.9 | 6.4564 | *0.1459* | 6204 | *159.2* | *4.5477* | *2.4988* |
| 9000 | 3405.2 | 25763 | 3.2741 | 0.0254 | 144 | 8452.9 | 6.4928 | *0.1445* | 6360.7 | *163.3* | *4.5869* | *2.4767* |
| 10000 | 3544.2 | 25622 | 3.294 | 0.0254 | 143.6 | 8423.3 | 6.5269 | *0.1449* | 6885.6 | *176.8* | *4.6223* | *2.4565* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2568.3 | 48142 | 3.0996 | 0.0221 | 240.6 | 14193 | 5.9498 | *0.2245* | 3254.3 | *82.8* | | |
| 4000 | 2970 | 47772 | 3.126 | 0.0222 | 239.9 | 14139 | 6.0817 | *0.1962* | 3932.1 | *100.3* | | |
| 5000 | 3385.2 | 47582 | 3.1396 | 0.0222 | 239.7 | 14124 | 6.1366 | *0.1765* | 4696.4 | *119.9* | | |
| 6000 | 3649.4 | 47382 | 3.1542 | 0.0222 | 239.5 | 14106 | 6.2303 | *0.165* | 5223.3 | *133.5* | | |
| 7000 | 3841.3 | 47054 | 3.1784 | 0.0222 | 238.7 | 14048 | 6.3051 | *0.1559* | 5636.1 | *144.2* | | |
| 8000 | 4071.6 | 47052 | 3.1786 | 0.0222 | 238.7 | 14048 | 6.3213 | *0.1493* | 6146.3 | *157.3* | | |
| 9000 | 4303.7 | 46840 | 3.1943 | 0.0223 | 238.5 | 14028 | 6.3639 | *0.1472* | 6696.3 | *171.5* | | |
| 10000 | 4492.8 | 46629 | 3.2103 | 0.0223 | 237.9 | 13990 | 6.4228 | *0.1478* | 7176.7 | *184* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2227.3 | 30465 | 2.7251 | 0.0247 | 154.5 | 9215.2 | 5.9026 | *0.2278* | 3089.8 | *78.55* | | *2.7076* |
| 4000 | 2506.5 | 30187 | 2.7524 | 0.0247 | 153.8 | 9164.5 | 6.0634 | *0.1926* | 3663.7 | *93.39* | | *2.6446* |
| 5000 | 2740.6 | 29906 | 2.7805 | 0.0249 | 154.2 | 9178.7 | 6.1843 | *0.1712* | 4183 | *106.8* | | *2.5988* |
| 6000 | 2959.7 | 29566 | 2.8154 | 0.025 | 153.5 | 9131.4 | 6.2816 | *0.1587* | 4730 | *121* | | *2.5602* |
| 7000 | 3079.7 | 29595 | 2.8124 | 0.025 | 153.6 | 9136.9 | 6.3213 | *0.1566* | 5042.2 | *129.1* | | *2.5304* |
| 8000 | 3228.7 | 29489 | 2.8234 | 0.0249 | 153 | 9100.6 | 6.3664 | *0.1485* | 5469.1 | *140.1* | | *2.5063* |
| 9000 | 3362.9 | 29412 | 2.8315 | 0.025 | 153.4 | 9118.5 | 6.402 | *0.1448* | 5857.3 | *150.1* | | *2.4836* |
| 10000 | 3463 | 29321 | 2.8411 | 0.025 | 153.1 | 9101.3 | 6.427 | *0.1435* | 6176.9 | *158.4* | | *2.464* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2550.6 | 55142 | 2.6724 | 0.0218 | 254.6 | 15207 | 5.7555 | *0.2199* | 3171.4 | *80.42* | | |
| 4000 | 2955.4 | 54831 | 2.6889 | 0.0218 | 254.2 | 15176 | 5.9136 | *0.1915* | 3824.4 | *97.25* | | |
| 5000 | 3300.4 | 54795 | 2.6908 | 0.0219 | 254.7 | 15205 | 5.984 | *0.1785* | 4420 | *112.5* | | |
| 6000 | 3648.2 | 54097 | 2.7285 | 0.0219 | 253.1 | 15095 | 6.101 | *0.1672* | 5080.9 | *129.6* | | |
| 7000 | 3841 | 53937 | 2.7373 | 0.0219 | 253.1 | 15090 | 6.1686 | *0.1591* | 5463.7 | *139.5* | | |
| 8000 | 4041.8 | 53974 | 2.7353 | 0.022 | 253.9 | 15135 | 6.1726 | *0.1524* | 5871.4 | *149.9* | | |
| 9000 | 4225.1 | 53767 | 2.7467 | 0.022 | 253.4 | 15102 | 6.2343 | *0.1483* | 6272.7 | *160.4* | | |
| 10000 | 4452 | 53533 | 2.7598 | 0.022 | 252.9 | 15064 | 6.2784 | *0.1469* | 6794.8 | *173.8* | | |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2098.2 | 20612 | 3.2096 | 0.0288 | 125.5 | 5797.6 | 6.1242 | *0.2965* | 3525.6 | *72.55* | *6.2818* | *2.5253* |
| 4000 | 2338.3 | 20474 | 3.2335 | 0.0286 | 124.4 | 5742.8 | 6.1694 | *0.2722* | 4293.8 | *88.43* | *6.4149* | *2.414* |
| 5000 | 2519.8 | 20219 | 3.2783 | 0.029 | 124.7 | 5751.8 | 6.2727 | *0.2596* | 4941.2 | *101.9* | *6.5202* | *2.3276* |
| 6000 | 2639 | 20191 | 3.2833 | 0.029 | 124.6 | 5746.4 | 6.345 | *0.2473* | 5426.5 | *112.1* | *6.6074* | *2.2583* |
| 7000 | 2711.7 | 20173 | 3.2865 | 0.029 | 124.6 | 5743.1 | 6.417 | *0.2435* | 5747.1 | *118.8* | *6.6821* | *2.204* |
| 8000 | 2782.7 | 20182 | 3.2849 | 0.0286 | 123.4 | 5687.9 | 6.4792 | *0.2292* | 6145.3 | *127.2* | *6.7474* | *2.1557* |
| 9000 | 2926.2 | 20070 | 3.3051 | 0.0286 | 123 | 5666.7 | 6.4919 | *0.2179* | 6926.4 | *143.4* | *6.8056* | *2.1174* |
| 10000 | 3045.8 | 19994 | 3.3189 | 0.0286 | 122.7 | 5652.3 | 6.5192 | *0.2164* | 7665.3 | *158.7* | *6.8581* | *2.0817* |
| **Experimental Conditions: Hot Water Inlet Temperature: 60 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2465.1 | 37444 | 3.1343 | 0.0233 | 196.2 | 9082.2 | 5.9379 | *0.2955* | 3549 | *72.81* | | |
| 4000 | 2879 | 37203 | 3.1566 | 0.0233 | 195.5 | 9046.7 | 6.0133 | *0.275* | 4484.8 | *92.12* | | |
| 5000 | 3135.1 | 36950 | 3.1803 | 0.0233 | 194.8 | 9009.4 | 6.118 | *0.256* | 5152.2 | *106* | | |
| 6000 | 3312.1 | 36591 | 3.2147 | 0.0238 | 196.9 | 9097.5 | 6.2511 | *0.2384* | 5610.5 | *115.7* | | |
| 7000 | 3591.6 | 36620 | 3.2119 | 0.0236 | 195.5 | 9031.3 | 6.2623 | *0.2429* | 6499.9 | *134.1* | | |
| 8000 | 3667 | 36593 | 3.2145 | 0.0236 | 195.4 | 9027.2 | 6.3565 | *0.2281* | 6753.7 | *139.5* | | |
| 9000 | 3928.6 | 36172 | 3.2556 | 0.0238 | 195.8 | 9033.5 | 6.3541 | *0.2242* | 7692.7 | *158.9* | | |
| 10000 | 4004.4 | 36411 | 3.2321 | 0.0237 | 195.7 | 9034.9 | 6.4109 | *0.2158* | 7987.2 | *165.1* | | |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.1125 kg/s** | | | | | | | | | | | | |
| 3000 | 2195.4 | 23646 | 2.7615 | 0.0277 | 132 | 6178.8 | 5.8179 | *0.297* | 3645.3 | *74.63* | | *2.5468* |
| 4000 | 2428.5 | 23365 | 2.7977 | 0.0277 | 131.1 | 6132 | 5.9565 | *0.2517* | 4362.2 | *89.52* | | *2.4295* |
| 5000 | 2642.1 | 23076 | 2.8359 | 0.0281 | 131.6 | 6147.9 | 6.0764 | *0.256* | 5091.3 | *104.7* | | *2.3394* |
| 6000 | 2771.6 | 22924 | 2.8566 | 0.0285 | 132.5 | 6185.6 | 6.182 | *0.2464* | 5560.9 | *114.5* | | *2.2688* |
| 7000 | 2855.1 | 22813 | 2.8717 | 0.0285 | 132.2 | 6166.2 | 6.2695 | *0.2349* | 5927.3 | *122.3* | | *2.2141* |
| 8000 | 3037.2 | 22755 | 2.8797 | 0.0285 | 132 | 6156.1 | 6.3026 | *0.231* | 6783.4 | *140* | | *2.1665* |
| 9000 | 3100.4 | 22729 | 2.8833 | 0.0281 | 130.5 | 6088.1 | 6.3541 | *0.226* | 7210 | *148.9* | | *2.124* |
| 10000 | 3145.4 | 22630 | 2.8971 | 0.0285 | 131.6 | 6134.2 | 6.4162 | *0.2169* | 7382.8 | *152.6* | | *2.0885* |
| **Experimental Conditions: Hot Water Inlet Temperature: 70 ± 0.5 °C Hot Water Mass Flowrate: 0.2 kg/s** | | | | | | | | | | | | |
| 3000 | 2573.7 | 42824 | 2.7065 | 0.0227 | 206.3 | 9672.4 | 5.6215 | *0.2908* | 3675.3 | *74.98* | | |
| 4000 | 3002.3 | 42438 | 2.7332 | 0.0229 | 206.3 | 9662.3 | 5.7485 | *0.2791* | 4618.9 | *94.44* | | |
| 5000 | 3275.1 | 42276 | 2.7446 | 0.0229 | 205.9 | 9640.9 | 5.9276 | *0.2462* | 5304.8 | *108.8* | | |
| 6000 | 3565.6 | 41797 | 2.7788 | 0.023 | 205.6 | 9617.1 | 6.0542 | *0.2393* | 6121.9 | *125.8* | | |
| 7000 | 3757.8 | 42057 | 2.7601 | 0.023 | 206.2 | 9651.9 | 6.0535 | *0.242* | 6692.7 | *137.6* | | |
| 8000 | 4047.9 | 41750 | 2.7822 | 0.0231 | 206.3 | 9650.4 | 6.1374 | *0.2302* | 7672.8 | *157.9* | | |
| 9000 | 4156.8 | 41656 | 2.7891 | 0.0231 | 206.1 | 9637.7 | 6.2439 | *0.2212* | 8083.6 | *166.7* | | |
| 10000 | 4327.8 | 41316 | 2.8141 | 0.0231 | 205.2 | 9591.5 | 6.2562 | *0.2106* | 8799.2 | *181.5* | | |

**Table C-37:** Isothermal Pressure Drop and Friction Factor for Smooth and Augmented Tubes (Using a Wire Coil of e = 1 mm and p = 10, 20, 30, and 40 mm) for Water Flowing at 20, 40, 60, and 70 °C.

