DESIGN STUDY OF A SMALL HYDROELECTRIC SYSTEM

A Thesis

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Mechanical Engineering

By

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Abstract

The design and construction of a small hydroelectric generator power by undershot waterwheel; the effect of the number of blades on the waterwheel velocity, the effect of the waterwheel radius on the waterwheel velocity, the effect of the water mass flow rate on the system efficiencies, the total head, and the output power, and the effect of the channel cross sectional area also on the system efficiencies, the total head, and the output power.

The maximum overall efficiency was η = 6.69 %, the total head was h = 15.45 cm and the output power was P_g = 0.18 W these values found at number of blades N = 36, waterwheel radius r = 22 cm, maximum mass flow rate $\dot{m}$ = 1.765 kg/s, and channel cross sectional area A = 12.75 cm^2.

Computer programs were made to [illegible] total head, and the output power of the [illegible] plotted in figures 5.22 to 5.27.

The performance curves may be used for larger waterwheels using similarity laws to predict the performance of the larger waterwheels, which is the aim of this thesis.

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CHAPTER FIVE

Nomenclature

Symbol	Description	Dimension
A	Cross sectional area of water.	cm^2
$\mathbf{A}_a$	Actual cross sectional area.	cm^2
$\mathbf{A}_b$	Cross sectional area loss from bellow.	cm^2
$\mathbf{A}_s$	Cross sectional area loss from sides.	cm^2
a	Sloping height from the gate to the wheel.	cm
B	Breadth of channel.	cm
c	Velocity of an infinitesimal gravity wave.	m/s
D	Diameter of the waterwheel.	m
D	Depth of channel.	cm
E	Specific energy.	J
F	Force of water.	N
Fr	Froude number.	—
g	Gravitational acceleration.	m/s^2
h	Total head.	cm
h_a	Actual head.	cm
h_c	Head loss in channel.	cm
h_f	Total head across the wheel.	cm
h[illegible]	Head loss in wheel.	cm
I	Current	amp
J	Momentum flow rate	[illegible]
K	Kinetic Energy flow rate.	[illegible]
K.E.	Kinetic Energy.	J
L	Length of channel.	m
m	Mass of water.	kg
N	Number of blades.	—
n	Number of revolutions per minute.	rpm
P	Wetted perimeter.	cm
$P.E.$	Potential Energy.	J
P_a	Actual power.	W
P_c	Power loss in channel.	W
P_e	Power loss in generator (Electric loss).	W
P_g	Power output from generator.	W
P_l	Power loss due to leakage.	W
P_m	Mechanical power losses.	W
$P_{P.E.}$	Total waterpower.	W
P_s	Power output from shaft.	W
P_t	Power loss due to transition.	W
P_w	Power loss due to wheel.	W
Q	Volume flow rate (discharge).	m^3/s

R	Hydraulic radius.	cm
Re	Reynolds number.	—
r	Wheel radius.	cm
r_o	Active radius.	cm
S	Channel bed slope.	—
S_f	Friction slope.	—
T	Surface width.	cm
t	Time.	s
u	Tangential velocity of wheel.	m/s
V	Velocity of water.	m/s
V	Velocity of water before the sluice gate.	m/s
V	Velocity of water after the sluice gate.	m/s
V	Voltage.	V
y	Height from channel bed to the free surface.	cm
y_c	Normal depth.	cm
y_c	Critical depth.	cm
z	Height of channel bed above datum.	cm

Greek Symbols

α	Impedance factor (load factor).	—
β	Intensive property.	—
η	Overall efficiency.	—
η_c	Channel efficiency.	—
η_e	Electrical efficiency.	
η_m	Mechanical efficiency.	
η_t	Transitional efficiency.	
η_c	Volumetric efficiency.	—
η_w	Wheel efficiency.	—
θ	Sluice gate angle.	Degree
ρ	Density of water.	kg/m^3

Other Symbols

$\dot{B}$	Net flow rate of an extensive property.	kg/s
$\dot{m}$	Total mass flow rate.	kg/s
$\dot{m}_a$	Actual mass flow rate.	kg/s
$\dot{m}_b$	Mass flow rate losses from below.	kg/s
$\dot{m}_1$	Total loss of mass flow rate.	kg/s
$\dot{m}_s$	Mass flow rate losses from sides.	kg/s

Abstract

The design and construction of a small hydroelectric system is a model of an undershot waterwheel turbine which was placed in the hydraulic channel and have a sluice gate as a small dam.

The design of the waterwheel had the ability to change the number of its blades and the blades may be taller or shorter this gives bigger or smaller waterwheel diameter.

The increasing of the water mass flow rate (0.341-1.765 kg/s) at fixed channel cross sectional area (12.75 cm^2) of the undershot waterwheel generated power system shows increased in the following the generator output power (0.0031-0.18 Watt), the mechanical efficiency (10.8%-99.6%), and the electrical efficiency (80.6%-97.[illegible]%) and the channel efficiency was decreased (100%-10.[illegible]%). The following were fixed [illegible] efficiency 72.9%, [illegible] transitional efficiency 97.2%.

The increasing of the channel cross sectional area (11.25-17.25 cm^2) at fixed water mass flow rate (1.765 kg/s) of the undershot waterwheel generated power system shows decreased in the following the generator output power (0.201-0.067 Watt), the mechanical efficiency (100%-26.7%) and the electrical efficiency (99.4%-94.4%) and increased in the following the channel efficiency (8.6%-100%), volumetric efficiency (70.9%-75.5%), and wheel efficiency (85.7%-91.3%). The transitional efficiency was fixed at 97.9%.

The maximum overall efficiency of the small generated power system was 6.69 %, the total head was 15.45 cm and the output power was 0.18 W, these values obtained at number of blades 36, number of revolutions per minute 57 rpm, waterwheel radius 22 cm, maximum

water mass flow rate 1.765 kg/s, and channel cross sectional area 12.75 cm^2.

The theoretical extrapolation of the waterwheel diameter (0.44-2 m) and the water head (0.1554-5 m) gives that the output generated power was increased (0.18-675 Watt).

Contents

Nomenclature

Symbol	Description	Dimension
A	Cross sectional area of water.	m^2
a	Sloping height from the gate to the wheel.	m
B	Breadth of channel.	m
D	Diameter of the waterwheel.	m
D	Depth of channel.	m
F	Force of water.	N
g	Gravitational acceleration.	m/s^2
h	Total head.	m
I	Current.	Amp.
K_h	Head coefficient.	—
K_{Pg}	Power coefficient.	—
K_Q	Flow coefficient.	—
L	Length of channel.	m
m	Mass of water.	kg
N	Number of blades.	—
n	Number of revolutions per minute.	rpm
P	Power.	W
Q	Volume flow rate (discharge).	m^3/s
r	Wheel radius.	m
S	Channel bed slope.	[illegible]
t	Time.	[illegible]
u	Tangential velocity of wheel.	m/s
V	Velocity of water.	m/s
V	Velocity of water before the sluice gate.	m/s
V	Velocity of water after the sluice gate.	m/s
V	Voltage.	V
y	Height from channel bed to the free surface.	m
	Greek Symbols	
ϕ	Impedance factor (load factor).	—
β	Intensive property.	—
η	Overall efficiency.	—
θ	Sluice gate angle.	Degree
ρ	Density of water.	kg/m^3
	Other Symbols	
$\dot{B}$	Net flow rate of an extensive property.	kg/s
$\dot{m}$	Total mass flow rate.	kg/s

Subscripts

a	Actual
b	Loss from bellow
s	Loss from sides
c	Channel
f	Fluid
w	Wheel
h	Head
Pg	Power
Q	Flow
e	Electrical
g	Generator
l	Leakage
m	Mechanical
sh	Shaft
t	Transitional
v	Volumetric

Chapter Two

Literature Review

2.1 Backgrounds

The first description of a waterwheel that can be definitely identified as vertical is from Vitruvius, an engineer of the Augustan Age (31 BC – 14 AD), who composed a 10-volume treatise on all aspects of Roman engineering. Vitruvius described an undershot wheel, but remarked that it was among the "machines which is rarely employed." One of the reasons hypothesized for its sparse application was the availability of cheap slave labor, which prevented the Romans from developing alternative sources of power.

One of the most remarkable mills constructed by the Romans was at Barbegal, near Arles in southern France. Dating from 4th Century AD, the flour [illegible] factory, which employed 16 [illegible]

There were at least 2 other multi[illegible] neither was as ambitious as the one at Barbegal. One was at Chemtou in western Tunisia, where a combination bridge/dam spanned the Medjerda River. Three horizontal waterwheels, side-by-side, were set into the bridge abutments. The other mill was in Palestine on a dam on the Crocodile River near ancient Caesarea, halfway to Haifa. Here, there were 2 horizontal wheels, each at the bottom of a penstock. According to Hodges (p. 111): "Neither installation has been fully studied, but together they remain the only known parallels to Barbegal." [8]

However, it was much later, in 1882, the first hydroelectric facility was built in the United States, Appleton, Wisconsin, and produced direct current (DC) for local industry (provided 12.5 kilowatts to light two paper mills and a house). This plant made use of a fast flowing river as its source. Some years later, dams were constructed to create artificial water storage areas at the most convenient locations. These dams also controlled the water flow rate to the power station turbines.