| **Re** | **Q** $\times 10^{-4}$ ($m^3/s$) | **Smooth Tube** | | | **Augmented Tube, Wire coil, e = 1 mm** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **p = 10 mm** | | **p = 20 mm** | | **p = 30 mm** | | **p = 40 mm** | |
| **Inner tube** | | **Δp** (mm $H_2O$) | $f_s$ **Exp.** | $f_s$ **Theo.** | **Δp** (mm $H_2O$) | $f_a$ | **Δp** (mm $H_2O$) | $f_a$ | **Δp** (mm $H_2O$) | $f_a$ | **Δp** (mm $H_2O$) | $f_a$ |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m** | | | | | | | | | | | | |
| **Experimental Conditions: Isothermal T = 20 °C** | | | | | | | | | | | | |
| 5000 | 0.4336 | 51 | *0.0425* | *0.0386* | 241 | *0.2009* | 143 | *0.1189* | 99 | *0.0824* | 79 | *0.0658* |
| 10000 | 0.8671 | 162 | *0.0338* | *0.0315* | 899 | *0.1873* | 524 | *0.1092* | 352 | *0.0733* | 272 | *0.0567* |
| 15000 | 1.3007 | 326 | *0.0302* | *0.0282* | 1961 | *0.1816* | 1131 | *0.1047* | 746 | *0.0691* | 566 | *0.0524* |
| 20000 | 1.7343 | 537 | *0.028* | *0.0262* | 3419 | *0.1781* | 1957 | *0.1019* | 1269 | *0.0661* | 950 | *0.0495* |
| 25000 | 2.1679 | 793 | *0.0264* | *0.0247* | 5267 * | *0.1756* | 2989 | *0.0997* | 1918 | *0.0639* | 1424 | *0.0475* |
| 30000 | 2.6014 | 1093 | *0.0253* | *0.0236* | 7506 * | *0.1738* | 4222 | *0.0977* | 2684 | *0.0621* | 1972 | *0.0457* |
| 35000 | 3.035 | 1433 | *0.0244* | *0.0228* | 10131 * | *0.1723* | 5653 * | *0.0962* | 3561 | *0.0606* | 2598 | *0.0442* |
| 40000 | 3.4686 | 1813 | *0.0236* | *0.0221* | 13128 * | *0.171* | 7263 * | *0.0946* | 4538 | *0.0591* | 3297 | *0.0429* |
| **Experimental Conditions: Isothermal T = 40 °C** | | | | | | | | | | | | |
| 5000 | 0.2843 | 21 | *0.0412* | *0.0386* | 105 | *0.2027* | 62 | *0.1206* | 42 | *0.0829* | 34 | *0.066* |
| 10000 | 0.5685 | 70 | *0.0341* | *0.0315* | 390 | *0.1891* | 227 | *0.1107* | 151 | *0.0736* | 115 | *0.0561* |
| 15000 | 0.8528 | 140 | *0.0303* | *0.0282* | 850 | *0.1831* | 491 | *0.1064* | 320 | *0.0694* | 240 | *0.052* |
| 20000 | 1.1371 | 230 | *0.028* | *0.0262* | 1483 | *0.1797* | 849 | *0.1035* | 545 | *0.0664* | 405 | *0.0494* |
| 25000 | 1.4213 | 339 | *0.0265* | *0.0247* | 2284 | *0.1771* | 1296 | *0.1011* | 825 | *0.0644* | 607 | *0.0474* |
| 30000 | 1.7056 | 466 | *0.0252* | *0.0236* | 3255 | *0.1753* | 1831 | *0.0992* | 1154 | *0.0625* | 842 | *0.0456* |
| 35000 | 1.9899 | 611 | *0.0243* | *0.0228* | 4393 | *0.1738* | 2452 | *0.0976* | 1531 | *0.0609* | 1110 | *0.0442* |
| 40000 | 2.2741 | 773 | *0.0236* | *0.0221* | 5693 * | *0.1725* | 3149 | *0.096* | 1951 | *0.0595* | 1409 | *0.0429* |
| **Experimental Conditions: Isothermal T = 60 °C** | | | | | | | | | | | | |
| 5000 | 0.2049 | 11 | *0.0423* | *0.0386* | 55 | *0.2067* | 32 | *0.1223* | 22.5 | *0.0847* | 18 | *0.0675* |
| 10000 | 0.4097 | 35 | *0.0332* | *0.0315* | 203 | *0.1924* | 119 | *0.1128* | 80 | *0.0758* | 63 | *0.0597* |
| 15000 | 0.6146 | 72 | *0.0303* | *0.0282* | 444 | *0.187* | 256 | *0.1078* | 169 | *0.0712* | 130 | *0.0547* |
| 20000 | 0.8195 | 120 | *0.0284* | *0.0262* | 773 | *0.1831* | 443 | *0.1049* | 287 | *0.068* | 218 | *0.0516* |
| 25000 | 1.0243 | 178 | *0.027* | *0.0247* | 1192 | *0.1807* | 676 | *0.1025* | 434 | *0.0658* | 326 | *0.0494* |
| 30000 | 1.2292 | 242 | *0.0255* | *0.0236* | 1698 | *0.1788* | 955 | *0.1005* | 607 | *0.0639* | 451 | *0.0475* |
| 35000 | 1.434 | 318 | *0.0246* | *0.0228* | 2292 | *0.1773* | 1279 | *0.0989* | 806 | *0.0623* | 595 | *0.046* |
| 40000 | 1.6389 | 405 | *0.024* | *0.0221* | 2970 | *0.1759* | 1643 | *0.0973* | 1027 | *0.0608* | 753 | *0.0446* |
| **Experimental Conditions: Isothermal T = 70 °C** | | | | | | | | | | | | |
| 5000 | 0.1767 | 8 | *0.0418* | *0.0386* | 39.5 | *0.2033* | 23.5 | *0.1203* | 16.5 | *0.0841* | 13 | *0.067* |
| 10000 | 0.3535 | 28 | *0.0358* | *0.0315* | 148 | *0.1895* | 86 | *0.1101* | 58 | *0.0743* | 47 | *0.0602* |
| 15000 | 0.5302 | 55 | *0.0313* | *0.0282* | 323 | *0.1838* | 186 | *0.1058* | 124 | *0.0706* | 92 | *0.0523* |
| 20000 | 0.7069 | 89 | *0.0285* | *0.0262* | 563 | *0.1802* | 322 | *0.1031* | 211 | *0.0675* | 160 | *0.0512* |
| 25000 | 0.8837 | 132 | *0.027* | *0.0247* | 867 | *0.1776* | 492 | *0.1008* | 319 | *0.0653* | 235 | *0.0481* |
| 30000 | 1.0604 | 181 | *0.0257* | *0.0236* | 1236 | *0.1758* | 695 | *0.0989* | 446 | *0.0634* | 330 | *0.0469* |
| 35000 | 1.2371 | 235 | *0.0246* | *0.0228* | 1668 | *0.1743* | 931 | *0.0973* | 592 | *0.0619* | 430 | *0.0449* |
| 40000 | 1.4139 | 297 | *0.0238* | *0.0221* | 2162 | *0.173* | 1196 | *0.0957* | 754 | *0.0603* | 550 | *0.044* |
| **Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m** | | | | | | | | | | | | |
| **Experimental Conditions: Isothermal T = 20 °C** | | | | | | | | | | | | |
| 5000 | 0.5518 | 23 | *0.0395* | *0.0386* | 106 | *0.1821* | 71 | *0.122* | 52 | *0.0894* | 42 | *0.0722* |
| 10000 | 1.1036 | 79 | *0.0339* | *0.0315* | 394 | *0.1693* | 261 | *0.1121* | 188 | *0.0808* | 148 | *0.0636* |
| 15000 | 1.6555 | 159 | *0.0304* | *0.0282* | 855 | *0.1632* | 563 | *0.1075* | 401 | *0.0766* | 311 | *0.0594* |
| 20000 | 2.2073 | 263 | *0.0282* | *0.0262* | 1488 | *0.1598* | 974 | *0.1046* | 688 | *0.0739* | 527 | *0.0566* |
| 25000 | 2.7591 | 387 | *0.0266* | *0.0247* | 2292 | *0.1575* | 1491 | *0.1025* | 1044 | *0.0718* | 792 | *0.0544* |
| 30000 | 3.3109 | 535 | *0.0255* | *0.0236* | 3265 | *0.1558* | 2109 | *0.1007* | 1468 | *0.0701* | 1106 | *0.0528* |
| 35000 | 3.8627 | 702 | *0.0246* | *0.0228* | 4405 | *0.1545* | 2829 | *0.0992* | 1957 | *0.0686* | 1463 | *0.0513* |
| 40000 | 4.4146 | 888 | *0.0238* | *0.0221* | 5716 * | *0.1535* | 3645 | *0.0979* | 2504 | *0.0672* | 1865 | *0.0501* |
| **Experimental Conditions: Isothermal T = 40 °C** | | | | | | | | | | | | |
| 5000 | 0.3618 | 10 | *0.0402* | *0.0386* | 46 | *0.1839* | 29 | *0.1166* | 22 | *0.0885* | 17 | *0.0684* |
| 10000 | 0.7236 | 33 | *0.0332* | *0.0315* | 172 | *0.1719* | 113 | *0.1136* | 81 | *0.0814* | 63 | *0.0633* |
| 15000 | 1.0854 | 69 | *0.0308* | *0.0282* | 373 | *0.1657* | 246 | *0.1099* | 172 | *0.0769* | 133 | *0.0594* |
| 20000 | 1.4472 | 113 | *0.0284* | *0.0262* | 650 | *0.1624* | 426 | *0.1071* | 296 | *0.0744* | 226 | *0.0568* |
| 25000 | 1.809 | 169 | *0.0272* | *0.0247* | 1002 | *0.1602* | 652 | *0.1049* | 449 | *0.0722* | 340 | *0.0547* |
| 30000 | 2.1708 | 232 | *0.0259* | *0.0236* | 1428 | *0.1586* | 922 | *0.103* | 631 | *0.0705* | 475 | *0.0531* |
| 35000 | 2.5325 | 304 | *0.0249* | *0.0228* | 1927 | *0.1572* | 1237 | *0.1015* | 841 | *0.069* | 628 | *0.0515* |
| 40000 | 2.8943 | 381 | *0.0239* | *0.0221* | 2500 | *0.1561* | 1594 | *0.1002* | 1076 | *0.0676* | 798 | *0.0501* |
| **Experimental Conditions: Isothermal T = 60 °C** | | | | | | | | | | | | |
| 5000 | 0.2607 | 5 | *0.0391* | *0.0386* | 24 | *0.1875* | 15 | *0.1172* | 11 | *0.086* | 9 | *0.0703* |
| 10000 | 0.5215 | 16 | *0.0313* | *0.0315* | 89 | *0.1739* | 58 | *0.1133* | 42 | *0.082* | 33 | *0.0645* |
| 15000 | 0.7822 | 35 | *0.0304* | *0.0282* | 194 | *0.1684* | 126 | *0.1094* | 90 | *0.0781* | 70 | *0.0608* |
| 20000 | 1.0429 | 58 | *0.0283* | *0.0262* | 338 | *0.1651* | 220 | *0.1074* | 155 | *0.0757* | 119 | *0.0581* |
| 25000 | 1.3037 | 85 | *0.0266* | *0.0247* | 520 | *0.1625* | 337 | *0.1053* | 236 | *0.0738* | 179 | *0.0559* |
| 30000 | 1.5644 | 117 | *0.0254* | *0.0236* | 741 | *0.1608* | 477 | *0.1035* | 332 | *0.0721* | 250 | *0.0543* |
| 35000 | 1.8252 | 155 | *0.0247* | *0.0228* | 997 | *0.159* | 640 | *0.1021* | 442 | *0.0705* | 331 | *0.0528* |
| 40000 | 2.0859 | 196 | *0.0239* | *0.0221* | 1298 | *0.1585* | 825 | *0.1007* | 566 | *0.0691* | 421 | *0.0514* |
| **Experimental Conditions: Isothermal T = 70 °C** | | | | | | | | | | | | |
| 5000 | 0.2249 | 4 | *0.0422* | *0.0386* | 17 | *0.1795* | 11 | *0.1161* | 9 | *0.095* | 7 | *0.0739* |
| 10000 | 0.4499 | 12 | *0.0317* | *0.0315* | 65 | *0.1716* | 42 | *0.1108* | 31 | *0.0818* | 24 | *0.0633* |
| 15000 | 0.6748 | 27 | *0.0317* | *0.0282* | 143 | *0.1677* | 91 | *0.1067* | 68 | *0.0798* | 51 | *0.0598* |
| 20000 | 0.8997 | 42 | *0.0277* | *0.0262* | 249 | *0.1643* | 159 | *0.1049* | 117 | *0.0772* | 87 | *0.0574* |
| 25000 | 1.1247 | 65 | *0.0274* | *0.0247* | 384 | *0.1622* | 243 | *0.1026* | 178 | *0.0752* | 131 | *0.0553* |
| 30000 | 1.3496 | 85 | *0.0249* | *0.0236* | 548 | *0.1607* | 344 | *0.1009* | 250 | *0.0733* | 183 | *0.0537* |
| 35000 | 1.5745 | 116 | *0.025* | *0.0228* | 741 | *0.1596* | 461 | *0.0993* | 330 | *0.0711* | 243 | *0.0524* |
| 40000 | 1.7995 | 143 | *0.0236* | *0.0221* | 960 | *0.1584* | 594 | *0.098* | 423 | *0.0698* | 309 | *0.051* |

* Values of pressure drop larger than 5000 mm $H_2O$ are obtained via extrapolation and not by experimental work.

**Table C-38:** Isothermal Pressure Drop and Friction Factor for Smooth and Augmented Annuli (Using a Wire Coil of e = 1 mm and p = 10, 20, 30, and 40 mm) for Water Flowing at 20, 40, 60, and 70 °C.