Originally, hydroelectric power stations were of a small size and were set up at waterfalls in the vicinity of towns because it was not possible at that time, to transmit electric energy over great distances. The main reason why there has been large-scale use of hydroelectric power is because it can now be transmitted inexpensively over hundreds of kilometers to where it is required, making hydropower economically viable. [7]

2.2 Literature Review

Rachel Alter [6] constructed a classic overshot waterwheel with a [illegible] on the sides, and a wooden base. This waterwheel was constructed to power the five-watt light bulb. As a result of the waterwheel's rotation, [illegible] produce [illegible] to light the five-watt light bulb. Despite the low efficiency (4.7%). The purpose of the experimentation and design was achieved.

Professor Carl R. Weidner [9] (Fitz Water Wheel Company**)** tested a ten-foot diameter Fitz steel overshot [John Fitz, inventor and manufacturer. 1847-1914] installed in the hydraulic laboratory of the University of Wisconsin.

A range of four hundred per cent in variation of the amount of water supplied to this waterwheel showed a difference of only 5% in the efficiency of the wheel. The article in the "Engineering News" of January 2, 1913, by prof. Carl R. Weidner, instructor in hydraulic engineering at the University of Wisconsin. The published test reports of the University of Wisconsin show the ten foot diameter Fitz wheel, mounted on out bronze lined bearings, yielded an efficiency of 89%, on the waterwheel shaft.

Later tests of this same wheel, made under the same supervision but with the mounting changed the-aligning ball bearings, showed an efficiency of 92%.

Mick Harris [10] an Australian lived more than ten kilometers away from the nearest connection to the electricity grid. The oldest and most simple technologies (the traditional waterwheel) would be perfect to use. All-steel, welded waterwheel included very basic components: mild steel sheet, square steel tube, two bearings for the wheel to pivot on, angle iron for a pulley and a V belt.

When first got the wheel up and running, they were getting 37 revolutions per minute. But when put the car alternator on it, the waterwheel came to a dead stop. After modified the alternator, the wheel began turning again, this time at seven revolutions per minute. The alternator, however, was whizzing at 130 [illegible] system was producing 2.5 amps at 12 volts.

CADDET [11] (Guests at the Lemon Thyme Lodge in Tasmania's Wilderness Area, Australia) have their electricity generated by a 52 kW Pelton P250/335 single-jet turbine from Tamar Designs, coupled to a 90kVA generator Fig. 2.1. Before installation, the alternatives to supply the lodge were either a diesel generator – with the consequent noise and air pollution – or clearing native forest to make way for a transmission line. Since 1991, the hydro turbine has provided all the electricity requirements of the 90-bed lodge. The system also provided water for the site.

Lemon Thyme Lodge is a successful demonstration of clean energy production catering for modern remote tourist accommodation.

The hydro installation meets all the electricity demand of the fully equipped tourist lodge. Log fires provide additional heating and the water heater is boosted by gas. The system has performed reliably, with an average output of 48 kW.

Reliability and quality of supply is of great importance to Lemon Thyme Lodge. To be commercially viable as a modern, wilderness-based tourist facility, its power system needs to meet the comfort requirements of tourists in an environmentally sensitive way. The hydro system fulfils the needs of the Lodge cost-effectively.

CADDET [12] (Mae Ya) small-scale hydropower plant in Thailand is owned and operated by the Provincial Electricity Authority (PEA) of Thailand. The project has been fully operational since 1991 and is meeting planned energy generation targets.

The hydropower plant is situated in a National Park and has been specifically designed to satisfy local environmental constraints. The design also includes special features to re[illegible] [illegible] system.

The Mae Ya hydro-power plant is sited in a National Park, on the Mae Ya River in the north west of Thailand. The project started in 1985 and was commissioned in 1989.

Mae Ya has a high head of 100 m. A 3 m high weir encloses a small stilling pond. From the stilling pond, water is fed into an open desander and then to the headrace, a concrete box section about 1,000 m long. The penstock is an exposed steel pipe, 900 mm diameter and 370 m long See Fig. 2.2.

The turbine house situated 100 m below and adjacent to the river, is a closed structure with ventilation grills at the eaves. It houses the twin-jet Turgo turbine rated at 1.15 MW Fig. 2.2*a*. The generator is connected to the main district grid by means of power lines mounted on overhead poles. The station is not required to operate independently, unlike those stations at Mae Pai and Mae Thoei.

Mae Ya has been performing with an average load factor of 55%, which is above the design load. The plant's power generation and maintenance levels are close to target, with a transformer failure resulted in some times in 1994.

By the end of the dry season, the installation was operating at 50 kW output power compared to the full flow design power of 1 MW. The Gilkes Turgo turbine has a good efficiency curve against reduced flow.

Joseph Hartvigsen [13] built a system using an ES&D 10 cm plastic pelton runner, which he purchased, locally. The system is on the family farm in the mountains of southeastern Idaho.

Start working on the hydro system in the fall of 95 when they put in the pipe. They put in about 0.4-0.5 km of 15cm PVC pipe to get about 28 m of head. The pipe was buried at least 1.2 m deep, much deeper in a few spots to maintain grade.

[illegible] surplus 3hp 208V inducti[illegible] mounted on a ~0.5 m pedestal (shaft horizontal) to allow room for a nozzle above and below. The shaft extended through a Plexiglas wall to keep water off the motor. A pressure relief valve and pressure gauge were on the top of the cross. From the two sides the water goes out, up on one side, down on the other, out toward the generator then turns to the tangent of the pelton runner. Most of the joints were glued but there were enough threaded joints to give 3 axis of motion to align them. He put in the generator, nozzles, pelton, etc. And started it up he got 15-16A.

DOST [14] project was demonstrated at Dulao, Malicbong, and Abra from August 1995 to June 1997(In Philippines). The piloting of community-based micro-hydro power generation technology was successfully established and now operational in Barangay Dulao and

Barangay Gacab both in the municipality of Malibcong, Abra in the year 1997 and 2000, respectively. The two-hydropower systems have similar operation schemes, but differ in the controlling mechanisms.

The plant now provides electricity to forty-four (44) households, allowing every house with 40 watts of power for lighting during low flows and maximum of 160 watts during peak flows. In addition, each house has a convenience outlet for radio and stereo plugging, and battery charging. The village was also provided with five (5) streetlights at 100-watt bulb each. Likewise, the church was installed with two 20-watt fluorescent lamps while the town hall has two 100-watt incandescent bulbs and a convenience outlet.

Micro-hydro power in Laos [15] Fig. 2.3 in the northern provinces of Laos bordering on China and Vietnam can be found an interesting example of an appropriate technology for generating electricity rudimentary, low-cost, robust, and not reliant on overseas experts to install. The turbine/generator, w[illegible] [illegible] propeller turbine is located at the [illegible] on a bamboo draft tube. The generator mounted at the upper end of the shaft is covered to protect it from the elements.

Numerous examples of this technology can be found in Muang Samphanh. Along the Nam Likna, just before it enters the Nam Ou, individual villagers have constructed canals in the streambed to direct a portion of the flow a short distance. The water then flows into one or more short channels each constructed of three wooden planks. Figure 2.3*b* shows three such channels in the foreground and more in the background.

Each channel has a hole at the end of the bottom board while the two side planks are joined by a bucket with its bottom removed and split along it side. This hole leads to a bamboo draft tube into which the end of the turbine/generator unit is inserted Fig. 2.3*c*. Water drops about 1 meter and generates an estimated output on the order of 50 W (with greater output for larger drops).

The permanent magnet generator, which is located at the top of the shaft from the propeller turbine, generates 220 V of alternating current.

Two small gauge wires draped over thin bamboo poles and trees and hanging from homes and other structures along the way transmit the electricity for each turbine/generator to the home of the owner of that unit. There, electricity is used for lighting, to power radios and fans, and in a few cases, to power satellite dishes and televisions.

CADDET [16] small hydropower project in southern Sweden demonstrates ways of minimizing the impact of micro hydro schemes on the environment Fig. 2.4. An old mill on the River Rössjöholmsån has been restored and now houses a catering company, which uses electricity produced by the hydro power plant.

In 1998, a semi-Kaplan turbine [illegible] since the 1960s. The new [illegible] and produces around 135 MWh/year. The Swedish company, Cargo & Kraft Turbine AB, was chosen to carry out the project.

To minimize the hydro power plant's impact on the environment, neither hydraulic oils nor grease are used. Instead, food-quality lubricants, which will not damage the environment in the event of leakage, are used in the plant.

The turbine is a 700 mm semi-Kaplan model with flexible turbine blades. When power is not required, the blades are adjusted to a minimum resistance and the turbine runs at idling speed. Water is allowed to flow through at 10–12% volume and the system never runs dry, which is important in maintaining biodiversity and because the river is a spawning site for salmon.

Mark Richard Allan [17] described a method for modifying predictive models of pump-as-turbine (PAT) performance in conjunction with complete pump characteristics diagrams. This method is applied to predict the performance of a water reservoir feed pump as a turbine, and the potential arising for pumped energy storage within the water network is examined.

Given an estimated output power of 660 kW, the simplest method of pumped storage would be to pump water uphill at night and release it during the day. As an absolute limit over 24 hours, pumping for 11½ hours with one 78% efficient 660 *l*/s pump and recovering energy from the same 8100 *l* of water over 12½ hours with one 82% efficient 660 kW 730 *l*/s turbine would allow the return of 7.5 MWh at the expense of 14.9 MWh, a roundtrip efficiency of 51%.

David Allender [18] used a vertical Turgo turbine built by Energy Systems and Design. It had 4 nozzles, enabling it to cope with a variety of flows.

The head was found to be [illegible] 170 meters. The flow varied from a minimum of 1 liter/sec in summer to over 80 liters/sec in winter. It rarely fell below 5 liters/sec between October and April.

The penstock was made up of 4" diameter PVC tubing. It was delivered in 6-meter lengths and thus required many joints to be made. He used solvent weld connectors because they were cheaper than the alternatives. The penstock was buried for about half its length adjacent to the house but was fixed on the surface for the remaining distance, via a system of brackets and stone supports.

A concrete base was made for the turbine into which a removable frame was mounted to which the turbine was bolted. To connect up the turbine to the battery required about 150 meters of 6mm cable. Six mm cable was required to prevent too much voltage drop along the length of the cable and hence loss of power.

The turbine started turning, the output meter read 10 amps - *i.e.* 250 watts output.

Paul Cunningham [19] wrote about a renewable energy dealer Harold Lunner of British Columbia, Canada, had recently completed an installation of a Stream Engine. The hydraulic system used was the pelton wheel. The head vertical drop at this site was approximately eight meters.

The system, with two 22 mm nozzles, uses about 10 l/s and was fed by a 150 mm pipe, 200 m long. Output from the machine was 8.5 amperes in a nominal 48V system; this actually operated at 54V at this current level.

This gives an output, in watts, of 459. A water to wire efficiency of 65% was achieved.

Al-Hand [20] studied the possibility of exploiting seasonal water valleys to solve the problem of electricity [illegible] course enough for the needs and depending on the availability of resources. Water flow should be controlled for this purpose. Small hydroelectric stations could be established along with the dams to use water and electric power for the development of rural areas.

A computer program was set to study water needs and resources, dams design and the suitable hydroelectric generation stations built up on seasonal water valleys. Another program was set up for controlling water and operating these stations for maximal exploitation of water.

These were more than 10000 valleys distributed in the Arab world with water volume of 10^{12} m^3. Unused valleys can be categorized into:

1. Large seasonal water valleys: water flows in it in the rate of 70-100% and transfer more than 10^8 m^3.

2. Medium seasonal water valleys: water flows in it 40-70% of the day of year. The water transfers through 10^6 to less 10^8 m^3.
3. Small seasonal water valleys: water flows at < 40% days of the year and the water transfer through it < 10^7 m^3.

All the above were suitable for micro hydropower produced electricity from 5 to 30 kW at rate of flow 0.01 m^3/s with head from less than 1 m of water to less than 100 m.

Majed S. [21] studied the possibility of exploiting the Tigris, the Euphrates and their branches to produce hydroelectric power. The estimated collected power was 100 TWh and the value of used electricity was 90 TWh [22] as shown in below.

Local height	*Storage water*	*Design power capacity*	*Power produce*	*Ref.*
(1) 24-27 m	30 million m^3	4×500 kW	9650000 kWh	
(2) 12-15 m	15 million m^3	6×300 kW	4850000 kWh	
[illegible]	[illegible]	6×200 kW	[illegible]	
(4) 12-15 m	15 million m^3	6×200 kW	4850000 kWh	
Total	75 million m^3	6200 kW	24200000 kWh	

The summarized parameters of the micro hydropower systems of the literature review are shown in table 2.1.

2.3 Objective of the Work

The aim of this project was to build a model for generate power from water by constructing undershot waterwheel turbine and then extrapolate this model theoretically to predict the performance of the undershot waterwheel turbine prototypes. Calculate the efficiencies of the waterwheel and the effect of number of blades on the waterwheel velocity.

Table 2.1 Parameters of the micro hydroelectric systems

Capacity	*Head*	*Type*	*Penstock*	*Flow*	*Turbine*	*Generator*	*Cost*	*Ref.*
52 kW	Gross head 208 m	Dam	Pipeline [illegible] m	46 l/s	Single-jet turbine from Tamar Designs Rty. Ltd.	90 kVA generator electric shunt-load governor	A$ 131,600	[11]
1 MW	100 m with surge tower	Run-of-river	Exposed steel pipe, [illegible] mm diameter, 37[illegible] m long	1.37 m^3/s max	Gilkes twin-jet Turgo 1.15 MW	Induction with cage rotor. Provides three-phase, 50 Hz output of 6,600 V at 113 A, running at 757 rpm.	£ 1000/kW	[12]
50 W	1m	–	–	–	Propeller turbine	220 V	–	[15]
25-33 kW	2.2 m	Open flow	–	3 m^3/s	Semi-Kaplan with variable-pitch blades	Belt-driven 380 V/50 Hz Asynchronous	–	[16]
Output 750 kW Grid modified 685 kW AF and water shower 650	– – –	Water supply network		630 l/s 760 l/s 700 l/s	Pump as turbine performance efficiency 80% 80% 83%	Power output 600 730 690	– – –	[17]
200 W	8/170 m	pipes		[illegible] l/s	Vertical Turgo turbine	Altermotor 200 W	C$ 1360	[18]
< 1 kW	8 m	Pipe	[illegible]	[illegible] l/s	Impulse turbine runner	459 W	–	[19]

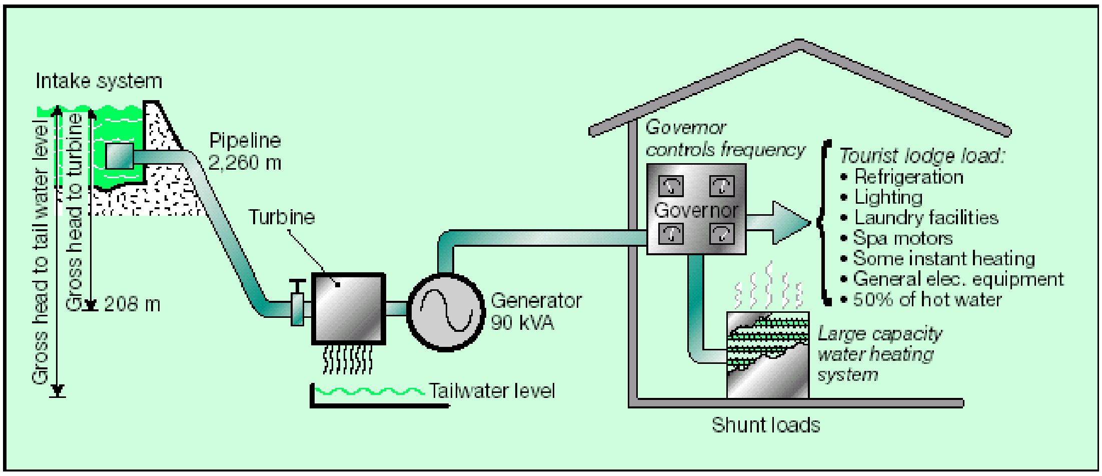


Figure 2.1: Diagram of the micro hydro system at Lemonthyme Lodge. [11]

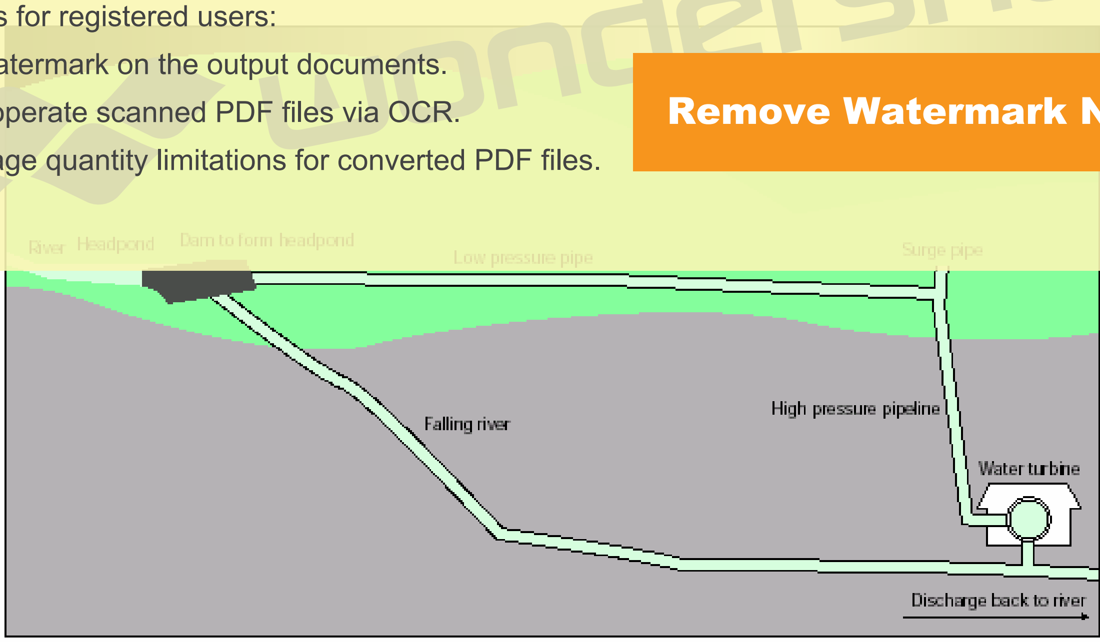


Figure 2.2: Schematic diagram of a hydro-power station. [12]