| Re Annulus | Q $\times 10^{-4}$ ($m^3/s$) | Smooth Annulus | | | Augmented Annulus, Wire coil, e = 1 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | | Δp (mm $H_2O$) | $f_s$ Exp. | $f_s$ Theo. | Δp (mm $H_2O$) | $f_a$ | Δp (mm $H_2O$) | $f_a$ | Δp (mm $H_2O$) | $f_a$ | Δp (mm $H_2O$) | $f_a$ |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | | | | | |
| Experimental Conditions: Isothermal T = 20 °C | | | | | | | | | | | | |
| 3000 | 0.9578 | 7 | 0.0453 | 0.0456 | 21 | 0.136 | 18 | 0.1166 | 15 | 0.0972 | 10 | 0.0648 |
| 4000 | 1.2771 | 11 | 0.0401 | 0.0414 | 32 | 0.1166 | 27 | 0.0984 | 23 | 0.0838 | 18 | 0.0656 |
| 5000 | 1.5963 | 17 | 0.0396 | 0.0386 | 42 | 0.0979 | 41 | 0.0956 | 37 | 0.0863 | 27 | 0.063 |
| 6000 | 1.9156 | 24 | 0.0389 | 0.0365 | 61 | 0.0988 | 59 | 0.0955 | 49 | 0.0794 | 39 | 0.0632 |
| 7000 | 2.2349 | 32 | 0.0381 | 0.0349 | 80 | 0.0952 | 70 | 0.0833 | 64 | 0.0761 | 51 | 0.0607 |
| 8000 | 2.5541 | 42 | 0.0383 | 0.0335 | 99 | 0.0902 | 90 | 0.082 | 81 | 0.0738 | 63 | 0.0574 |
| 9000 | 2.8734 | 52 | 0.0374 | 0.0324 | 123 | 0.0885 | 118 | 0.0849 | 102 | 0.0734 | 80 | 0.0576 |
| 10000 | 3.1927 | 65 | 0.0379 | 0.0315 | 150 | 0.0874 | 150 | 0.0874 | 135 | 0.0787 | 102 | 0.0595 |
| Experimental Conditions: Isothermal T = 40 °C | | | | | | | | | | | | |
| 3000 | 0.628 | 3 | 0.0455 | 0.0456 | 9 | 0.1356 | 7.5 | 0.1137 | 6 | 0.091 | 5 | 0.0758 |
| 4000 | 0.8373 | 5 | 0.0426 | 0.0414 | 13 | 0.1102 | 12 | 0.1023 | 9 | 0.0767 | 7 | 0.0597 |
| 5000 | 1.0466 | 7.5 | 0.0409 | 0.0386 | 20 | 0.1085 | 15 | 0.0819 | 13 | 0.0709 | 11 | 0.0600 |
| 6000 | 1.2559 | 10 | 0.0379 | 0.0365 | 25 | 0.0942 | 20 | 0.0758 | 18 | 0.0682 | 17 | 0.0644 |
| 7000 | 1.4653 | 14 | 0.039 | 0.0349 | 35 | 0.0969 | 29 | 0.0807 | 24 | 0.0668 | 21 | 0.0585 |
| 8000 | 1.6746 | 18 | 0.0384 | 0.0335 | 42 | 0.089 | 35 | 0.0746 | 30 | 0.064 | 29 | 0.0618 |
| 9000 | 1.8839 | 22 | 0.0371 | 0.0324 | 53 | 0.0887 | 46 | 0.0775 | 39 | 0.0657 | 34 | 0.0573 |
| 10000 | 2.0932 | 28 | 0.0382 | 0.0315 | 62 | 0.0841 | 56 | 0.0764 | 49 | 0.0669 | 41 | 0.0559 |
| Experimental Conditions: Isothermal T = 60 °C | | | | | | | | | | | | |
| 3000 | 0.4526 | 1.5 | 0.0442 | 0.0456 | 5 | 0.1473 | 4 | 0.1178 | 3 | 0.0884 | 2.5 | 0.0736 |
| 4000 | 0.6034 | 2.5 | 0.0414 | 0.0414 | 7 | 0.116 | 5 | 0.0828 | 4 | 0.0663 | 4 | 0.0663 |
| 5000 | 0.7543 | 3.5 | 0.0371 | 0.0386 | 10 | 0.106 | 8 | 0.0848 | 7 | 0.0742 | 5 | 0.053 |
| 6000 | 0.9051 | 5.5 | 0.0405 | 0.0365 | 14 | 0.1031 | 12 | 0.0884 | 9 | 0.0663 | 7 | 0.0515 |
| 7000 | 1.056 | 7.5 | 0.0406 | 0.0349 | 18 | 0.0974 | 15 | 0.0812 | 12 | 0.0649 | 11 | 0.0595 |
| 8000 | 1.2068 | 9.5 | 0.0394 | 0.0335 | 22 | 0.0911 | 19 | 0.0787 | 15 | 0.0621 | 13 | 0.0539 |
| 9000 | 1.3577 | 12 | 0.0393 | 0.0324 | 26 | 0.0851 | 23 | 0.0753 | 19 | 0.0622 | 16 | 0.0524 |
| 10000 | 1.5085 | 14 | 0.0371 | 0.0315 | 33 | 0.0875 | 30 | 0.0795 | 25 | 0.0663 | 20 | 0.053 |
| Experimental Conditions: Isothermal T = 70 °C | | | | | | | | | | | | |
| 3000 | 0.3904 | 1.5 | 0.0597 | 0.0456 | 3 | 0.1194 | 3 | 0.1194 | 2.5 | 0.0995 | 2 | 0.0796 |
| 4000 | 0.5206 | 2 | 0.0448 | 0.0414 | 5 | 0.1119 | 4 | 0.0895 | 4 | 0.0895 | 3 | 0.0672 |
| 5000 | 0.6507 | 3 | 0.043 | 0.0386 | 8 | 0.1146 | 6 | 0.086 | 6 | 0.086 | 4 | 0.0573 |
| 6000 | 0.7808 | 4 | 0.0398 | 0.0365 | 11 | 0.1094 | 8 | 0.0796 | 7 | 0.0696 | 6 | 0.0597 |
| 7000 | 0.911 | 5 | 0.0365 | 0.0349 | 14 | 0.1023 | 11 | 0.0804 | 9 | 0.0658 | 8 | 0.0585 |
| 8000 | 1.0411 | 7 | 0.0392 | 0.0335 | 17 | 0.0951 | 13 | 0.0728 | 11 | 0.0616 | 10 | 0.056 |
| 9000 | 1.1713 | 9 | 0.0398 | 0.0324 | 21 | 0.0929 | 17 | 0.0752 | 15 | 0.0663 | 12 | 0.0531 |
| 10000 | 1.3014 | 10 | 0.0358 | 0.0315 | 24 | 0.086 | 21 | 0.0752 | 17 | 0.0609 | 15 | 0.0537 |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | | | | | |
| Experimental Conditions: Isothermal T = 20 °C | | | | | | | | | | | | |
| 3000 | 1.0288 | 15 | 0.051 | 0.0456 | 45 | 0.1529 | 41 | 0.1393 | 28 | 0.0951 | 24 | 0.0815 |
| 4000 | 1.3717 | 24 | 0.0459 | 0.0414 | 75 | 0.1433 | 69 | 0.1319 | 43 | 0.0822 | 37 | 0.0707 |
| 5000 | 1.7146 | 36 | 0.044 | 0.0386 | 110 | 0.1345 | 100 | 0.1223 | 63 | 0.0771 | 52 | 0.0636 |
| 6000 | 2.0575 | 46 | 0.0391 | 0.0365 | 150 | 0.1274 | 141 | 0.1198 | 82 | 0.0696 | 72 | 0.0612 |
| 7000 | 2.4004 | 61 | 0.0381 | 0.0349 | 198 | 0.1236 | 181 | 0.1129 | 107 | 0.0668 | 85 | 0.053 |
| 8000 | 2.7433 | 78 | 0.0373 | 0.0335 | 240 | 0.1147 | 230 | 0.1099 | 136 | 0.065 | 107 | 0.0511 |
| 9000 | 3.0863 | 94 | 0.0355 | 0.0324 | 305 | 0.1151 | 287 | 0.1083 | 171 | 0.0646 | 133 | 0.0502 |
| 10000 | 3.4292 | 113 | 0.0346 | 0.0315 | 372 | 0.1137 | 343 | 0.1049 | 203 | 0.0621 | 161 | 0.0492 |
| Experimental Conditions: Isothermal T = 40 °C | | | | | | | | | | | | |
| 3000 | 0.6745 | 6 | 0.0477 | 0.0456 | 20 | 0.1581 | 17 | 0.1352 | 12 | 0.0954 | 11 | 0.0875 |
| 4000 | 0.8993 | 10 | 0.0447 | 0.0414 | 33 | 0.1467 | 29 | 0.1297 | 18 | 0.0805 | 17 | 0.076 |
| 5000 | 1.1241 | 15 | 0.0429 | 0.0386 | 47 | 0.1337 | 43 | 0.1231 | 25 | 0.0716 | 25 | 0.0716 |
| 6000 | 1.349 | 20 | 0.0398 | 0.0365 | 64 | 0.1265 | 59 | 0.1173 | 34 | 0.0676 | 33 | 0.0656 |
| 7000 | 1.5738 | 25 | 0.0365 | 0.0349 | 88 | 0.1277 | 80 | 0.1168 | 45 | 0.0657 | 43 | 0.0628 |
| 8000 | 1.7986 | 31 | 0.0347 | 0.0335 | 114 | 0.1267 | 103 | 0.1152 | 59 | 0.066 | 55 | 0.0615 |
| 9000 | 2.0234 | 39 | 0.0345 | 0.0324 | 141 | 0.1238 | 132 | 0.1166 | 70 | 0.0618 | 67 | 0.0592 |
| 10000 | 2.2483 | 48 | 0.0343 | 0.0315 | 175 | 0.1245 | 163 | 0.1166 | 87 | 0.0623 | 78 | 0.0558 |
| Experimental Conditions: Isothermal T = 60 °C | | | | | | | | | | | | |
| 3000 | 0.4861 | 3 | 0.0463 | 0.0456 | 11 | 0.1699 | 9 | 0.139 | 6 | 0.0927 | 6 | 0.0927 |
| 4000 | 0.6481 | 5 | 0.0435 | 0.0414 | 18 | 0.1564 | 15 | 0.1304 | 10 | 0.0869 | 9 | 0.0782 |
| 5000 | 0.8101 | 7 | 0.0389 | 0.0386 | 24 | 0.1335 | 22 | 0.1224 | 15 | 0.0834 | 13 | 0.0723 |
| 6000 | 0.9722 | 10 | 0.0386 | 0.0365 | 34 | 0.1313 | 31 | 0.1197 | 20 | 0.0772 | 17 | 0.0657 |
| 7000 | 1.1342 | 13 | 0.0369 | 0.0349 | 45 | 0.1277 | 41 | 0.1163 | 26 | 0.0738 | 20 | 0.0568 |
| 8000 | 1.2962 | 17 | 0.0369 | 0.0335 | 59 | 0.1282 | 52 | 0.113 | 32 | 0.0695 | 24 | 0.0521 |
| 9000 | 1.4583 | 21 | 0.036 | 0.0324 | 71 | 0.1219 | 65 | 0.1116 | 38 | 0.0652 | 33 | 0.0566 |
| 10000 | 1.6203 | 25 | 0.0348 | 0.0315 | 87 | 0.121 | 76 | 0.1057 | 45 | 0.0626 | 37 | 0.0514 |
| Experimental Conditions: Isothermal T = 70 °C | | | | | | | | | | | | |
| 3000 | 0.4193 | 2 | 0.0417 | 0.0456 | 8 | 0.167 | 6.5 | 0.1357 | 5 | 0.1044 | 4 | 0.0835 |
| 4000 | 0.5591 | 3.5 | 0.0411 | 0.0414 | 14 | 0.1644 | 11 | 0.1292 | 8 | 0.0939 | 7 | 0.0822 |
| 5000 | 0.6989 | 5.5 | 0.0413 | 0.0386 | 20 | 0.1503 | 15 | 0.1127 | 11 | 0.0827 | 10 | 0.0751 |
| 6000 | 0.8387 | 8 | 0.0417 | 0.0365 | 27 | 0.1409 | 21 | 0.1096 | 14 | 0.0731 | 13 | 0.0678 |
| 7000 | 0.9785 | 10.5 | 0.0403 | 0.0349 | 35 | 0.1342 | 28 | 0.1073 | 19 | 0.0728 | 17 | 0.0652 |
| 8000 | 1.1182 | 13 | 0.0382 | 0.0335 | 43 | 0.1262 | 35 | 0.1027 | 23 | 0.0675 | 21 | 0.0616 |
| 9000 | 1.258 | 16 | 0.0371 | 0.0324 | 53 | 0.1229 | 44 | 0.102 | 27 | 0.0626 | 25 | 0.058 |
| 10000 | 1.3978 | 17 | 0.0319 | 0.0315 | 70 | 0.1315 | 55 | 0.1033 | 34 | 0.0639 | 30 | 0.0564 |

**Table C-39:** Isothermal Pressure Drop and Friction Factor for Smooth and Augmented Annuli (Using a Wire Coil of e = 2.2 mm and p = 10, 20, 30, and 40 mm) for Water Flowing at 20, 40, 60, and 70 °C.

| Re Annulus | Q × $10^{-4}$ ($m^3/s$) | Smooth Annulus | | | Augmented Annulus, Wire coil, e = 2.2 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | | Δp (mm $H_2O$) | $f_s$ Exp. | $f_s$ Theo. | Δp (mm $H_2O$) | $f_a$ | Δp (mm $H_2O$) | $f_a$ | Δp (mm $H_2O$) | $f_a$ | Δp (mm $H_2O$) | $f_a$ |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Isothermal T = 20 °C** | | | | | | | | | | | | |
| 3000 | 0.9578 | 7 | *0.0453* | *0.0456* | 47 | *0.2639* | 34 | *0.1909* | 29 | *0.1628* | 22 | *0.1235* |
| 4000 | 1.2771 | 11 | *0.0401* | *0.0414* | 76 | *0.24* | 56 | *0.1769* | 43 | *0.1358* | 37 | *0.1169* |
| 5000 | 1.5963 | 17 | *0.0396* | *0.0386* | 110 | *0.2224* | 85 | *0.1718* | 62 | *0.1253* | 55 | *0.1112* |
| 6000 | 1.9156 | 24 | *0.0389* | *0.0365* | 142 | *0.1993* | 117 | *0.1642* | 85 | *0.1193* | 75 | *0.1053* |
| 7000 | 2.2349 | 32 | *0.0381* | *0.0349* | 188 | *0.1939* | 154 | *0.1588* | 115 | *0.1186* | 100 | *0.1031* |
| 8000 | 2.5541 | 42 | *0.0383* | *0.0335* | 241 | *0.1903* | 199 | *0.1571* | 139 | *0.1098* | 125 | *0.0987* |
| 9000 | 2.8734 | 52 | *0.0374* | *0.0324* | 302 | *0.1884* | 244 | *0.1522* | 165 | *0.1029* | 157 | *0.0979* |
| 10000 | 3.1927 | 65 | *0.0379* | *0.0315* | 360 | *0.1819* | 300 | *0.1516* | 200 | *0.1011* | 183 | *0.0925* |
| **Experimental Conditions: Isothermal T = 40 °C** | | | | | | | | | | | | |
| 3000 | 0.628 | 3 | *0.0455* | *0.0456* | 19 | *0.2863* | 13 | *0.1971* | 12 | *0.1819* | 9 | *0.1364* |
| 4000 | 0.8373 | 5 | *0.0426* | *0.0414* | 29 | *0.2458* | 23 | *0.1961* | 17 | *0.145* | 13 | *0.1109* |
| 5000 | 1.0466 | 7.5 | *0.0409* | *0.0386* | 44 | *0.2387* | 35 | *0.191* | 24 | *0.131* | 22 | *0.1201* |
| 6000 | 1.2559 | 10 | *0.0379* | *0.0365* | 60 | *0.226* | 48 | *0.1819* | 35 | *0.1326* | 31 | *0.1175* |
| 7000 | 1.4653 | 14 | *0.039* | *0.0349* | 80 | *0.2214* | 63 | *0.1754* | 45 | *0.1253* | 41 | *0.1142* |
| 8000 | 1.6746 | 18 | *0.0384* | *0.0335* | 102 | *0.2161* | 81 | *0.1727* | 56 | *0.1194* | 54 | *0.1151* |
| 9000 | 1.8839 | 22 | *0.0371* | *0.0324* | 129 | *0.216* | 101 | *0.1701* | 70 | *0.1179* | 67 | *0.1129* |
| 10000 | 2.0932 | 28 | *0.0382* | *0.0315* | 158 | *0.2143* | 124 | *0.1692* | 84 | *0.1146* | 83 | *0.1132* |
| **Experimental Conditions: Isothermal T = 60 °C** | | | | | | | | | | | | |
| 3000 | 0.4526 | 1.5 | *0.0442* | *0.0456* | 9 | *0.2651* | 7 | *0.2062* | 6 | *0.1767* | 4.5 | *0.1326* |
| 4000 | 0.6034 | 2.5 | *0.0414* | *0.0414* | 16 | *0.2651* | 12 | *0.1988* | 9 | *0.1491* | 7 | *0.116* |
| 5000 | 0.7543 | 3.5 | *0.0371* | *0.0386* | 25 | *0.2651* | 17 | *0.1803* | 12 | *0.1273* | 10 | *0.106* |
| 6000 | 0.9051 | 5.5 | *0.0405* | *0.0365* | 32 | *0.2357* | 25 | *0.1841* | 17 | *0.1252* | 15 | *0.1105* |
| 7000 | 1.056 | 7.5 | *0.0406* | *0.0349* | 40 | *0.2164* | 32 | *0.1731* | 24 | *0.1298* | 20 | *0.1082* |
| 8000 | 1.2068 | 9.5 | *0.0394* | *0.0335* | 51 | *0.2113* | 40 | *0.1657* | 29 | *0.1201* | 23 | *0.0953* |
| 9000 | 1.3577 | 12 | *0.0393* | *0.0324* | 64 | *0.2095* | 52 | *0.1702* | 35 | *0.1146* | 29 | *0.0949* |
| 10000 | 1.5085 | 14 | *0.0371* | *0.0315* | 77 | *0.2041* | 62 | *0.1644* | 42 | *0.1113* | 38 | *0.1007* |
| **Experimental Conditions: Isothermal T = 70 °C** | | | | | | | | | | | | |
| 3000 | 0.3904 | 1.5 | *0.0597* | *0.0456* | 7 | *0.2786* | 5 | *0.199* | 4.5 | *0.1791* | 3.5 | *0.1393* |
| 4000 | 0.5206 | 2 | *0.0448* | *0.0414* | 12 | *0.2686* | 9 | *0.2015* | 7 | *0.1567* | 5 | *0.1119* |
| 5000 | 0.6507 | 3 | *0.043* | *0.0386* | 18 | *0.2579* | 13 | *0.1863* | 10 | *0.1433* | 8 | *0.1146* |
| 6000 | 0.7808 | 4 | *0.0398* | *0.0365* | 25 | *0.2487* | 20 | *0.199* | 13 | *0.1293* | 11 | *0.1094* |
| 7000 | 0.911 | 5 | *0.0365* | *0.0349* | 34 | *0.2485* | 25 | *0.1827* | 18 | *0.1316* | 15 | *0.1096* |
| 8000 | 1.0411 | 7 | *0.0392* | *0.0335* | 42 | *0.2351* | 32 | *0.1791* | 23 | *0.1287* | 19 | *0.1063* |
| 9000 | 1.1713 | 9 | *0.0398* | *0.0324* | 53 | *0.2344* | 40 | *0.1769* | 27 | *0.1194* | 25 | *0.1105* |
| 10000 | 1.3014 | 10 | *0.0358* | *0.0315* | 61 | *0.2185* | 48 | *0.1719* | 33 | *0.1182* | 30 | *0.1075* |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Isothermal T = 20 °C** | | | | | | | | | | | | |
| 3000 | 1.0288 | 15 | *0.051* | *0.0456* | 105 | *0.3567* | 88 | *0.299* | 65 | *0.2208* | 54 | *0.1835* |
| 4000 | 1.3717 | 24 | *0.0459* | *0.0414* | 179 | *0.3421* | 145 | *0.2771* | 110 | *0.2102* | 90 | *0.172* |
| 5000 | 1.7146 | 36 | *0.044* | *0.0386* | 261 | *0.3192* | 215 | *0.263* | 171 | *0.2091* | 132 | *0.1614* |
| 6000 | 2.0575 | 46 | *0.0391* | *0.0365* | 375 | *0.3185* | 301 | *0.2557* | 230 | *0.1954* | 185 | *0.1571* |
| 7000 | 2.4004 | 61 | *0.0381* | *0.0349* | 509 | *0.3176* | 387 | *0.2415* | 312 | *0.1947* | 239 | *0.1491* |
| 8000 | 2.7433 | 78 | *0.0373* | *0.0335* | 661 | *0.3158* | 504 | *0.2408* | 402 | *0.1921* | 305 | *0.1457* |
| 9000 | 3.0863 | 94 | *0.0355* | *0.0324* | 836 | *0.3156* | 634 | *0.2393* | 508 | *0.1918* | 390 | *0.1472* |
| 10000 | 3.4292 | 113 | *0.0346* | *0.0315* | 1023 | *0.3128* | 767 | *0.2345* | 622 | *0.1902* | 475 | *0.1452* |
| **Experimental Conditions: Isothermal T = 40 °C** | | | | | | | | | | | | |
| 3000 | 0.6745 | 6 | *0.0477* | *0.0456* | 42 | *0.332* | 34 | *0.2703* | 27 | *0.2147* | 22 | *0.1749* |
| 4000 | 0.8993 | 10 | *0.0447* | *0.0414* | 72 | *0.3201* | 60 | *0.2683* | 46 | *0.2057* | 37 | *0.1655* |
| 5000 | 1.1241 | 15 | *0.0429* | *0.0386* | 110 | *0.313* | 88 | *0.2519* | 68 | *0.1946* | 56 | *0.1603* |
| 6000 | 1.349 | 20 | *0.0398* | *0.0365* | 151 | *0.2984* | 121 | *0.2405* | 93 | *0.1849* | 75 | *0.1491* |
| 7000 | 1.5738 | 25 | *0.0365* | *0.0349* | 212 | *0.3078* | 162 | *0.2366* | 130 | *0.1899* | 100 | *0.146* |
| 8000 | 1.7986 | 31 | *0.0347* | *0.0335* | 270 | *0.3001* | 211 | *0.2359* | 167 | *0.1867* | 131 | *0.1465* |
| 9000 | 2.0234 | 39 | *0.0345* | *0.0324* | 339 | *0.2977* | 263 | *0.2323* | 211 | *0.1864* | 166 | *0.1467* |
| 10000 | 2.2483 | 48 | *0.0343* | *0.0315* | 430 | *0.3059* | 322 | *0.2304* | 258 | *0.1846* | 196 | *0.1403* |
| **Experimental Conditions: Isothermal T = 60 °C** | | | | | | | | | | | | |
| 3000 | 0.4861 | 3 | *0.0463* | *0.0456* | 23 | *0.3553* | 18 | *0.2781* | 15 | *0.2317* | 12 | *0.1854* |
| 4000 | 0.6481 | 5 | *0.0435* | *0.0414* | 40 | *0.3476* | 31 | *0.2694* | 22 | *0.1912* | 18 | *0.1564* |
| 5000 | 0.8101 | 7 | *0.0389* | *0.0386* | 56 | *0.3115* | 46 | *0.2558* | 33 | *0.1835* | 28 | *0.1557* |
| 6000 | 0.9722 | 10 | *0.0386* | *0.0365* | 79 | *0.3051* | 64 | *0.2472* | 46 | *0.1777* | 40 | *0.1545* |
| 7000 | 1.1342 | 13 | *0.0369* | *0.0349* | 103 | *0.2923* | 81 | *0.2299* | 62 | *0.1759* | 52 | *0.1476* |
| 8000 | 1.2962 | 17 | *0.0369* | *0.0335* | 139 | *0.302* | 105 | *0.2281* | 81 | *0.176* | 63 | *0.1369* |
| 9000 | 1.4583 | 21 | *0.036* | *0.0324* | 174 | *0.2987* | 130 | *0.2232* | 103 | *0.1768* | 78 | *0.1339* |
| 10000 | 1.6203 | 25 | *0.0348* | *0.0315* | 215 | *0.2989* | 158 | *0.2197* | 123 | *0.171* | 95 | *0.1321* |
| **Experimental Conditions: Isothermal T = 70 °C** | | | | | | | | | | | | |
| 3000 | 0.4193 | 2 | *0.0417* | *0.0456* | 17 | *0.3548* | 14 | *0.2922* | 11 | *0.2296* | 9 | *0.1879* |
| 4000 | 0.5591 | 3.5 | *0.0411* | *0.0414* | 30 | *0.3522* | 25 | *0.2935* | 16 | *0.1879* | 15 | *0.1761* |
| 5000 | 0.6989 | 5.5 | *0.0413* | *0.0386* | 45 | *0.3381* | 37 | *0.278* | 26 | *0.1954* | 22 | *0.1653* |
| 6000 | 0.8387 | 8 | *0.0417* | *0.0365* | 60 | *0.3131* | 51 | *0.2661* | 36 | *0.1879* | 29 | *0.1513* |
| 7000 | 0.9785 | 10.5 | *0.0403* | *0.0349* | 83 | *0.3182* | 67 | *0.2569* | 47 | *0.1802* | 39 | *0.1495* |
| 8000 | 1.1182 | 13 | *0.0382* | *0.0335* | 105 | *0.3082* | 82 | *0.2407* | 59 | *0.1732* | 48 | *0.1409* |
| 9000 | 1.258 | 16 | *0.0371* | *0.0324* | 134 | *0.3108* | 102 | *0.2366* | 74 | *0.1716* | 62 | *0.1438* |
| 10000 | 1.3978 | 17 | *0.0319* | *0.0315* | 160 | *0.3006* | 122 | *0.2292* | 90 | *0.1691* | 75 | *0.1409* |

**Table C-40:** Isothermal Pressure Drop and Friction Factor for Smooth and Augmented Annuli (Using Circular Ribs of e = 2.2 mm and p = 10, 20, 30, and 40 mm) for Water Flowing at 20, 40, 60, and 70 °C.