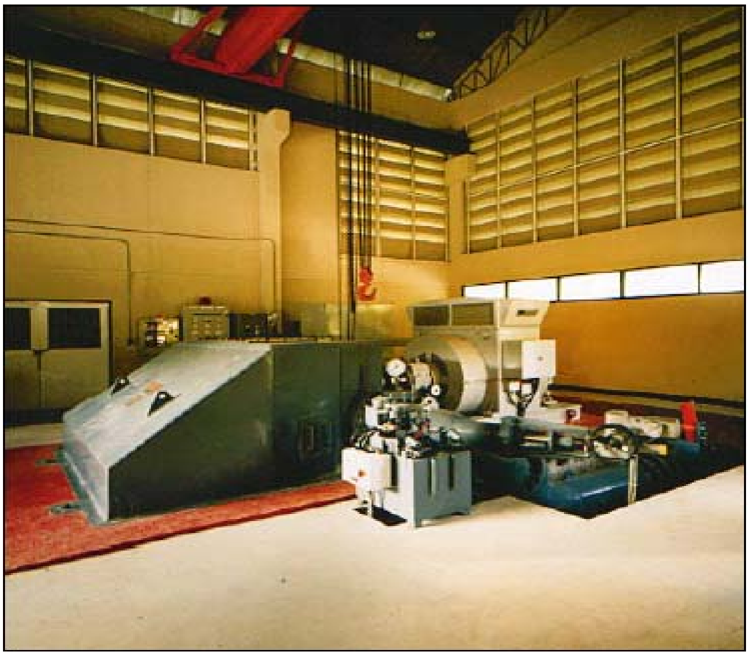
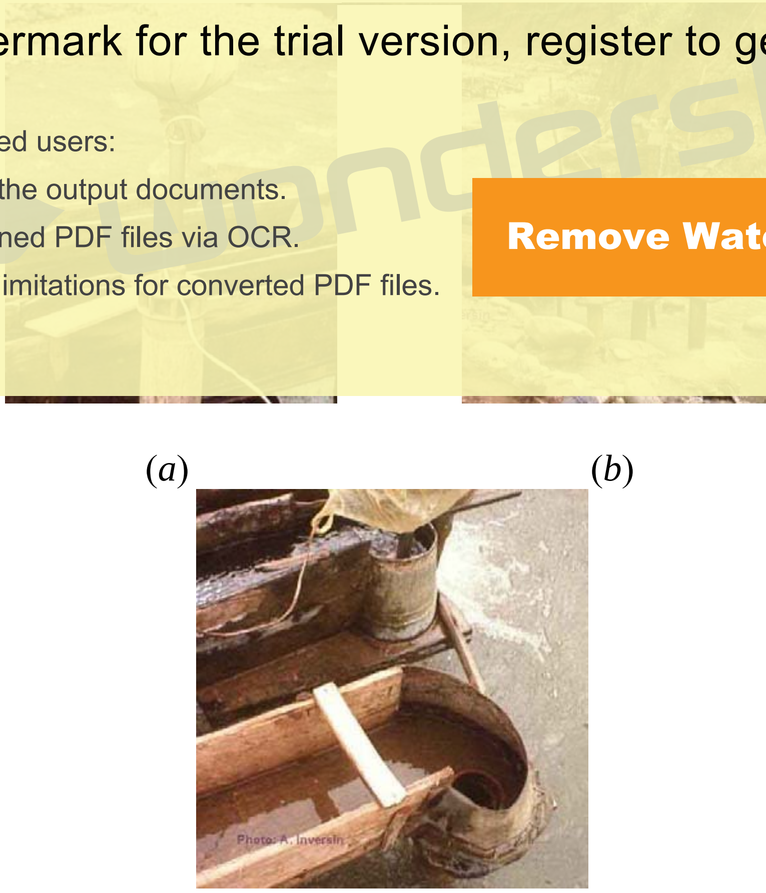


Figure 2.2a: The twin-jet Turgo turbine. [12]



(*a*) (*b*)

(*c*)

Figure 2.3: Micro-hydro power project in Laos. [15]

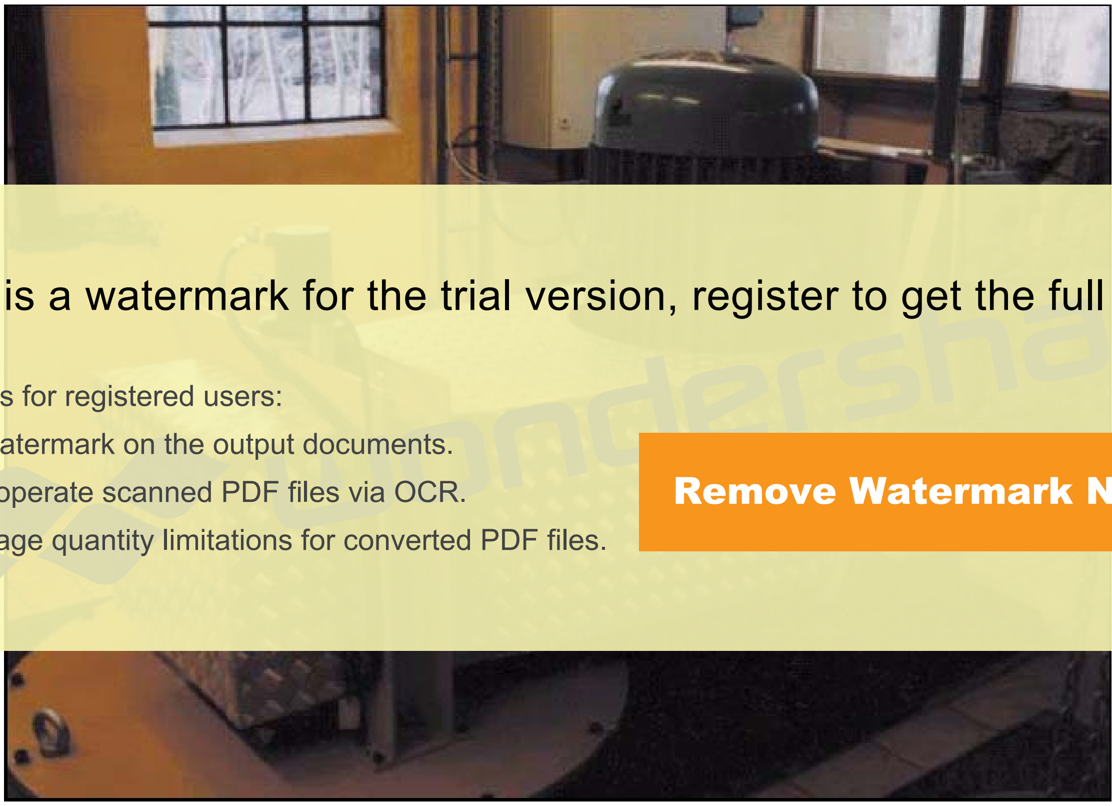


Figure 2.4: Östra Kvarn micro hydropower project. [16]

Chapter One

Introduction

1.1 Hydropower and Micro-Hydropower

The increasing demand of electrical power causes increasing in the fuel cost and as knowing that the sources of crude oil will finish after one or two hundred years, so the world countries turn to some alternative energy sources like water energy (hydropower), solar energy, thermal energy, wind energy and etc. to generate electrical power.

As the heat of solar radiation converts water to water vapor, or steam, which rises in the atmosphere to form clouds. When this water precipitates as rain or snow in upland areas, the water stored in rivers above sea level is like storage of potential energy. This potential energy changes to kinetic energy when the stored water is channeled to turn blades of a water wheel or turbine to gene[illegible] generated in this way is called hydropower [illegible]

A hydroelectric power plant uses a renewable source of energy that does not pollute the environment. However, the construction of dams to enable hydroelectric generation may cause significant environmental damage. Also, water used to drive the power plant could have other uses at other times, for example for irrigation or town water supply. [1]

There are three types of hydropower systems, the first type is the large-scale hydropower systems which generate more than 30 megawatts (MW), the second one is the small-scale hydropower systems which generates between 0.01 to 30 megawatts (MW) of electricity, the third one is the micro-hydro system that generate up to 100 kilowatts (kW) of electricity. [2]

Micro hydropower is probably the least common of the other used renewable energy sources, but it has the potential to produce the most power, more reliably than solar or wind power if the right sit is used. This means having access to a river or stream that has high enough flow to produce power for a good part of the year.

Micro-hydro power was one of the earliest of the small-scale renewable energy technologies to be developed, and is still an important source of energy today.

The amount of energy produced depends on water pressure (measured in terms of “head” or the vertical distance from the water take-off point down to the turbine), and volume, (measured as “flow” in cubic meter per second). [3]

The heart of the hydroelectric system is the mechanism for converting the energy of the water source to mechanical energy to drive the generator. Waterwheels were the traditional means of conversion. [4]

Waterwheels are cheap to build, [illegible] reliable power under great range of [illegible]

Waterwheels, although falling into disuse, have been employed for centuries as sources of power. The first information on them dates back to approximately 400 B.C., in a poem by Antipater, a Greek author. He wrote about the use of waterwheels in grinding grain, but by the time of the Industrial Revolution, they were used for driving anything from sawmills to forge bellows to textile mills.