| Re Annulus | Q $\times 10^{-4}$ ($m^3/s$) | Smooth Annulus | | | Augmented Annulus, Circular ribs, e = 2.2 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | | Δp (mm $H_2O$) | $f_s$ Exp. | $f_s$ Theo. | Δp (mm $H_2O$) | $f_a$ | Δp (mm $H_2O$) | $f_a$ | Δp (mm $H_2O$) | $f_a$ | Δp (mm $H_2O$) | $f_a$ |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m** | | | | | | | | | | | | |
| **Experimental Conditions: Isothermal T = 20 °C** | | | | | | | | | | | | |
| 3000 | 0.9578 | 7 | *0.0453* | *0.0456* | 79 | *0.4436* | 64 | *0.3594* | 43 | *0.2414* | 41 | *0.2302* |
| 4000 | 1.2771 | 11 | *0.0401* | *0.0414* | 127 | *0.4011* | 103 | *0.3253* | 69 | *0.2179* | 65 | *0.2053* |
| 5000 | 1.5963 | 17 | *0.0396* | *0.0386* | 177 | *0.3578* | 143 | *0.2891* | 96 | *0.1941* | 91 | *0.1839* |
| 6000 | 1.9156 | 24 | *0.0389* | *0.0365* | 244 | *0.3425* | 197 | *0.2765* | 132 | *0.1853* | 125 | *0.1755* |
| 7000 | 2.2349 | 32 | *0.0381* | *0.0349* | 314 | *0.3238* | 254 | *0.262* | 170 | *0.1753* | 161 | *0.166* |
| 8000 | 2.5541 | 42 | *0.0383* | *0.0335* | 396 | *0.3127* | 320 | *0.2527* | 214 | *0.169* | 203 | *0.1603* |
| 9000 | 2.8734 | 52 | *0.0374* | *0.0324* | 485 | *0.3026* | 392 | *0.2446* | 262 | *0.1635* | 249 | *0.1553* |
| 10000 | 3.1927 | 65 | *0.0379* | *0.0315* | 582 | *0.2941* | 471 | *0.238* | 315 | *0.1592* | 299 | *0.1511* |
| **Experimental Conditions: Isothermal T = 40 °C** | | | | | | | | | | | | |
| 3000 | 0.628 | 3 | *0.0455* | *0.0456* | 30 | *0.4521* | 24 | *0.3638* | 16.5 | *0.2501* | 15 | *0.2274* |
| 4000 | 0.8373 | 5 | *0.0426* | *0.0414* | 50 | *0.4238* | 40 | *0.3411* | 27 | *0.2302* | 26 | *0.2217* |
| 5000 | 1.0466 | 7.5 | *0.0409* | *0.0386* | 74 | *0.4014* | 59 | *0.322* | 40 | *0.2183* | 37 | *0.2019* |
| 6000 | 1.2559 | 10 | *0.0379* | *0.0365* | 102 | *0.3843* | 81 | *0.307* | 55 | *0.2084* | 52 | *0.1971* |
| 7000 | 1.4653 | 14 | *0.039* | *0.0349* | 134 | *0.3709* | 106 | *0.2951* | 72 | *0.2005* | 68 | *0.1893* |
| 8000 | 1.6746 | 18 | *0.0384* | *0.0335* | 168 | *0.356* | 133 | *0.2835* | 91 | *0.194* | 85 | *0.1812* |
| 9000 | 1.8839 | 22 | *0.0371* | *0.0324* | 207 | *0.3466* | 164 | *0.2762* | 112 | *0.1887* | 105 | *0.1769* |
| 10000 | 2.0932 | 28 | *0.0382* | *0.0315* | 249 | *0.3377* | 197 | *0.2688* | 134 | *0.1828* | 125 | *0.1705* |
| **Experimental Conditions: Isothermal T = 60 °C** | | | | | | | | | | | | |
| 3000 | 0.4526 | 1.5 | *0.0442* | *0.0456* | 14.5 | *0.4271* | 12 | *0.3535* | 8.5 | *0.2504* | 7 | *0.2062* |
| 4000 | 0.6034 | 2.5 | *0.0414* | *0.0414* | 24 | *0.3977* | 20 | *0.3314* | 14 | *0.232* | 12 | *0.1988* |
| 5000 | 0.7543 | 3.5 | *0.0371* | *0.0386* | 35 | *0.3712* | 29 | *0.3075* | 20 | *0.2121* | 17 | *0.1803* |
| 6000 | 0.9051 | 5.5 | *0.0405* | *0.0365* | 48 | *0.3535* | 40 | *0.2946* | 28 | *0.2062* | 24 | *0.1767* |
| 7000 | 1.056 | 7.5 | *0.0406* | *0.0349* | 63 | *0.3409* | 52 | *0.2813* | 37 | *0.2002* | 31 | *0.1677* |
| 8000 | 1.2068 | 9.5 | *0.0394* | *0.0335* | 80 | *0.3314* | 66 | *0.2734* | 46 | *0.1905* | 39 | *0.1616* |
| 9000 | 1.3577 | 12 | *0.0393* | *0.0324* | 98 | *0.3207* | 81 | *0.2651* | 57 | *0.1866* | 48 | *0.1571* |
| 10000 | 1.5085 | 14 | *0.0371* | *0.0315* | 117 | *0.3102* | 97 | *0.2572* | 68 | *0.1803* | 58 | *0.1538* |
| **Experimental Conditions: Isothermal T = 70 °C** | | | | | | | | | | | | |
| 3000 | 0.3904 | 1.5 | *0.0597* | *0.0456* | 12 | *0.4776* | 9 | *0.3582* | 6.5 | *0.2587* | 5.5 | *0.2189* |
| 4000 | 0.5206 | 2 | *0.0448* | *0.0414* | 21 | *0.4701* | 16 | *0.3582* | 11 | *0.2462* | 9 | *0.2015* |
| 5000 | 0.6507 | 3 | *0.043* | *0.0386* | 30 | *0.4298* | 23 | *0.3295* | 16 | *0.2292* | 14 | *0.2006* |
| 6000 | 0.7808 | 4 | *0.0398* | *0.0365* | 42 | *0.4179* | 32 | *0.3184* | 22 | *0.2189* | 19 | *0.189* |
| 7000 | 0.911 | 5 | *0.0365* | *0.0349* | 56 | *0.4093* | 42 | *0.307* | 29 | *0.212* | 25 | *0.1827* |
| 8000 | 1.0411 | 7 | *0.0392* | *0.0335* | 69 | *0.3862* | 52 | *0.291* | 36 | *0.2015* | 31 | *0.1735* |
| 9000 | 1.1713 | 9 | *0.0398* | *0.0324* | 85 | *0.3759* | 64 | *0.283* | 44 | *0.1946* | 38 | *0.168* |
| 10000 | 1.3014 | 10 | *0.0358* | *0.0315* | 102 | *0.3653* | 77 | *0.2758* | 53 | *0.1898* | 46 | *0.1648* |
| **Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m** | | | | | | | | | | | | |
| **Experimental Conditions: Isothermal T = 20 °C** | | | | | | | | | | | | |
| 3000 | 1.0288 | 15 | *0.051* | *0.0456* | 184 | *0.6251* | 142 | *0.4824* | 113 | *0.3839* | 87 | *0.2956* |
| 4000 | 1.3717 | 24 | *0.0459* | *0.0414* | 304 | *0.581* | 234 | *0.4472* | 186 | *0.3555* | 144 | *0.2752* |
| 5000 | 1.7146 | 36 | *0.044* | *0.0386* | 448 | *0.5479* | 345 | *0.422* | 275 | *0.3363* | 212 | *0.2593* |
| 6000 | 2.0575 | 46 | *0.0391* | *0.0365* | 615 | *0.5224* | 474 | *0.4026* | 377 | *0.3202* | 291 | *0.2472* |
| 7000 | 2.4004 | 61 | *0.0381* | *0.0349* | 805 | *0.5023* | 620 | *0.3869* | 494 | *0.3083* | 381 | *0.2377* |
| 8000 | 2.7433 | 78 | *0.0373* | *0.0335* | 1014 | *0.4844* | 781 | *0.3731* | 622 | *0.2972* | 480 | *0.2293* |
| 9000 | 3.0863 | 94 | *0.0355* | *0.0324* | 1241 | *0.4685* | 956 | *0.3609* | 761 | *0.2873* | 587 | *0.2216* |
| 10000 | 3.4292 | 113 | *0.0346* | *0.0315* | 1494 | *0.4568* | 1151 | *0.3519* | 916 | *0.2801* | 707 | *0.2162* |
| **Experimental Conditions: Isothermal T = 40 °C** | | | | | | | | | | | | |
| 3000 | 0.6745 | 6 | *0.0477* | *0.0456* | 77 | *0.6086* | 60 | *0.4771* | 48 | *0.3816* | 37 | *0.2942* |
| 4000 | 0.8993 | 10 | *0.0447* | *0.0414* | 133 | *0.5913* | 103 | *0.4607* | 81 | *0.3623* | 63 | *0.2818* |
| 5000 | 1.1241 | 15 | *0.0429* | *0.0386* | 195 | *0.5548* | 152 | *0.4336* | 119 | *0.3406* | 93 | *0.2662* |
| 6000 | 1.349 | 20 | *0.0398* | *0.0365* | 252 | *0.4979* | 196 | *0.3886* | 155 | *0.3081* | 121 | *0.2405* |
| 7000 | 1.5738 | 25 | *0.0365* | *0.0349* | 333 | *0.4834* | 259 | *0.3782* | 205 | *0.2994* | 160 | *0.2337* |
| 8000 | 1.7986 | 31 | *0.0347* | *0.0335* | 425 | *0.4724* | 331 | *0.3695* | 262 | *0.2929* | 205 | *0.2292* |
| 9000 | 2.0234 | 39 | *0.0345* | *0.0324* | 533 | *0.4681* | 415 | *0.3662* | 327 | *0.2889* | 257 | *0.227* |
| 10000 | 2.2483 | 48 | *0.0343* | *0.0315* | 643 | *0.4574* | 500 | *0.3578* | 396 | *0.2834* | 310 | *0.2218* |
| **Experimental Conditions: Isothermal T = 60 °C** | | | | | | | | | | | | |
| 3000 | 0.4861 | 3 | *0.0463* | *0.0456* | 41 | *0.6334* | 32 | *0.4944* | 25 | *0.3862* | 20 | *0.309* |
| 4000 | 0.6481 | 5 | *0.0435* | *0.0414* | 68 | *0.5909* | 52 | *0.4519* | 40 | *0.3476* | 32 | *0.2781* |
| 5000 | 0.8101 | 7 | *0.0389* | *0.0386* | 101 | *0.5617* | 77 | *0.4283* | 59 | *0.3281* | 47 | *0.2614* |
| 6000 | 0.9722 | 10 | *0.0386* | *0.0365* | 139 | *0.5369* | 106 | *0.4094* | 81 | *0.3129* | 65 | *0.2511* |
| 7000 | 1.1342 | 13 | *0.0369* | *0.0349* | 180 | *0.5108* | 138 | *0.3916* | 106 | *0.3008* | 84 | *0.2384* |
| 8000 | 1.2962 | 17 | *0.0369* | *0.0335* | 227 | *0.4932* | 174 | *0.378* | 133 | *0.289* | 106 | *0.2303* |
| 9000 | 1.4583 | 21 | *0.036* | *0.0324* | 280 | *0.4807* | 214 | *0.3674* | 164 | *0.2815* | 130 | *0.2232* |
| 10000 | 1.6203 | 25 | *0.0348* | *0.0315* | 336 | *0.4672* | 257 | *0.3573* | 197 | *0.2739* | 157 | *0.2183* |
| **Experimental Conditions: Isothermal T = 70 °C** | | | | | | | | | | | | |
| 3000 | 0.4193 | 2 | *0.0417* | *0.0456* | 30 | *0.6262* | 23 | *0.4801* | 17 | *0.3548* | 14 | *0.2922* |
| 4000 | 0.5591 | 3.5 | *0.0411* | *0.0414* | 49 | *0.5753* | 39 | *0.4579* | 28 | *0.3288* | 23 | *0.27* |
| 5000 | 0.6989 | 5.5 | *0.0413* | *0.0386* | 72 | *0.541* | 57 | *0.4283* | 41 | *0.3081* | 34 | *0.2555* |
| 6000 | 0.8387 | 8 | *0.0417* | *0.0365* | 100 | *0.5218* | 79 | *0.4122* | 57 | *0.2974* | 47 | *0.2453* |
| 7000 | 0.9785 | 10.5 | *0.0403* | *0.0349* | 131 | *0.5022* | 103 | *0.3949* | 74 | *0.2837* | 62 | *0.2377* |
| 8000 | 1.1182 | 13 | *0.0382* | *0.0335* | 165 | *0.4843* | 130 | *0.3816* | 93 | *0.273* | 78 | *0.229* |
| 9000 | 1.258 | 16 | *0.0371* | *0.0324* | 201 | *0.4662* | 159 | *0.3688* | 114 | *0.2644* | 95 | *0.2203* |
| 10000 | 1.3978 | 17 | *0.0319* | *0.0315* | 242 | *0.4546* | 191 | *0.3588* | 137 | *0.2574* | 114 | *0.2142* |

**Table C-41:** Description of Turbulence Promoters (Inserts) in Terms of the Dimensionless Parameters ($e/d_i$) and ($p/d_i$) or ($e/D_e$) and ($p/D_e$)

| Type of Insert | | | Wire coil inside the inner tube | | | Wire coil on the outer surface of the inner tube | | | Circular rib on the outer surface of the inner tube | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wire or circular rib diameter | Coiling or ribbing pitch, $p$ (mm) | | Param-eter | $d_i = 11.0$ Para. value | $d_i = 14.0$ Para. value | Param-eter | $D_i = 12.5$ $D_o = 28.0$ Para. value | $D_i = 15.5$ $D_o = 28.0$ Para. value | $D_i = 12.5$ $D_o = 28.0$ Para. value | $D_i = 15.5$ $D_o = 28.0$ Para. value |
| $e = 1$ mm | 10 | | $e/d_i$ | 0.0909 | 0.0714 | $e/D_e$ | 0.0645 | 0.0800 | — | — |
| | | | $p/d_i$ | 0.9091 | 0.7143 | $p/D_e$ | 0.6452 | 0.8000 | — | — |
| | 20 | | $e/d_i$ | 0.0909 | 0.0714 | $e/D_e$ | 0.0645 | 0.0800 | — | — |
| | | | $p/d_i$ | 1.8182 | 1.4286 | $p/D_e$ | 1.2903 | 1.6000 | — | — |
| | 30 | | $e/d_i$ | 0.0909 | 0.0714 | $e/D_e$ | 0.0645 | 0.0800 | — | — |
| | | | $p/d_i$ | 2.7273 | 2.1429 | $p/D_e$ | 1.9355 | 2.4000 | — | — |
| | 40 | | $e/d_i$ | 0.0909 | 0.0714 | $e/D_e$ | 0.0645 | 0.0800 | — | — |
| | | | $p/d_i$ | 3.6364 | 2.8571 | $p/D_e$ | 2.5806 | 3.2000 | — | — |
| $e = 2.2$ mm | 10 | | $e/d_i$ | — | — | $e/D_e$ | 0.1419 | 0.1760 | 0.1419 | 0.1760 |
| | | | $p/d_i$ | — | — | $p/D_e$ | 0.6452 | 0.8000 | 0.6452 | 0.8000 |
| | 20 | | $e/d_i$ | — | — | $e/D_e$ | 0.1419 | 0.1760 | 0.1419 | 0.1760 |
| | | | $p/d_i$ | — | — | $p/D_e$ | 1.2903 | 1.6000 | 1.2903 | 1.6000 |
| | 30 | | $e/d_i$ | — | — | $e/D_e$ | 0.1419 | 0.1760 | 0.1419 | 0.1760 |
| | | | $p/d_i$ | — | — | $p/D_e$ | 1.9355 | 2.4000 | 1.9355 | 2.4000 |
| | 40 | | $e/d_i$ | — | — | $e/D_e$ | 0.1419 | 0.1760 | 0.1419 | 0.1760 |
| | | | $p/d_i$ | — | — | $p/D_e$ | 2.5806 | 3.2000 | 2.5806 | 3.2000 |

**Table C-42:** Application of FG-2a Criterion to the Tube-Side Heat Transfer Enhancement for all Geometrical Characteristics and Conditions.

| Re Inner tube | FG-2a Criterion, Wire Coil, e = 1 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | $Re_o$ | $q_a/q_o$ | $Re_o$ | $q_a/q_o$ | $Re_o$ | $q_a/q_o$ | $Re_o$ | $q_a/q_o$ |
| Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m | | | | | | | | |
| $\Delta T_i$= 40 °C, Pr= 3.14 | | | | | | | | |
| 5000 | 8936.1 | *1.4505* | 7319.8 | *1.3408* | 6513.4 | *1.2806* | 5995.8 | *1.2395* |
| 10000 | 18682 | *1.3605* | 15303 | *1.2576* | 13617 | *1.2011* | 12535 | *1.1625* |
| 15000 | 28758 | *1.3104* | 23556 | *1.2114* | 20961 | *1.1569* | 19296 | *1.1198* |
| 20000 | 39055 | *1.2761* | 31991 | *1.1796* | 28467 | *1.1266* | 26205 | *1.0904* |
| 25000 | 49520 | *1.25* | 40563 | *1.1555* | 36095 | *1.1036* | 33226 | *1.0681* |
| 30000 | 60121 | *1.2291* | 49246 | *1.1362* | 43821 | *1.0851* | 40339 | *1.0503* |
| 35000 | 70835 | *1.2117* | 58023 | *1.1201* | 51631 | *1.0698* | 47528 | *1.0354* |
| 40000 | 81649 | *1.1969* | 66880 | *1.1064* | 59513 | *1.0566* | 54783 | *1.0227* |
| $\Delta T_i$= 50 °C, Pr= 2.72 | | | | | | | | |
| 5000 | 8936.1 | *1.4486* | 7319.8 | *1.3391* | 6513.4 | *1.2789* | 5995.8 | *1.2378* |
| 10000 | 18682 | *1.3587* | 15303 | *1.256* | 13617 | *1.1995* | 12535 | *1.161* |
| 15000 | 28758 | *1.3087* | 23556 | *1.2098* | 20961 | *1.1554* | 19296 | *1.1183* |
| 20000 | 39055 | *1.2744* | 31991 | *1.178* | 28467 | *1.1251* | 26205 | *1.089* |
| 25000 | 49520 | *1.2484* | 40563 | *1.154* | 36095 | *1.1021* | 33226 | *1.0667* |
| 30000 | 60121 | *1.2275* | 49246 | *1.1347* | 43821 | *1.0837* | 40339 | *1.0489* |
| 35000 | 70835 | *1.2101* | 58023 | *1.1187* | 51631 | *1.0684* | 47528 | *1.0341* |
| 40000 | 81649 | *1.1953* | 66880 | *1.1049* | 59513 | *1.0553* | 54783 | *1.0214* |
| Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m | | | | | | | | |
| $\Delta T_i$= 40 °C, Pr= 3.14 | | | | | | | | |
| 5000 | 8852.2 | *1.5151* | 7251.1 | *1.4005* | 6452.3 | *1.3376* | 5939.5 | *1.2947* |
| 10000 | 18506 | *1.4211* | 15159 | *1.3136* | 13489 | *1.2546* | 12417 | *1.2143* |
| 15000 | 28488 | *1.3688* | 23335 | *1.2653* | 20765 | *1.2084* | 19114 | *1.1696* |
| 20000 | 38689 | *1.3329* | 31691 | *1.2321* | 28200 | *1.1767* | 25959 | *1.139* |
| 25000 | 49056 | *1.3057* | 40183 | *1.2069* | 35756 | *1.1527* | 32914 | *1.1157* |
| 30000 | 59557 | *1.2838* | 48784 | *1.1868* | 43410 | *1.1334* | 39960 | *1.0971* |
| 35000 | 70170 | *1.2657* | 57478 | *1.17* | 51146 | *1.1174* | 47082 | *1.0815* |
| 40000 | 80882 | *1.2501* | 66252 | *1.1556* | 58954 | *1.1037* | 54269 | *1.0683* |
| $\Delta T_i$= 50 °C, Pr= 2.71 | | | | | | | | |
| 5000 | 8852.2 | *1.5131* | 7251.1 | *1.3987* | 6452.3 | *1.3358* | 5939.5 | *1.293* |
| 10000 | 18506 | *1.4192* | 15159 | *1.3119* | 13489 | *1.2529* | 12417 | *1.2127* |
| 15000 | 28488 | *1.367* | 23335 | *1.2636* | 20765 | *1.2068* | 19114 | *1.1681* |
| 20000 | 38689 | *1.3311* | 31691 | *1.2305* | 28200 | *1.1752* | 25959 | *1.1375* |
| 25000 | 49056 | *1.304* | 40183 | *1.2054* | 35756 | *1.1512* | 32914 | *1.1142* |
| 30000 | 59557 | *1.2822* | 48784 | *1.1852* | 43410 | *1.1319* | 39960 | *1.0956* |
| 35000 | 70170 | *1.264* | 57478 | *1.1685* | 51146 | *1.1159* | 47082 | *1.0801* |
| 40000 | 80882 | *1.2485* | 66252 | *1.1541* | 58954 | *1.1022* | 54269 | *1.0669* |

**Table C-43:** Application of FG-3 Criterion to the Tube-Side Heat Transfer Enhancement for all Geometrical Characteristics and Conditions.

| Re Inner tube | FG-3 Criterion, Wire Coil, e = 1 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | $Re_o$ | $P_a/P_o$ | $Re_o$ | $P_a/P_o$ | $Re_o$ | $P_a/P_o$ | $Re_o$ | $P_a/P_o$ |
| **Inner Tube Dimensions: L=1.245 m  $d_i$= 0.011 m** | | | | | | | | |
| **$\Delta T_i$= 40 °C, Pr= 3.14** | | | | | | | | |
| 5000 | 13965.3 | *0.2957* | 10409 | *0.3825* | 8764.86 | *0.4447* | 7758.35 | *0.4949* |
| 10000 | 27034.1 | *0.3647* | 20149.9 | *0.4719* | 16967.1 | *0.5486* | 15018.7 | *0.6105* |
| 15000 | 39784.8 | *0.4124* | 29653.6 | *0.5335* | 24969.7 | *0.6203* | 22102.3 | *0.6903* |
| 20000 | 52333.1 | *0.4499* | 39006.5 | *0.5821* | 32845.3 | *0.6768* | 29073.5 | *0.7531* |
| 25000 | 64733.1 | *0.4814* | 48248.8 | *0.6228* | 40627.7 | *0.7241* | 35962.3 | *0.8058* |
| 30000 | 77016 | *0.5087* | 57403.9 | *0.6581* | 48336.7 | *0.7652* | 42786 | *0.8515* |
| 35000 | 89202.6 | *0.533* | 66487.2 | *0.6896* | 55985.2 | *0.8017* | 49556.2 | *0.8922* |
| 40000 | 101307 | *0.555* | 75509.4 | *0.7181* | 63582.3 | *0.8348* | 56280.9 | *0.929* |
| **$\Delta T_i$= 50 °C, Pr= 2.72** | | | | | | | | |
| 5000 | 13943.4 | *0.2969* | 10392.7 | *0.3842* | 8751.12 | *0.4467* | 7746.19 | *0.497* |
| 10000 | 26991.8 | *0.3663* | 20118.3 | *0.4739* | 16940.5 | *0.551* | 14995.2 | *0.6131* |
| 15000 | 39722.5 | *0.4141* | 29607.1 | *0.5358* | 24930.6 | *0.623* | 22067.7 | *0.6932* |
| 20000 | 52251.1 | *0.4518* | 38945.4 | *0.5846* | 32793.8 | *0.6797* | 29027.9 | *0.7563* |
| 25000 | 64631.6 | *0.4834* | 48173.2 | *0.6255* | 40564 | *0.7272* | 35905.9 | *0.8092* |
| 30000 | 76895.3 | *0.5109* | 57313.9 | *0.661* | 48261 | *0.7685* | 42719 | *0.8552* |
| 35000 | 89062.8 | *0.5353* | 66383 | *0.6926* | 55897.5 | *0.8052* | 49478.6 | *0.896* |
| 40000 | 101148 | *0.5574* | 75391 | *0.7211* | 63482.7 | *0.8384* | 56192.7 | *0.933* |
| **Inner Tube Dimensions: L=1.245 m  $d_i$= 0.014 m** | | | | | | | | |
| **$\Delta T_i$= 40 °C, Pr= 3.14** | | | | | | | | |
| 5000 | 14576.8 | *0.2564* | 10864.8 | *0.3317* | 9148.65 | *0.3856* | 8098.2 | *0.4291* |
| 10000 | 28217.9 | *0.3162* | 21032.2 | *0.4091* | 17710.1 | *0.4757* | 15676.6 | *0.5293* |
| 15000 | 41526.9 | *0.3575* | 30952.1 | *0.4626* | 26063.1 | *0.5378* | 23070.5 | *0.5985* |
| 20000 | 54624.7 | *0.3901* | 40714.5 | *0.5047* | 34283.5 | *0.5868* | 30347 | *0.6529* |
| 25000 | 67567.6 | *0.4174* | 50361.5 | *0.54* | 42406.7 | *0.6278* | 37537.5 | *0.6986* |
| 30000 | 80388.4 | *0.441* | 59917.5 | *0.5706* | 50453.3 | *0.6634* | 44660.2 | *0.7382* |
| 35000 | 93108.6 | *0.4621* | 69398.5 | *0.5979* | 58436.7 | *0.6951* | 51727 | *0.7735* |
| 40000 | 105743 | *0.4812* | 78815.8 | *0.6226* | 66366.5 | *0.7238* | 58746.2 | *0.8054* |
| **$\Delta T_i$= 50 °C, Pr= 2.71** | | | | | | | | |
| 5000 | 14553.9 | *0.2575* | 10847.8 | *0.3331* | 9134.31 | *0.3873* | 8085.5 | *0.4309* |
| 10000 | 28173.7 | *0.3176* | 20999.3 | *0.4109* | 17682.3 | *0.4777* | 15652 | *0.5316* |
| 15000 | 41461.8 | *0.3591* | 30903.6 | *0.4646* | 26022.2 | *0.5401* | 23034.3 | *0.601* |
| 20000 | 54539.1 | *0.3918* | 40650.7 | *0.5069* | 34229.7 | *0.5893* | 30299.5 | *0.6557* |
| 25000 | 67461.7 | *0.4191* | 50282.6 | *0.5423* | 42340.2 | *0.6305* | 37478.7 | *0.7016* |
| 30000 | 80262.4 | *0.4429* | 59823.6 | *0.5731* | 50374.2 | *0.6663* | 44590.2 | *0.7414* |
| 35000 | 92962.7 | *0.4641* | 69289.7 | *0.6005* | 58345.1 | *0.6981* | 51645.9 | *0.7768* |
| 40000 | 105578 | *0.4833* | 78692.2 | *0.6252* | 66262.4 | *0.7269* | 58654.1 | *0.8089* |

**Table C-44:** Application of FN-1 Criterion to the Tube-Side Heat Transfer Enhancement for all Geometrical Characteristics and Conditions.

| Re Inner tube | FN-1 Criterion, Wire Coil, e = 1 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | $Re_o$ | $A_a/A_o$ | $Re_o$ | $A_a/A_o$ | $Re_o$ | $A_a/A_o$ | $Re_o$ | $A_a/A_o$ |
| Inner Tube Dimensions: L=1.245 m $d_i$= 0.011 m | | | | | | | | |
| $\Delta T_i$= 40 °C, Pr= 3.14 | | | | | | | | |
| 5000 | 7344.63 | *0.5855* | 6270.82 | *0.6556* | 5717.02 | *0.7005* | 5354.01 | *0.7342* |
| 10000 | 15882.2 | *0.6421* | 13560.1 | *0.719* | 12362.6 | *0.7682* | 11577.6 | *0.8051* |
| 15000 | 24936.6 | *0.6776* | 21290.8 | *0.7588* | 19410.5 | *0.8108* | 18178 | *0.8497* |
| 20000 | 34343.9 | *0.7041* | 29322.7 | *0.7884* | 26733.1 | *0.8424* | 25035.6 | *0.8829* |
| 25000 | 44022.6 | *0.7253* | 37586.4 | *0.8122* | 34267 | *0.8678* | 32091.2 | *0.9095* |
| 30000 | 53923.3 | *0.7431* | 46039.6 | *0.8321* | 41973.6 | *0.8891* | 39308.5 | *0.9318* |
| 35000 | 64012.5 | *0.7585* | 54653.7 | *0.8494* | 49827 | *0.9075* | 46663.2 | *0.9511* |
| 40000 | 74265.9 | *0.7721* | 63408 | *0.8646* | 57808.2 | *0.9238* | 54137.6 | *0.9682* |
| $\Delta T_i$= 50 °C, Pr= 2.72 | | | | | | | | |
| 5000 | 7349.69 | *0.5866* | 6275.14 | *0.6569* | 5720.96 | *0.7018* | 5357.7 | *0.7356* |
| 10000 | 15893.1 | *0.6433* | 13569.5 | *0.7203* | 12371.1 | *0.7696* | 11585.6 | *0.8066* |
| 15000 | 24953.8 | *0.6789* | 21305.5 | *0.7603* | 19423.9 | *0.8123* | 18190.5 | *0.8513* |
| 20000 | 34367.6 | *0.7054* | 29342.9 | *0.7899* | 26751.5 | *0.844* | 25052.9 | *0.8846* |
| 25000 | 44053 | *0.7267* | 37612.3 | *0.8137* | 34290.6 | *0.8694* | 32113.3 | *0.9112* |
| 30000 | 53960.5 | *0.7445* | 46071.3 | *0.8337* | 42002.6 | *0.8907* | 39335.6 | *0.9336* |
| 35000 | 64056.6 | *0.7599* | 54691.4 | *0.851* | 49861.3 | *0.9092* | 46695.3 | *0.9529* |
| 40000 | 74317.1 | *0.7735* | 63451.7 | *0.8662* | 57848 | *0.9255* | 54174.9 | *0.97* |
| Inner Tube Dimensions: L=1.245 m $d_i$= 0.014 m | | | | | | | | |
| $\Delta T_i$= 40 °C, Pr= 3.14 | | | | | | | | |
| 5000 | 7110.46 | *0.5499* | 6070.89 | *0.6158* | 5534.74 | *0.6579* | 5183.27 | *0.6896* |
| 10000 | 15375.8 | *0.603* | 13127.8 | *0.6753* | 11968.4 | *0.7215* | 11208.4 | *0.7562* |
| 15000 | 24141.5 | *0.6365* | 20612 | *0.7127* | 18791.6 | *0.7615* | 17598.3 | *0.7981* |
| 20000 | 33248.9 | *0.6613* | 28387.8 | *0.7405* | 25880.8 | *0.7912* | 24237.3 | *0.8292* |
| 25000 | 42619.1 | *0.6812* | 36388 | *0.7628* | 33174.4 | *0.815* | 31067.8 | *0.8542* |
| 30000 | 52204.1 | *0.6979* | 44571.7 | *0.7816* | 40635.4 | *0.835* | 38054.9 | *0.8752* |
| 35000 | 61971.6 | *0.7124* | 52911.2 | *0.7978* | 48238.3 | *0.8523* | 45175.1 | *0.8933* |
| 40000 | 71898.1 | *0.7252* | 61386.4 | *0.8121* | 55965.1 | *0.8676* | 52411.2 | *0.9093* |
| $\Delta T_i$= 50 °C, Pr= 2.71 | | | | | | | | |
| 5000 | 7115.36 | *0.551* | 6075.07 | *0.617* | 5538.56 | *0.6592* | 5186.85 | *0.6909* |
| 10000 | 15386.4 | *0.6042* | 13136.9 | *0.6766* | 11976.7 | *0.7229* | 11216.1 | *0.7576* |
| 15000 | 24158.2 | *0.6377* | 20626.2 | *0.7141* | 18804.6 | *0.7629* | 17610.5 | *0.7996* |
| 20000 | 33271.8 | *0.6625* | 28407.4 | *0.7419* | 25898.6 | *0.7927* | 24254 | *0.8308* |
| 25000 | 42648.4 | *0.6825* | 36413.1 | *0.7643* | 33197.3 | *0.8166* | 31089.2 | *0.8558* |
| 30000 | 52240.1 | *0.6993* | 44602.4 | *0.783* | 40663.4 | *0.8366* | 38081.2 | *0.8768* |
| 35000 | 62014.3 | *0.7137* | 52947.6 | *0.7993* | 48271.6 | *0.854* | 45206.3 | *0.895* |
| 40000 | 71947.6 | *0.7265* | 61428.7 | *0.8136* | 56003.6 | *0.8693* | 52447.3 | *0.911* |

**Table C-45:** Application of FG-2a Criterion to the Annulus-Side Heat Transfer Enhancement for all Geometrical Characteristics and Conditions.