Many types of waterwheels exist, these all depend on where water comes in contact with the paddles. In each one, the paddles are spaced evenly around the center, but that is usually where similarity ends. One of the more common types of waterwheels is the undershot waterwheel Fig. 1.1. This is the kind that is always seen positioned over a stream. Due to where the water comes in contact with the paddles, the paddles are usually slightly curved. This allows the paddles to cup the water for as long as possible while allowing it to fall away with relatively no velocity. Unfortunately, due to the small amount of time that the water is in contact with the paddles, it is the least efficient of all the types of waterwheels. The other types of waterwheels come under the main type called an overshot waterwheel. The traditional overshot waterwheel Fig 1.1 has water striking the top of the waterwheel to be carried down to the bottom and drop. It usually has sharply bent paddles to exploit the energy of the running water to the fullest. Another type of overshot waterwheel is the breast waterwheel fig. 1.1. On this waterwheel, the water hits the paddles halfway down the side of the waterwheel. Some say that this is the most efficient waterwheel, however, no tests could be found to prove this assertion. The last type of overshot waterwheel is the pitch-black waterwheel fig 1.2. This is very similar to the traditional overshot wheel; however the wheel pitches backwards when the water hits it. This wheel also has the sharply bent paddles, to ma[illegible] [illegible] that this is the most efficie[illegible] proof of this. Every type of waterwheel has been used; however, the choice of the waterwheel to be use depends on the surrounding land.

The type of waterwheel used is not the only factor in determining the efficiency of the waterwheel. The materials also contribute to how well the waterwheel harnesses the energy of the water. It was John Smeaton in 1759 that first started using cast-iron to make the wheel. Two years later, he found that making a completely cast-iron waterwheel almost tripled the efficiency of the undershot waterwheel. This ended the use of wood as the only component in waterwheels. From then on, waterwheels used in industry were made completely out of cast-iron. [6]

Waterwheels which were made from local trees are been used in irrigation and grain grinding and would have been located on the banks of the river Euphrates especially where the river is deep such as Ana, Hadetha, Heet and Al-Baghdady.

These wooden waterwheels could be used to generate electricity after certain improvements.

1.2 The Future of Micro-Hydropower

As a cheap, renewable source of energy with negligible environmental impacts, micro-hydro power has an important role to play in future energy supply scenarios, particularly in developing countries. It is an attractive alternative to diesel systems in rural and remote areas of developing countries as a means of achieving rural electrification. [7]

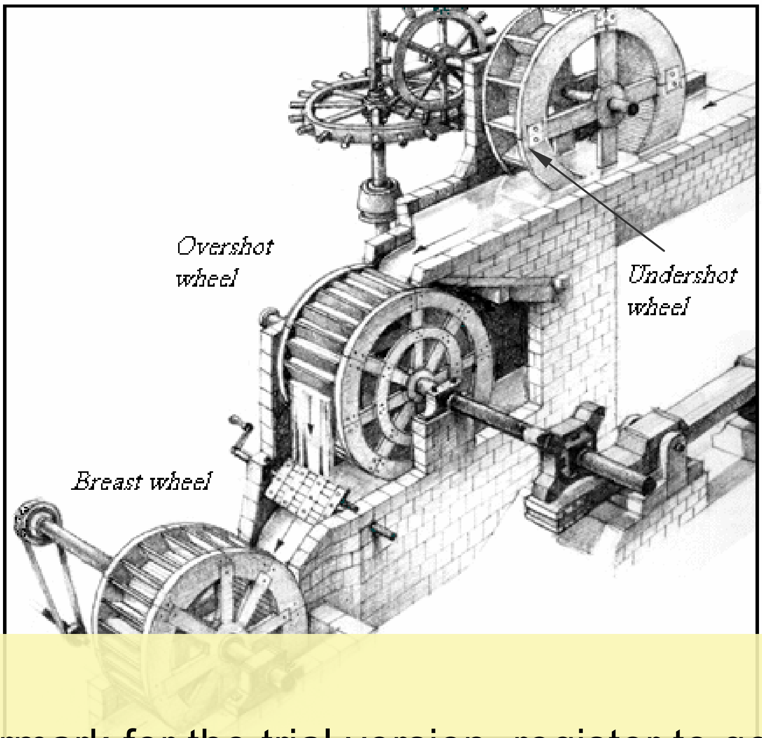


Figure 1.1: The Undershot, Overshot, and Breast wheel waterwheels. [6]

Figure 1.2: A Model of a Pitch-Back Waterwheel. [6]

Chapter Three

The Design Study and Construction Procedure of the Small (Micro) Hydroelectric Power System

3.1 Introduction

The hydro-power plant specifically designed to satisfy local environmental constraints. The micro-hydroelectric power system consist the following design parts:

1) Water supply network 2) Waterwheel/Turbine 3) Generator

The layout of the general micro hydroelectric system is shown in Fig. 3.1

3.2 The Hydraulic Channel

The hydraulic channel used in this project as the water intake having length 5 m, breadth [illegible] [illegible]

Slope adjustable by screw jack giving 100 mm vertical adjustment between pivots at 4.313 m centers. Scale divided into m and 0.1 m provided along channel length.

Pump capacity 2.2 *l*/s, pump motor power 150 W, sump tank capacity 180 *l*, and gravimetric tank capacity 60 *l*.

220/240V A.C. supply and earth, single phase, cold water supply point initial filling, and drain outlet for occasional draining.

The channel operates in a closed water circuit. Water pumped from the supply tank to the channel inlet through a precision control valve. The valve may be adjusted by a control rod from any location along the length of the channel. From the outlet the water drops into a gravimetric measuring tank and then returns to the supply tank.

3.2.1 Leveling the Flow Channel

Leveling the flow channel by set a small flow and seal off the end of the channel with the sealed exit gate provided. Fed the channel to a depth of approximately 100 mm. switches off the pump and shut off the supply valve. Adjust the vernier depth gauges. Place a vernier depth gauge at each end of the channel. When the water has settled completely, measure the depth at each end. Since the water surface is horizontal, any difference between the readings indicates that the channel is sloping. To raise or to lower the downstream end of the channel use the screw jack as required bringing it level. Successive corrections will be needed, until the vernier gauges agree on the depth, indicating that the channel is perfectly level. Allow the water to settle completely after each movement of the channel.

3.3 The Waterwheel

The undershot waterwheel is made of [illegible] with outer diameter of [illegible] and thickne[illegible]

At 4 cm diameter there are two holes have a diameter of 0.4 cm to connect the wheel with the shaft, at 12 cm diameter there are four holes with 4 cm diameter for decreasing the moment of inertia.

There are grooves every 10 degrees made readily all over the circumference of the wheel to put the blades inside it. Each groove have a length of 10 cm and thickness of 0.4 cm, at 1 cm on the right of any groove there are 9 holes to connect the blades with the wheel so that to change the radius of the wheel (r), the distance between each hole is 1 cm Fig. 3.3 shows the details of the wheel.

The blades made of plastic with 12 cm length, 6.2 cm width and 0.4 cm thickness and there are two holes to connect the blades with the wheel see Fig. 3.4.

The shaft is made of iron with maximum length of 30 cm, minimum diameter of 1 cm, and maximum diameter of 1.2 cm see Fig. 3.5.

Other things like the stand, is made of two pipes and the base is made of two parts of iron. The assembly of the waterwheel is shown in Fig. 3.2.

There are two gears to connect between the waterwheel shaft and the generator shaft. The two gears have a gear ratio of 80:16. Attach the larger gear to the wheel shaft and the smaller gear to the generator shaft.

3.4 The Generator

The generator is a bicycle generator Fig. 3.6.

The spinning generator shaft causes magnet to pass by coils of wire inside the generator. This produces electrical energy, or electricity. This energy is carried through electrical wires from the generator which are being connected to an appliance [e.g. lights].

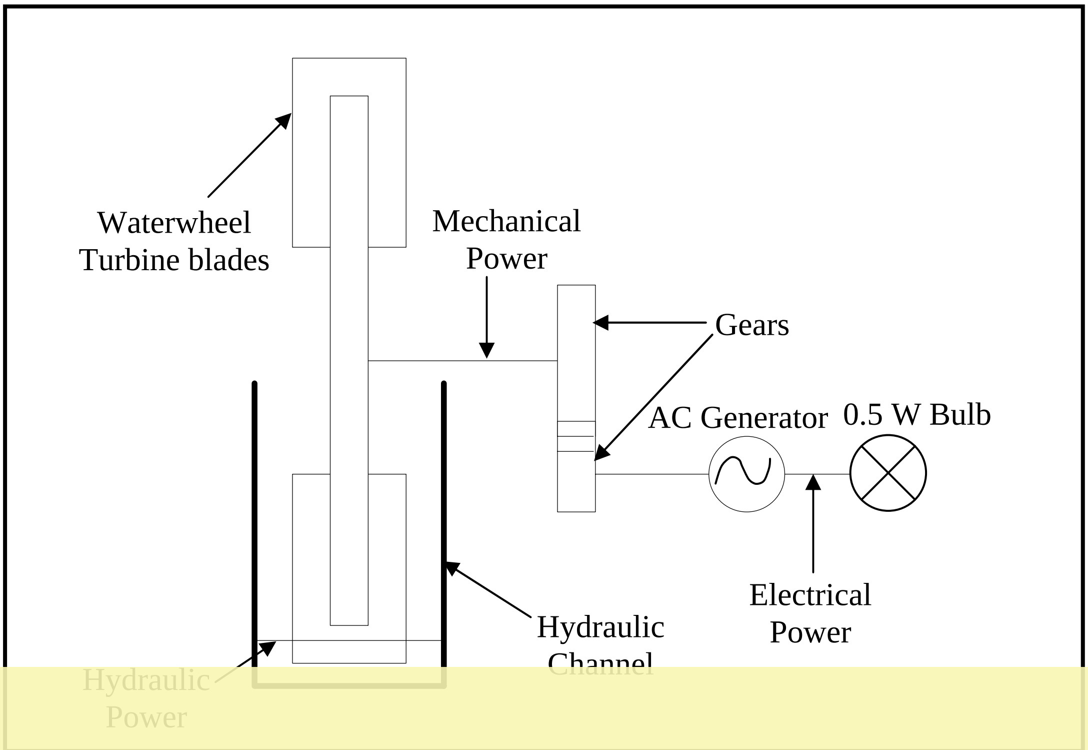


Figure 3.2: The project constructed micro hydropower system components.