| Re Annulus | FG-2a Criterion, Wire Coil, e = 1 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | $Re_o$ | $q_a/q_o$ | $Re_o$ | $q_a/q_o$ | $Re_o$ | $q_a/q_o$ | $Re_o$ | $q_a/q_o$ |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | |
| 3000 | 4314.35 | 2.3679 | 3800.3 | 2.3669 | 3528.44 | 2.2033 | 3347.46 | 2.0056 |
| 4000 | 5810.48 | 2.1562 | 5118.17 | 2.1921 | 4752.04 | 2.0626 | 4508.29 | 1.8927 |
| 5000 | 7319.85 | 2.0051 | 6447.71 | 2.0654 | 5986.46 | 1.9597 | 5679.4 | 1.8094 |
| 6000 | 8839.86 | 1.8896 | 7786.61 | 1.9674 | 7229.58 | 1.8794 | 6858.76 | 1.7442 |
| 7000 | 10368.8 | 1.7971 | 9133.35 | 1.8882 | 8479.98 | 1.8141 | 8045.02 | 1.6908 |
| 8000 | 11905.3 | 1.7206 | 10486.8 | 1.8221 | 9736.65 | 1.7594 | 9237.24 | 1.6459 |
| 9000 | 13448.6 | 1.6559 | 11846.3 | 1.7657 | 10998.8 | 1.7125 | 10434.7 | 1.6073 |
| 10000 | 14998 | 1.6001 | 13211 | 1.7168 | 12265.9 | 1.6716 | 11636.8 | 1.5736 |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | |
| 3000 | 4733.81 | 2.1126 | 4169.72 | 2.0804 | 3871.45 | 1.8978 | 3672.86 | 1.7009 |
| 4000 | 6375.39 | 1.9507 | 5615.7 | 1.9567 | 5214 | 1.806 | 4946.53 | 1.6328 |
| 5000 | 8031.51 | 1.8337 | 7074.48 | 1.8659 | 6568.42 | 1.7378 | 6231.48 | 1.5818 |
| 6000 | 9699.3 | 1.7433 | 8543.53 | 1.7948 | 7932.39 | 1.684 | 7525.48 | 1.5414 |
| 7000 | 11376.9 | 1.6704 | 10021.2 | 1.7368 | 9304.35 | 1.6398 | 8827.07 | 1.5079 |
| 8000 | 13062.8 | 1.6097 | 11506.3 | 1.688 | 10683.2 | 1.6025 | 10135.2 | 1.4796 |
| 9000 | 14756.2 | 1.558 | 12997.8 | 1.6462 | 12068.1 | 1.5703 | 11449 | 1.455 |
| 10000 | 16456.1 | 1.5132 | 14495.2 | 1.6097 | 13458.3 | 1.542 | 12768 | 1.4334 |

| Re Annulus | FG-2a Criterion, Wire Coil, e = 2.2 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | $Re_o$ | $q_a/q_o$ | $Re_o$ | $q_a/q_o$ | $Re_o$ | $q_a/q_o$ | $Re_o$ | $q_a/q_o$ |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | |
| 3000 | 5824.29 | 1.6344 | 5130.34 | 1.8074 | 4763.33 | 1.7938 | 4519.01 | 1.7129 |
| 4000 | 7844.04 | 1.5393 | 6909.44 | 1.7376 | 6415.16 | 1.7472 | 6086.11 | 1.6848 |
| 5000 | 9881.66 | 1.4694 | 8704.28 | 1.6854 | 8081.61 | 1.7119 | 7667.08 | 1.6632 |
| 6000 | 11933.6 | 1.4147 | 10511.8 | 1.6439 | 9759.8 | 1.6836 | 9259.19 | 1.6459 |
| 7000 | 13997.6 | 1.37 | 12329.9 | 1.6096 | 11447.8 | 1.6601 | 10860.6 | 1.6313 |
| 8000 | 16072 | 1.3324 | 14157.1 | 1.5804 | 13144.3 | 1.6399 | 12470.1 | 1.6188 |
| 9000 | 18155.4 | 1.3001 | 15992.3 | 1.5552 | 14848.2 | 1.6223 | 14086.6 | 1.6078 |
| 10000 | 20247 | 1.2719 | 17834.6 | 1.5329 | 16558.8 | 1.6068 | 15709.4 | 1.5981 |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | |
| 3000 | 6390.55 | 1.2978 | 5629.05 | 1.4266 | 5226.39 | 1.3955 | 4958.29 | 1.3175 |
| 4000 | 8606.67 | 1.2431 | 7581.09 | 1.3975 | 7038.8 | 1.3865 | 6677.73 | 1.323 |
| 5000 | 10842.4 | 1.2023 | 9550.41 | 1.3753 | 8867.25 | 1.3796 | 8412.39 | 1.3273 |
| 6000 | 13093.9 | 1.17 | 11533.6 | 1.3575 | 10708.6 | 1.374 | 10159.3 | 1.3308 |
| 7000 | 15358.6 | 1.1433 | 13528.4 | 1.3425 | 12560.7 | 1.3693 | 11916.4 | 1.3338 |
| 8000 | 17634.6 | 1.1207 | 15533.2 | 1.3297 | 14422.1 | 1.3652 | 13682.3 | 1.3364 |
| 9000 | 19920.6 | 1.1012 | 17546.8 | 1.3186 | 16291.7 | 1.3616 | 15456 | 1.3387 |
| 10000 | 22215.5 | 1.084 | 19568.3 | 1.3086 | 18168.5 | 1.3584 | 17236.5 | 1.3407 |

| Re Annulus | FG-2a Criterion, Circular Ribs, e = 2.2 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | $Re_o$ | $q_a/q_o$ | $Re_o$ | $q_a/q_o$ | $Re_o$ | $q_a/q_o$ | $Re_o$ | $q_a/q_o$ |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | |
| 3000 | 6754.83 | 1.277 | 5957.6 | 1.4423 | 5535.55 | 1.5593 | 5254.4 | 1.6529 |
| 4000 | 9077.71 | 1.2701 | 8006.34 | 1.4193 | 7439.14 | 1.5253 | 7061.31 | 1.6101 |
| 5000 | 11416.7 | 1.2649 | 10069.3 | 1.4018 | 9355.96 | 1.4994 | 8880.77 | 1.5777 |
| 6000 | 13768.7 | 1.2606 | 12143.7 | 1.3876 | 11283.4 | 1.4786 | 10710.3 | 1.5517 |
| 7000 | 16131.5 | 1.2569 | 14227.6 | 1.3758 | 13219.7 | 1.4613 | 12548.2 | 1.53 |
| 8000 | 18503.5 | 1.2538 | 16319.7 | 1.3656 | 15163.6 | 1.4464 | 14393.4 | 1.5115 |
| 9000 | 20883.8 | 1.251 | 18419 | 1.3566 | 17114.2 | 1.4334 | 16244.9 | 1.4954 |
| 10000 | 23271.3 | 1.2486 | 20524.7 | 1.3487 | 19070.7 | 1.4218 | 18102.1 | 1.4811 |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | |
| 3000 | 7694.74 | 1.035 | 6786.49 | 1.2078 | 6305.75 | 1.3302 | 5985.45 | 1.4282 |
| 4000 | 10340.9 | 1.0025 | 9120.27 | 1.1589 | 8474.2 | 1.2695 | 8043.76 | 1.3579 |
| 5000 | 13005.3 | 0.978 | 11470.3 | 1.1223 | 10657.7 | 1.2243 | 10116.4 | 1.3058 |
| 6000 | 15684.6 | 0.9585 | 13833.2 | 1.0933 | 12853.3 | 1.1885 | 12200.4 | 1.2647 |
| 7000 | 18376.1 | 0.9423 | 16207.1 | 1.0693 | 15059 | 1.1592 | 14294.1 | 1.231 |
| 8000 | 21078.3 | 0.9284 | 18590.3 | 1.049 | 17273.4 | 1.1343 | 16396 | 1.2025 |
| 9000 | 23789.7 | 0.9164 | 20981.7 | 1.0314 | 19495.4 | 1.1128 | 18505.1 | 1.1779 |
| 10000 | 26509.4 | 0.9058 | 23380.4 | 1.0159 | 21724.1 | 1.0939 | 20620.7 | 1.1564 |

**Table C-46:** Application of FG-3 Criterion to the Annulus-Side Heat Transfer Enhancement for all Geometrical Characteristics and Conditions.

| Re Annulus | FG-3 Criterion, Wire Coil, e = 1 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | $Re_o$ | $P_a/P_o$ | $Re_o$ | $P_a/P_o$ | $Re_o$ | $P_a/P_o$ | $Re_o$ | $P_a/P_o$ |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | |
| 3000 | 11995 | 0.0658 | 10560.4 | 0.0659 | 9006.28 | 0.0827 | 7642.77 | 0.1112 |
| 4000 | 14455.9 | 0.0885 | 12985.3 | 0.084 | 11216.3 | 0.1018 | 9609.15 | 0.1335 |
| 5000 | 16707.5 | 0.1113 | 15243.4 | 0.1014 | 13297.5 | 0.1196 | 11476.6 | 0.1539 |
| 6000 | 18805.1 | 0.1342 | 17377 | 0.1182 | 15281.7 | 0.1365 | 13268.7 | 0.1728 |
| 7000 | 20782.7 | 0.1573 | 19412.3 | 0.1345 | 17188.5 | 0.1526 | 15000.6 | 0.1906 |
| 8000 | 22663.2 | 0.1804 | 21367.1 | 0.1505 | 19031.5 | 0.1681 | 16682.6 | 0.2075 |
| 9000 | 24462.7 | 0.2036 | 23254.1 | 0.1662 | 20820.6 | 0.1831 | 18322 | 0.2236 |
| 10000 | 26193.1 | 0.2269 | 25082.8 | 0.1816 | 22563 | 0.1976 | 19924.6 | 0.2391 |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | |
| 3000 | 11495.2 | 0.0944 | 9942.94 | 0.0991 | 8278.59 | 0.1324 | 6896.85 | 0.1871 |
| 4000 | 14084.3 | 0.1214 | 12451.7 | 0.1202 | 10512.2 | 0.1548 | 8848.8 | 0.2128 |
| 5000 | 16487.7 | 0.1476 | 14826 | 0.1397 | 12652 | 0.1748 | 10735.9 | 0.2352 |
| 6000 | 18753 | 0.1731 | 17098.2 | 0.1579 | 14719.8 | 0.193 | 12572.8 | 0.2553 |
| 7000 | 20909.4 | 0.1981 | 19289 | 0.1751 | 16729.7 | 0.2099 | 14369 | 0.2735 |
| 8000 | 22976.7 | 0.2226 | 21412.4 | 0.1916 | 18691.3 | 0.2258 | 16131.1 | 0.2904 |
| 9000 | 24969.3 | 0.2467 | 23478.5 | 0.2074 | 20611.5 | 0.2407 | 17863.9 | 0.3062 |
| 10000 | 26897.7 | 0.2706 | 25495.2 | 0.2226 | 22495.9 | 0.2549 | 19571.1 | 0.321 |

| Re Annulus | FG-3 Criterion, Wire Coil, e = 2.2 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | $Re_o$ | $P_a/P_o$ | $Re_o$ | $P_a/P_o$ | $Re_o$ | $P_a/P_o$ | $Re_o$ | $P_a/P_o$ |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | |
| 3000 | 10431.2 | 0.2122 | 10353.2 | 0.1544 | 9527.06 | 0.1581 | 8556.88 | 0.1829 |
| 4000 | 13084.6 | 0.2563 | 13307.4 | 0.1749 | 12436.5 | 0.1718 | 11299.8 | 0.1928 |
| 5000 | 15599.3 | 0.2968 | 16168 | 0.1925 | 15292.3 | 0.1833 | 14019.6 | 0.2008 |
| 6000 | 18008.7 | 0.3346 | 18956.1 | 0.2083 | 18106 | 0.1932 | 16721.2 | 0.2075 |
| 7000 | 20334 | 0.3703 | 21685.3 | 0.2227 | 20885.3 | 0.202 | 19407.6 | 0.2134 |
| 8000 | 22589.6 | 0.4043 | 24365.1 | 0.2359 | 23635.4 | 0.2099 | 22081.2 | 0.2187 |
| 9000 | 24786 | 0.4368 | 27002.5 | 0.2482 | 26360.2 | 0.2172 | 24743.5 | 0.2234 |
| 10000 | 26931 | 0.4681 | 29602.7 | 0.2597 | 29062.7 | 0.2239 | 27396 | 0.2277 |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | |
| 3000 | 8706.04 | 0.4393 | 8580.1 | 0.3258 | 7760.2 | 0.3494 | 6877.05 | 0.4188 |
| 4000 | 11141.8 | 0.5032 | 11276.1 | 0.3477 | 10371.8 | 0.3565 | 9307.73 | 0.4133 |
| 5000 | 13491.3 | 0.559 | 13938.2 | 0.3658 | 12988.9 | 0.3622 | 11770.6 | 0.4092 |
| 6000 | 15774.4 | 0.6093 | 16573.4 | 0.3812 | 15610.4 | 0.3669 | 14259.4 | 0.4058 |
| 7000 | 18003.6 | 0.6552 | 19186.6 | 0.3947 | 18235.6 | 0.3709 | 16770 | 0.4029 |
| 8000 | 20187.7 | 0.6979 | 21781.1 | 0.4068 | 20863.9 | 0.3744 | 19299.4 | 0.4005 |
| 9000 | 22333.2 | 0.7377 | 24359.3 | 0.4178 | 23495 | 0.3775 | 21845.3 | 0.3983 |
| 10000 | 24444.9 | 0.7754 | 26923.1 | 0.4279 | 26128.5 | 0.3804 | 24406 | 0.3964 |

| Re Annulus | FG-3 Criterion, Circular Ribs, e = 2.2 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | $Re_o$ | $P_a/P_o$ | $Re_o$ | $P_a/P_o$ | $Re_o$ | $P_a/P_o$ | $Re_o$ | $P_a/P_o$ |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | |
| 3000 | 9027.7 | 0.4622 | 9199.1 | 0.3148 | 9376.2 | 0.2461 | 9537.1 | 0.2047 |
| 4000 | 12055 | 0.4702 | 12130 | 0.3311 | 12275 | 0.2638 | 12424 | 0.2224 |
| 5000 | 15086 | 0.4764 | 15032 | 0.3444 | 15128 | 0.2785 | 15253 | 0.2372 |
| 6000 | 18121 | 0.4815 | 17911 | 0.3556 | 17945 | 0.291 | 18036 | 0.2499 |
| 7000 | 21158 | 0.4859 | 20772 | 0.3654 | 20731 | 0.3021 | 20782 | 0.2613 |
| 8000 | 24198 | 0.4898 | 23617 | 0.3741 | 23493 | 0.312 | 23496 | 0.2715 |
| 9000 | 27239 | 0.4932 | 26448 | 0.3819 | 26232 | 0.321 | 26183 | 0.2809 |
| 10000 | 30283 | 0.4963 | 29267 | 0.389 | 28953 | 0.3293 | 28845 | 0.2895 |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | |
| 3000 | 8014.8 | 0.8972 | 8490.4 | 0.551 | 8845.5 | 0.4064 | 9135.1 | 0.3247 |
| 4000 | 10371 | 0.9922 | 10864 | 0.6279 | 11246 | 0.471 | 11563 | 0.3807 |
| 5000 | 12667 | 1.0726 | 13153 | 0.6948 | 13549 | 0.528 | 13883 | 0.4308 |
| 6000 | 14915 | 1.1432 | 15377 | 0.7547 | 15776 | 0.5798 | 16120 | 0.4765 |
| 7000 | 17124 | 1.2065 | 17548 | 0.8094 | 17943 | 0.6274 | 18291 | 0.519 |
| 8000 | 19301 | 1.2641 | 19675 | 0.8599 | 20058 | 0.6719 | 20406 | 0.5588 |
| 9000 | 21449 | 1.3173 | 21764 | 0.9071 | 22131 | 0.7137 | 22473 | 0.5964 |
| 10000 | 23573 | 1.3667 | 23821 | 0.9516 | 24165 | 0.7533 | 24499 | 0.6322 |