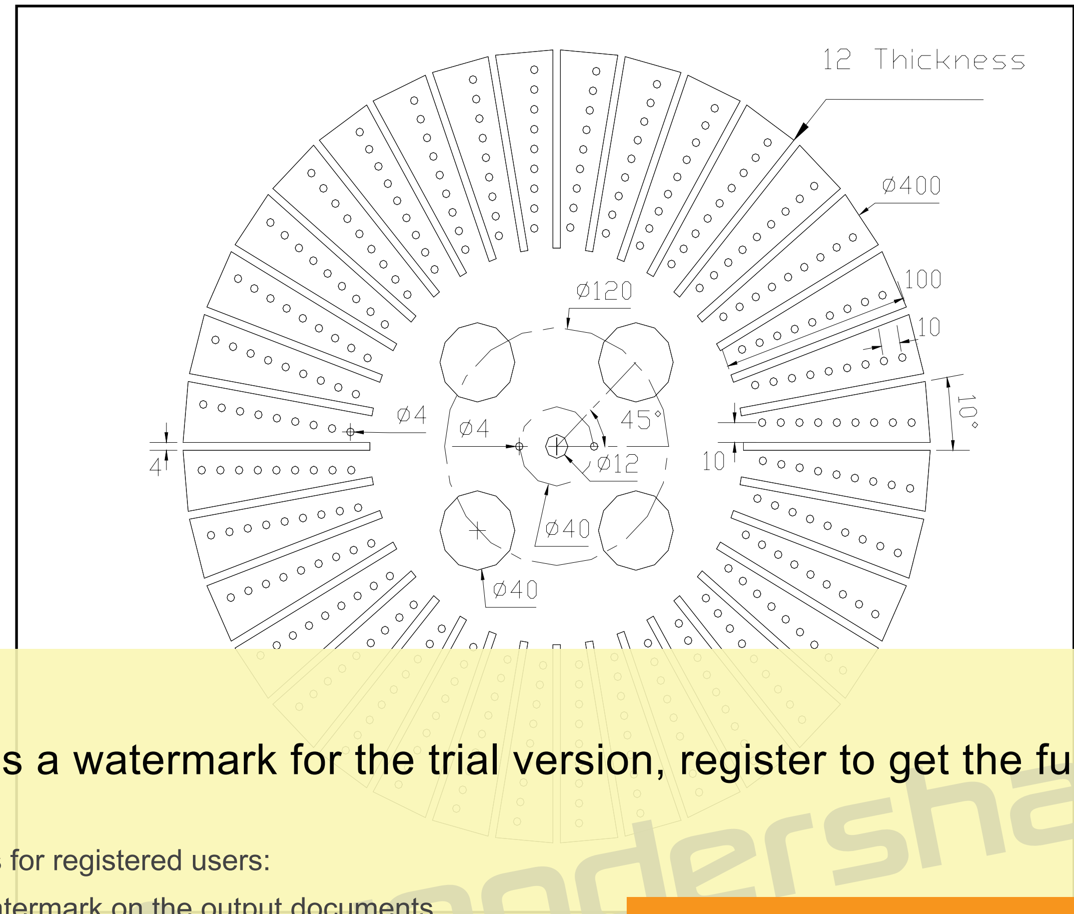


Figure 3.3: The constructed undershot
system.

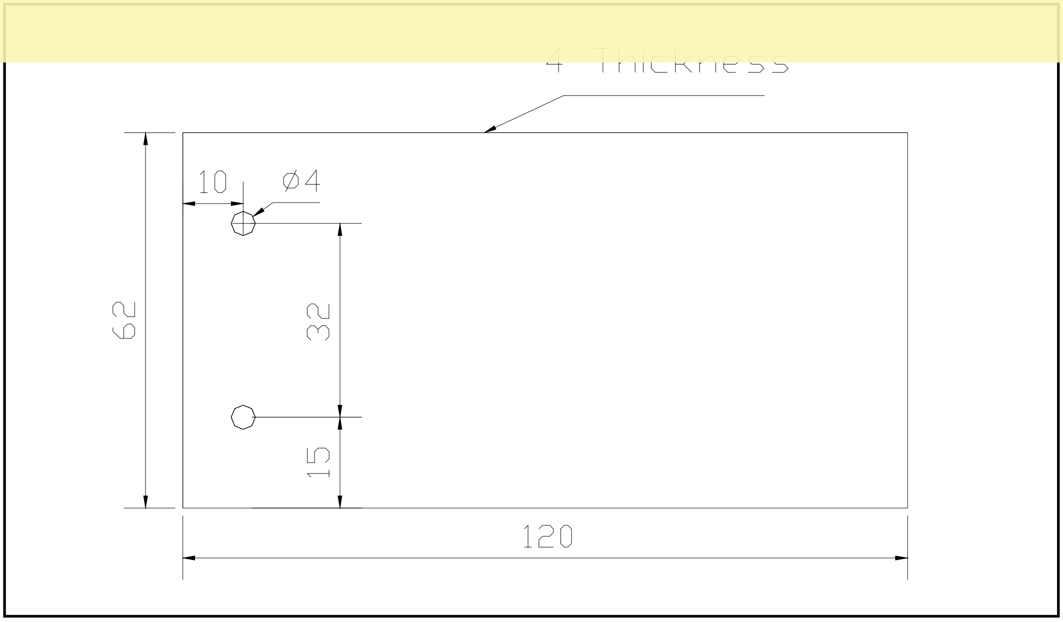


Figure 3.4: The plastic blade of the waterwheel.

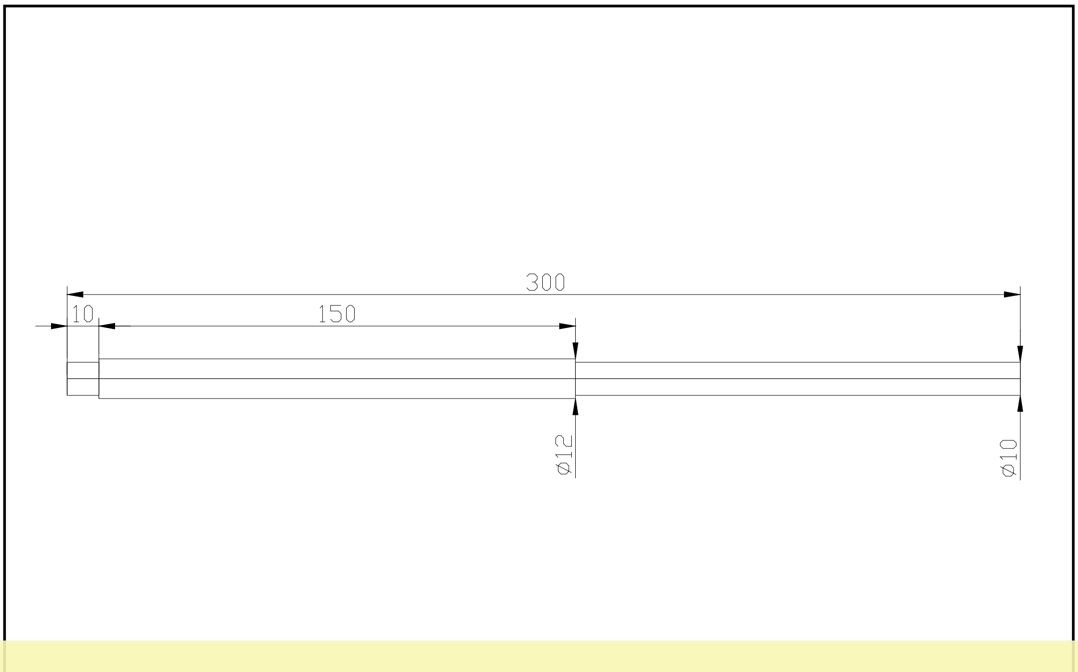


Figure 3.6: The project constructed small hydroelectric power system.

Chapter Four

Flow Principles and Power Calculations

4.1 Flows through Open Channels

The flow in open channels is characterized by the existence of a free surface. The free surface may be defined as the surface of contact between the liquid and the overlying gaseous fluid, (*i.e.* liquid-gas interface), the interface being subjected to a constant pressure throughout its length and breadth. In most of the engineering problems of open channel flow the gaseous fluid happens to be air at local atmospheric pressure. In such cases, the free surface is a liquid-air interface, which is [illegible]

Open-channel flow, however, in general, may have a free surface arising out of a liquid-gas interface subjected to a constant pressure. The [illegible] either be p[illegible] depending on whether it runs full under pressure, or has a free surface. A drainage pipeline, *i.e.* a sewer, under ordinary conditions of flow behaves as an open channel while at times of heavy rains, the sewer gets completely filled and runs full under pressure. The analysis of flow in the first case will involve principles of open channel flow whereas in the second case, principles of pipe flow will have to be employed.

4.2 Classification of Flow

Open channel flow can be classified into many types. The following classification is due to change in flow depth with respect to time and space [25].

(A) Classification With Respect To Time

Steady Flow. Flow in an open channel is said to be steady if the depth of flow at a section does not change during the time interval under consideration.

Unsteady Flow. If the flow depth at a section changes with time, the flow is known as unsteady.

(B) Classification With Respect To Space

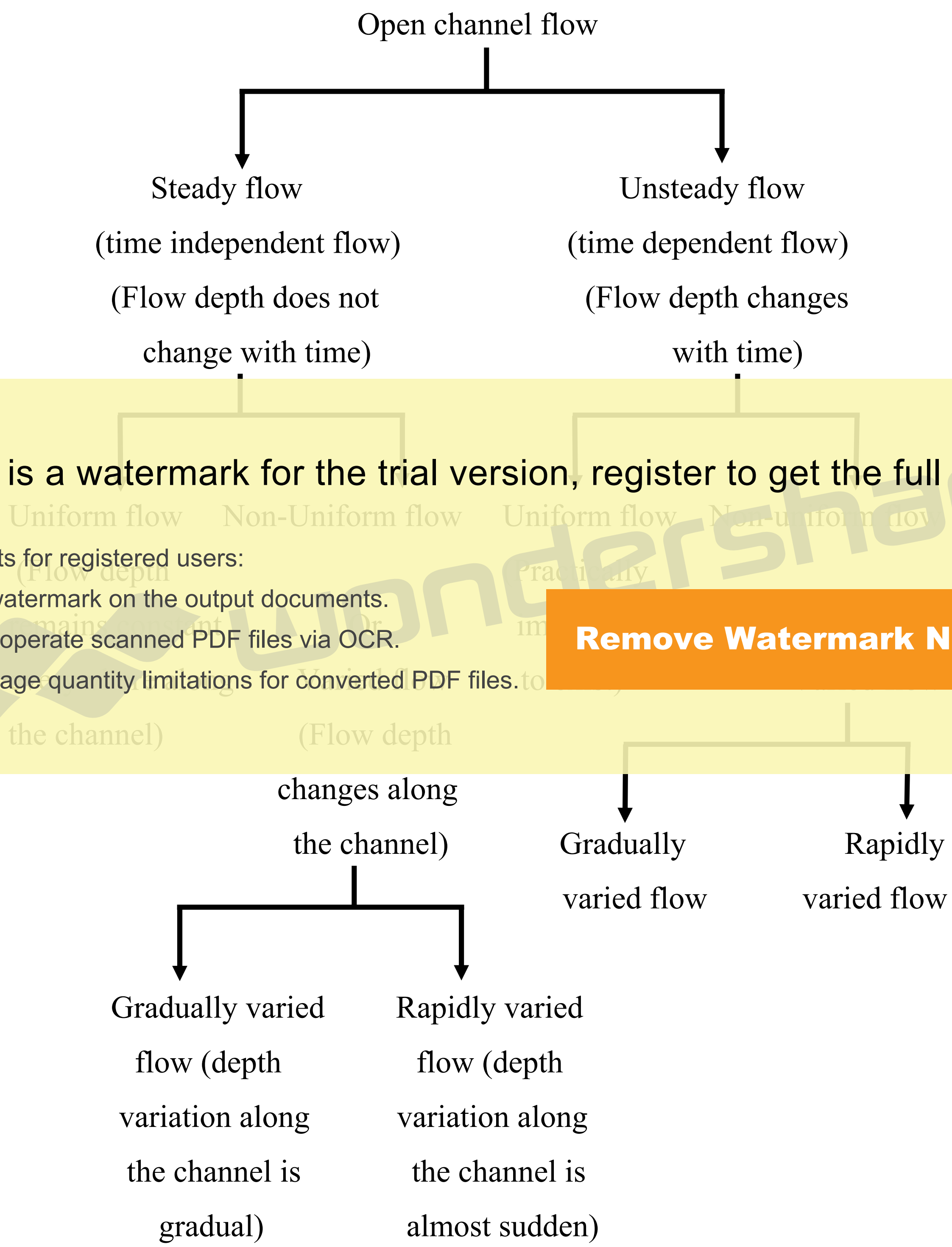
Spatially Varied Flow. The steady flow in main channel, which is joined by lateral channels at different points along its length, is non-uniform. Such a flow where water flows into or out of the channel is known as spatially varied or discontinuous flow. The examples of this type of flow are: flow in roadside gutters, flow in rivers having tributaries, flow in side channel spillways, and flow in effluent channels around sewage-treatment tanks.

Uniform Flow. Flow in an open channel is said to be uniform when the depth of flow remains the same at ev[illegible] being uniform it may be stead[illegible] whether or not depth remains constant with time. Uniform unsteady flow, however, may not be possible in practice.

Non-uniform or Varied Flow. Flow is said to be non-uniform or varied if the depth of flow changes along the length of the channel. It may be either steady or unsteady. In most of the natural open channels the flow is generally non-uniform as indicated by the varying depths across and along the channel.

The non-uniform flow may further be classified as either gradually varied or rapidly varied. If the changes in depth of flow are gradual, the flow is said to be gradually varied. On the contrary, if the depth changes abruptly within a short distance it is known as rapidly varied flow. It is called a local phenomenon, as it occupies a short length of the channel.

Examples of these types are the hydraulic drop and the hydraulic jump. The following chart shows the above-mentioned classification of flow.



4.3 Derivation of the Control-Volume Equation

To drive the basic control-volume equation, by first focusing on a *system* that moves through space; however, in the process of derivation, the control volume becomes significant.

The basic equation for the control-volume approach is derived by considering the rate of change of an extensive property of the *system* of fluid that is flowing through the control volume. In Fig. 4.3 the solid line identifies the control surface that encloses the control volume, and this same surface serves to define the system, a given mass of fluid, at time t. At time $t + \Delta t$, this system, or mass of fluid, is identified by the dashed line in Fig. 4.3, and it has moved with respect to the control surface; it has moved downstream. The rate of change of the extensive property B of the

a derivative as

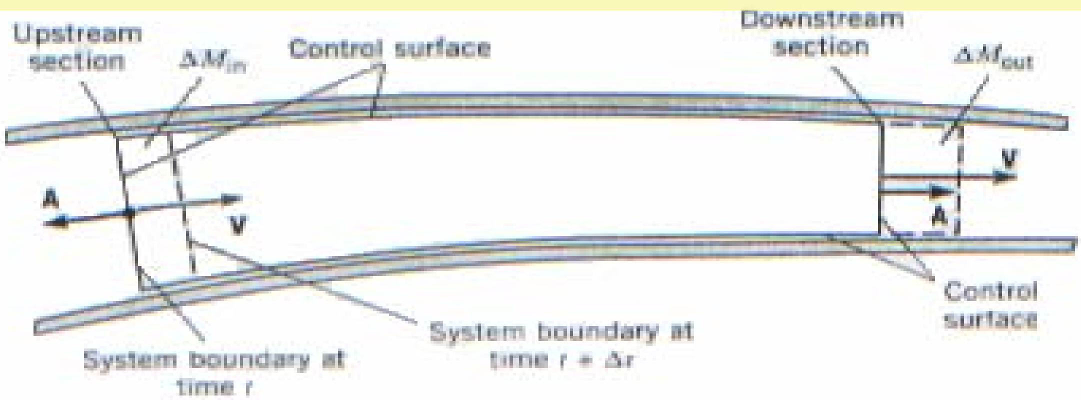


Figure 4.3: [26]

The mass of this system at time $t + \Delta t$ is the mass of the fluid within the control volume at time $t + \Delta t$ plus the mass that has moved out of the control volume in time Δt minus the mass of fluid that has moved into the control volume in time Δt see Fig. 4.3. Let us call ΔM_{out} the mass that has moved out of the control volume in time Δt and ΔM_{in} the mass that has moved into the control volume in time Δt. Likewise, let the extensive property of the system that has moved out of the control volume in time Δt be ΔB_{out} and let the extensive property of the system that has moved into the control volume in time Δt be ΔB_{in}. Thus the extensive property B of the system at time $t + \Delta t$ can be written $B_{cv.t+\Delta t} + \Delta B_{out} - \Delta B_{in}$, and the rate of change of the extensive property of the system with respect to time can be expressed as

$$\frac{dB_{sys}}{dt} = \lim_{\Delta t \to 0}\left[\frac{(B_{cv.t+\Delta t} + \Delta B_{out} - \Delta B_{in}) - (B_{cv.t})}{\Delta t}\right] \quad (4.2)$$

Rearranging terms yields

$$\frac{dB_{sys}}{dt} = \lim_{\Delta t \to 0}\left[\frac{B_{cv.t+\Delta t} - B_{cv.t}}{\Delta t}\right] + \lim_{\Delta t \to 0}\left[\frac{\Delta B_{out} - \Delta B_{in}}{\Delta t}\right] \quad (4.3)$$

The first term on the right-hand side of Eq. (4.3) is simply the rate of change with respect to time of the extensive property B of the fluid inside the control volume at time t. That is,

$$\lim_{\Delta t \to 0}\left[\frac{B_{cv.t+\Delta t} - B_{cv.t}}{\Delta t}\right] = \frac{dB_{cv}}{dt} = \frac{d}{dt}\int_{cv} \beta \rho \, d\forall \quad (4.4)$$

The second term on the right-hand side of Eq. (4.3) can be analyzed in the following manner. The quantity $\Delta B_{out} - \Delta B_{in}$ represents the amount of the property B that has passed out of the control volume minus the amount of the property B that has passed into the control volume in time Δt. Thus, when this is divided by Δt and by taking the limit as $\Delta t \to 0$, obtain the rate of flow of B out of the control volume minus the rate of flow of B into the control volume or, in other words, the net rate of flow of B from the control volume.