**Table C-47:** Application of FN-1 Criterion to the Annulus-Side Heat Transfer Enhancement for all Geometrical Characteristics and Conditions.

| Re Annulus | FN-1 Criterion, Wire Coil, e = 1 mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | $Re_o$ | $A_a/A_o$ | $Re_o$ | $A_a/A_o$ | $Re_o$ | $A_a/A_o$ | $Re_o$ | $A_a/A_o$ |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | |
| 3000 | 2684.96 | *0.2831* | 2365.62 | *0.2833* | 2284.67 | *0.3146* | 2282.54 | *0.361* |
| 4000 | 3807.28 | *0.3247* | 3323.34 | *0.317* | 3190.71 | *0.3465* | 3173.7 | *0.393* |
| 5000 | 4991.87 | *0.3612* | 4325.99 | *0.3458* | 4134.36 | *0.3735* | 4098.26 | *0.4198* |
| 6000 | 6228.59 | *0.394* | 5365.96 | *0.3714* | 5109.09 | *0.3971* | 5050.35 | *0.443* |
| 7000 | 7510.41 | *0.424* | 6438.03 | *0.3944* | 6110.46 | *0.4182* | 6025.94 | *0.4636* |
| 8000 | 8832.14 | *0.4519* | 7538.37 | *0.4155* | 7135.22 | *0.4373* | 7022.13 | *0.4822* |
| 9000 | 10189.8 | *0.4779* | 8664.03 | *0.4351* | 8180.87 | *0.455* | 8036.68 | *0.4992* |
| 10000 | 11580.2 | *0.5026* | 9812.68 | *0.4533* | 9245.44 | *0.4714* | 9067.82 | *0.515* |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | |
| 3000 | 3136.87 | *0.3346* | 2786.49 | *0.3422* | 2721.29 | *0.3915* | 2742.08 | *0.4595* |
| 4000 | 4414.14 | *0.376* | 3881.52 | *0.3743* | 3766.4 | *0.4209* | 3777 | *0.4879* |
| 5000 | 5753.28 | *0.4117* | 5019.43 | *0.4013* | 4846.32 | *0.4453* | 4841.89 | *0.5111* |
| 6000 | 7143.87 | *0.4433* | 6192.72 | *0.4248* | 5954.82 | *0.4663* | 5931.3 | *0.5308* |
| 7000 | 8578.77 | *0.4719* | 7396.27 | *0.4457* | 7087.67 | *0.4848* | 7041.53 | *0.5481* |
| 8000 | 10052.7 | *0.4981* | 8626.34 | *0.4647* | 8241.77 | *0.5014* | 8169.89 | *0.5636* |
| 9000 | 11561.7 | *0.5225* | 9880.09 | *0.4821* | 9414.8 | *0.5166* | 9314.36 | *0.5775* |
| 10000 | 13102.5 | *0.5454* | 11155.2 | *0.4982* | 10604.9 | *0.5305* | 10473.3 | *0.5903* |
| **Re Annulus** | **FN-1 Criterion, Wire Coil, e = 2.2 mm** | | | | | | | |
| | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | $Re_o$ | $A_a/A_o$ | $Re_o$ | $A_a/A_o$ | $Re_o$ | $A_a/A_o$ | $Re_o$ | $A_a/A_o$ |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | |
| 3000 | 4444.81 | *0.4872* | 3704.36 | *0.4205* | 3453.64 | *0.4251* | 3360.76 | *0.4548* |
| 4000 | 6186.83 | *0.5318* | 5098.17 | *0.4454* | 4719.13 | *0.4418* | 4567.68 | *0.466* |
| 5000 | 7995.86 | *0.5693* | 6531.3 | *0.4657* | 6012.16 | *0.4552* | 5795.07 | *0.4749* |
| 6000 | 9860.13 | *0.6018* | 7996.56 | *0.4831* | 7327.55 | *0.4665* | 7039.03 | *0.4822* |
| 7000 | 11771.6 | *0.6308* | 9489.09 | *0.4982* | 8661.84 | *0.4762* | 8296.93 | *0.4885* |
| 8000 | 13724.6 | *0.657* | 11005.4 | *0.5117* | 10012.5 | *0.4848* | 9566.89 | *0.4941* |
| 9000 | 15714.4 | *0.681* | 12542.7 | *0.5239* | 11377.7 | *0.4925* | 10847.5 | *0.499* |
| 10000 | 17737.6 | *0.7033* | 14099.1 | *0.5351* | 12755.9 | *0.4995* | 12137.6 | *0.5034* |
| *Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m* | | | | | | | | |
| 3000 | 5536.74 | *0.6828* | 4629.44 | *0.5944* | 4350.88 | *0.614* | 4260.26 | *0.6679* |
| 4000 | 7635.37 | *0.7272* | 6306.02 | *0.6127* | 5880.46 | *0.6198* | 5724.51 | *0.6638* |
| 5000 | 9797.01 | *0.7636* | 8014.37 | *0.6272* | 7428.38 | *0.6243* | 7198.74 | *0.6607* |
| 6000 | 12010.2 | *0.7947* | 9748.49 | *0.6393* | 8991.08 | *0.6281* | 8680.99 | *0.6581* |
| 7000 | 14267.3 | *0.8219* | 11504.3 | *0.6497* | 10566.2 | *0.6313* | 10169.9 | *0.656* |
| 8000 | 16562.6 | *0.8463* | 13279 | *0.6589* | 12152 | *0.634* | 11664.6 | *0.6541* |
| 9000 | 18891.8 | *0.8684* | 15070.2 | *0.6671* | 13747.2 | *0.6365* | 13164.4 | *0.6525* |
| 10000 | 21251.6 | *0.8887* | 16876.3 | *0.6745* | 15350.8 | *0.6387* | 14668.6 | *0.651* |
| **Re Annulus** | **FN-1 Criterion, Circular Ribs, e = 2.2 mm** | | | | | | | |
| | p = 10 mm | | p = 20 mm | | p = 30 mm | | p = 40 mm | |
| | $Re_o$ | $A_a/A_o$ | $Re_o$ | $A_a/A_o$ | $Re_o$ | $A_a/A_o$ | $Re_o$ | $A_a/A_o$ |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0125 m | | | | | | | | |
| 3000 | 5904.58 | *0.6991* | 4870.34 | *0.585* | 4335.18 | *0.5219* | 3985.13 | *0.4792* |
| 4000 | 7958.58 | *0.7047* | 6603.18 | *0.5989* | 5897.11 | *0.539* | 5433.39 | *0.498* |
| 5000 | 10032.2 | *0.709* | 8361.61 | *0.6099* | 7486.72 | *0.5527* | 6910.31 | *0.513* |
| 6000 | 12121.7 | *0.7125* | 10140.7 | *0.6191* | 9098.75 | *0.5641* | 8410.47 | *0.5257* |
| 7000 | 14224.3 | *0.7155* | 11937.2 | *0.6269* | 10729.7 | *0.5739* | 9930.23 | *0.5366* |
| 8000 | 16338.4 | *0.7181* | 13748.7 | *0.6338* | 12376.9 | *0.5826* | 11467 | *0.5462* |
| 9000 | 18462.4 | *0.7205* | 15573.5 | *0.6399* | 14038.6 | *0.5904* | 13018.7 | *0.5549* |
| 10000 | 20595.4 | *0.7225* | 17410 | *0.6454* | 15713.2 | *0.5974* | 14584 | *0.5627* |
| Annulus Dimensions: L=1.245 m $D_o$= 0.028 m $D_i$= 0.0155 m | | | | | | | | |
| 3000 | 7550.65 | *0.951* | 6116.79 | *0.7585* | 5389.65 | *0.6586* | 4919.6 | *0.5935* |
| 4000 | 10326.6 | *0.9964* | 8409.48 | *0.8058* | 7431.69 | *0.7052* | 6797.46 | *0.639* |
| 5000 | 13165.3 | *1.0331* | 10764.7 | *0.8446* | 9534.84 | *0.7436* | 8734.98 | *0.6766* |
| 6000 | 16054.8 | *1.064* | 13170.9 | *0.8776* | 11688 | *0.7766* | 10721.4 | *0.7091* |
| 7000 | 18987.4 | *1.091* | 15620.4 | *0.9066* | 13883.7 | *0.8056* | 12749.5 | *0.7377* |
| 8000 | 21957.4 | *1.1148* | 18107.6 | *0.9324* | 16116.4 | *0.8316* | 14813.9 | *0.7634* |
| 9000 | 24960.4 | *1.1363* | 20628.2 | *0.9558* | 18382 | *0.8552* | 16910.6 | *0.7868* |
| 10000 | 27993.1 | *1.1559* | 23178.8 | *0.9772* | 20677.3 | *0.8769* | 19036.4 | *0.8084* |

# الخلاصة

تم استخدام ثلاث طرق لتعزيز انتقال الحرارة باستخدام مسببات شدة الاضطراب وذلك من اجل زيادة الكفائة الحرارية لمبادل حراري من نوع الانابيب المتمركزة بطول 1245 ملم وبقطر خارجي 28 ملم وانبوب داخلي قابل للتغيير بقطرين 11 و 14 ملم. محلزنات سلكية بقطر 1 ملم وفواصل لف بمقدار 10، 20، 30 و40 ملم استخدمت كمسببات شدة الاضطراب داخل الانبوب الداخلي للمبادل الحراري في مدى رقم رينولدز بين 5000 و40000. كما تم استخدام نوعين جديدين من مسببات شدة الاضطراب لزيادة انتقال الحرارة في الجانب الخارجي لنفس المبادل الحراري في مدى رقم رينولدز بين 3000 و 10000. النوع الاول تم باستخدام محلزنات سلكية بقطر 1 و2.2 ملم وفواصل لف بمقدار 10، 20، 30 و40 ملم تم تركيبها على السطح الخارجي للانبوب الداخلي. اما الطريقة الثانية فكانت باستخدام نتوءات دائرية المقطع بقطر 2.2 ملم ركبت بنفس الفواصل والموقع. أستخدام الماء في جانبي المبادل الحراري كما تم تنويع الظروف التجريبية وذلك بتغيير معدل الجريان الكتلي للجانب الغير المراد رفع كفائته وكذلك بتغيير درجة حرارة الدخول للمائع الساخن. الهدف من تغيير الظروف التجريبية هو الحصول على اكبر قدر من النقاط التجريبية للحصول على معادلات تجريبية بأدق مايمكن بالاضافة الى معرفة مدى تأثير تغيير تلك الظروف.

تم زيادة انتقال الحرارة في داخل الانبوب الداخلي بمقدار 2.43 ضعف ماهو عليه في حالة استخدام انبوب املس بنفس رقم رينولدز وكان ذلك مصحوبا بازدياد معامل الاحتكاك بمقدار 4.75 اضعاف. اما في الجانب الخارجي للمبادل فقد تم زيادة انتقال الحرارة بمقدار 3.25 اضعاف مقارنة بالجانب الخارجي الاملس وكان ذلك مصحوباً بزيادة معامل الاحتكاك بمقدار 2.63 اضعاف.

تم الحصول على معادلات تجريبية جديدة لرقم نسلت ومعامل الاحتكال لجانبي المبادل الحراري وذلك كدوال لرقمي رينولدز وبرانتل بالاضافة للخواص الهندسية للمضافات والانابيب. كما تم تطبيق معايير تقييم الانجاز (PEC) الموضوعة من قبل وب وبيرجلز وذلك لتحديد الطريقة الاكثر فائدة.

## شكر وتقدير

بعد شكر الباري عز وجل والثناء عليه، اود ان اتقدم بالشكر الجزيل الى استاذي الفاضل والمشرف على هذه الرسالة الاستاذ الدكتور قاسم جبار السليمان والذي لولا توجيهاته لما خرج هذا العمل بهذه الصورة البهية، كما أتقدم بوافر الشكر والامتنان للسيد عميد كلية الهندسة لما ابداه من دعم معنوي لي اثناء العمل التجريبي، وأشكر السيد رئيس قسم الهندسة الكيمياوية والسادة التدريسيين والكادر العامل في قسم الهندسة الكيمياوية.

ولا انسى ان أشكر جميع زملائي وزميلاتي في جامعة النهرين لما كان لهم من دور كبير في التخفيف من معاناة التعب والانتظار.

**عباس نوار**

# تعزيز إنتقال الحرارة
# بإستخدام مسبباب شدة الإضطراب

**رسالة**

**مقدمة إلى كلية الهندسة في جامعة النهرين**

**وهي جزء من متطلبات نيل درجة ماجستير علوم**

**في الهندسة الكيمياوية**

**من قبل**

**عباس نوار زناد**

**(بكالوريوس علوم في الهندسة الكيمياوية ، 1995)**

ربيع الأول 1432هـ

شباط 2011 م