$$\frac{dB_{sys}}{dt} = \frac{d}{dt}\int_{cv} \beta\rho \, d\forall + \sum_{cs} \beta\rho \; \mathbf{V} \bullet \mathbf{A} \qquad (4.5a)$$

The subscript on the summation sign of the second term on the right side of Eq. (4.5a) indicates that the summing flows across the entire control surface. In the derivation of Eq. (4.5a), it first considered the rate of change of the extensive property B of the system, dB_{sys}/dt; then it showed that this could be expressed as the sum of the rate of change of B within the control volume plus the net rate of flow of B out of the control volume. Thus the left-hand side of Eq. (4.5a) is still the rate of change of the extensive property of the system (ra[illegible] [illegible] of the given quantity of matter), [illegible] conditions within the control volume and to flow across the control surface for the first and second terms, respectively. In the derivation of Eq. (4.5a), one-dimensional flow was assumed; thus the rate of flow of B at each section was given as $\beta\rho\mathbf{V} \bullet \mathbf{A}$. However, when the velocity is variable across a section, the more general form for the rate of flow of the extensive property, thus the control-volume equation is given as

$$\frac{dB_{sys}}{dt} = \frac{d}{dt}\int_{cv} \beta\rho \, d\forall + \int_{cs} \beta\rho \; \mathbf{V} \bullet d\mathbf{A} \qquad (4.5b)$$

4.4 Momentum Principle

In solid mechanics the impulse, $\int \mathbf{F}\, dt$, applied to a body is equal to the change of momentum, $M\mathbf{V}_2 - M\mathbf{V}_1$, for a given time interval. The directly analogous situation for fluid flow is the case where liquid in a pipe is accelerated by means of a pressure differential along the pipe. Both these cases may be termed simple unsteady-state cases, for which the basic equation of linear momentum is applicable. At the non-uniform flow, which may be either steady or unsteady, the process becomes more complicated, and returns to the basic control-volume approach to develop the momentum equations.

4.5 Derivation of Basic Momentum Equation

First, consider Eq. (4.5*b*), which is rewritten here for convenience:

$$\frac{dB_{sys}}{dt} = \frac{d}{dt}\int_{cv} \beta\rho\, d\forall + \int_{cs} \beta\rho\, \mathbf{V} \bullet d\mathbf{A} \qquad (4.5b)$$

[illegible] equal the momentum of the momentum of a given quantity of matter. Then dB/dt will be the rate of change of momentum of the system with respect to time, $d(\text{momentum})/dt$. Momentum, by definition, is the product of mass and velocity. Therefore β, the corresponding intensive property (or momentum per unit mass) is simply the velocity $\mathbf{v}$ referenced to an inertial reference frame. The small $\mathbf{v}$ used here to distinguish it from the $\mathbf{V}$ in $\mathbf{V} \bullet \mathbf{A}$ of Eq. (4.5*a*). By substituting $d(\text{momentum})/dt$ for dB/dt and $\mathbf{v}$ for β in Eq. (4.5*b*) to obtain

$$\frac{d(momentum)}{dt} = \int_{cs} \mathbf{v}\rho\mathbf{V} \bullet d\mathbf{A} + \frac{d}{dt}\int_{cv} \mathbf{v}\rho\, d\forall \qquad (4.6)$$

According to Newton's second law, the summation of all external forces on a system is equal to the rate of change of momentum of that system, $\Sigma\ \mathbf{F} = d(\text{momentum})/dt$. Thus when the appropriate substitution is made in Eq. (4.9), which gives

$$\sum \mathbf{F} = \int_{cs} \mathbf{v}\rho\mathbf{V} \bullet d\mathbf{A} + \frac{d}{dt}\int_{cv} \mathbf{v}\rho\, d\forall \tag{4.7}$$

A simplified form of the momentum equation results when there is uniform velocity in the streams crossing the control surface. It is

$$\sum \mathbf{F} = \sum_{cs} \mathbf{v}\rho\mathbf{V} \bullet \mathbf{A} + \frac{d}{dt}\int_{cv} \mathbf{v}\rho\, d\forall \tag{4.8}$$

For steady flow the second term is equal to zero and the equation becomes

$$\sum \mathbf{F} = \sum_{cs} \mathbf{v}\rho\mathbf{V} \bullet \mathbf{A} \tag{4.9}$$

4.6 Power Calculations

To allow [illegible] thorough [illegible] understanding [illegible] specifying and sizing the hardware required for a successful hydro power installation the following chapter shows the basic laws of physics which have to be obeyed if anyone want to generate any electricity from undershot waterwheels installation.

Hydropower is essentially based upon the fundamental laws of physics state that a "body" may contain energy (amongst other means) by virtue of its velocity (through "space") and/or by its relative height. These are termed Kinetic and Potential Energies respectively. Now the first law of thermodynamics states that "Energy cannot be created or destroyed, but its form may be changed". So knowing this one can already convert the "Kinetic Energy" of fast moving water in a stream, or the "Potential Energy" of a small pond high up a hillside to some other type of energy such as electricity.

The potential energy of a body (water in this case) is proportional to its relative height and its mass, and may be expressed by the following equation:

$$P.E. = \mathrm{m} \times g \times h \text{ Joules (J)} \qquad (4.10)$$

The kinetic energy of a body may be expressed by the following equation:

$$K.E. = \tfrac{1}{2} \times \mathrm{m} \times \mathbf{V}^2 \text{ Joules (J)} \qquad (4.11)$$

So the previous equations can now be written as:

$$P.E. = \forall \times \rho \times g \times h \text{ Joules (J)} \qquad (4.12)$$

$$K.E. = \tfrac{1}{2} \times (\forall \times \rho) \times \mathbf{V}^2 \text{ Joules (J)} \qquad (4.13)$$

[illegible] this is simply the energy in a volume of water, given that one has determined what volume flows in [illegible] case, one second) these equations now bec[illegible]

$$P.E. = (\forall/\mathrm{sec}) \times \rho \times g \times h \text{ Watt (W)} \qquad (4.14)$$

$$K.E. = \tfrac{1}{2} \times ((\forall/\mathrm{sec}) \times \rho) \times \mathbf{V}^2 \text{ Watt (W)} \qquad (4.15)$$

The above equations actually gives power in Watts, which are much familiar with, and knowing that the volume of water passing through the blades of the waterwheel, of cross sectional area **A** m^2, per second, is dependent upon the velocity of water, **V** m/s. The mass flow rate $\dot{m}$ kg/s is dependent upon the velocity of water **V** m/s, the cross sectional area **A** m^2, and the density of water ρ kg/m^3.

The two energy equations become:

$$P.E. = \dot{m} \times g \times h \text{ Watts} \tag{4.16}$$

$$K.E. = \tfrac{1}{2}\dot{m} \times \mathbf{V}^2 \text{ Watts} \tag{4.17}$$

From these two equations one can exactly know how much energy is in the water at a point in time and space, and this indicate how much energy is available from the water, but in reality not all of this is available for conversion, e.g. in a turbine water needs some velocity on exit otherwise it would not get out of the turbine. Also for a turbine fed from a pipeline such as a pelton wheel, there will be losses in the pipeline giving a lower pressure (than that provided by static head alone) at nozzle the turbine. So even on a very well deigned installation using a "high [illegible] 50% of the initial energy by the time that generated volts and amps. In some installations, such as flow of river-undershot water wheels, overall [illegible] % or 10% [illegible] upon the technology being used.

Determining Mass Flow Rate

To weigh water in the gravimetric tank the principle used is the difference principle. The tank is suspended on a balance arm, which is offset to be heavy on the side of the weight hanger, so that when water is collected steadily in the tank there comes a point at which the arm rises to the point of balance. At this instant a time measurement is started. A weight is now added to the weight hanger so that the balance arm is again pulled down. As water continues to be collected, a second balance point is reached, and at that instant the timing stops. The weight of water collected over the timed interval clearly corresponds to the weight added at the weight hanger.

Figure 4.4 illustrates the procedure and shows how the motion of the balance arm is controlled by the balance arm stop. When standing by as in Fig. 4.4*a* the stop is set to position 1 in which it supports the balance arm in its uppermost position, and water falling into the gravimetric tank passes through the valve in its base to the sump tank below. To obtain a measurement of mass flow rate, the stop is turned briefly aside, allowing the arm to fall below the horizontal. The stop is then returned to position 2 as shown in Fig. 4.4*b*; in this position it serves to restrain the balance arm from rising above the horizontal. The valve in the base of the gravimetric tank closes automatically as the balance arm falls, so that water falling into the tank now starts to collect. When the balance point is reached, as indicated by the arm rising to the horizontal, the timing is started. A weight is now added to the hanger so that the balance arm again drops. The continuing accumulation of water in the tank ultimately causes the balance arm to rise for a second time as shown in Fig. 4.4*c*, and at this instant the timing is ended. *Sin*[illegible] *weight added at the weigh*[illegible] *weight of water collected in the gravimetric tank over the timed interval.* The balance arm stop is now turned briefly aside, allowing the arm to rise to its uppermost position, and is then returned as shown in Fig. 4.4*d* to its original position 1, locking the balance arm in the uppermost position for stand-by.

$$\text{The weight added to the weight hanger} = 10 \text{ kilogram.}$$

$$\text{The water mass (m)} \times 1 = 10 \times 3$$

$$\text{m} = 30 \text{ kilogram.}$$

$$\text{The total mass flow rate } (\dot{m}) = \frac{\text{m}}{\text{t}} \qquad (4.18)$$

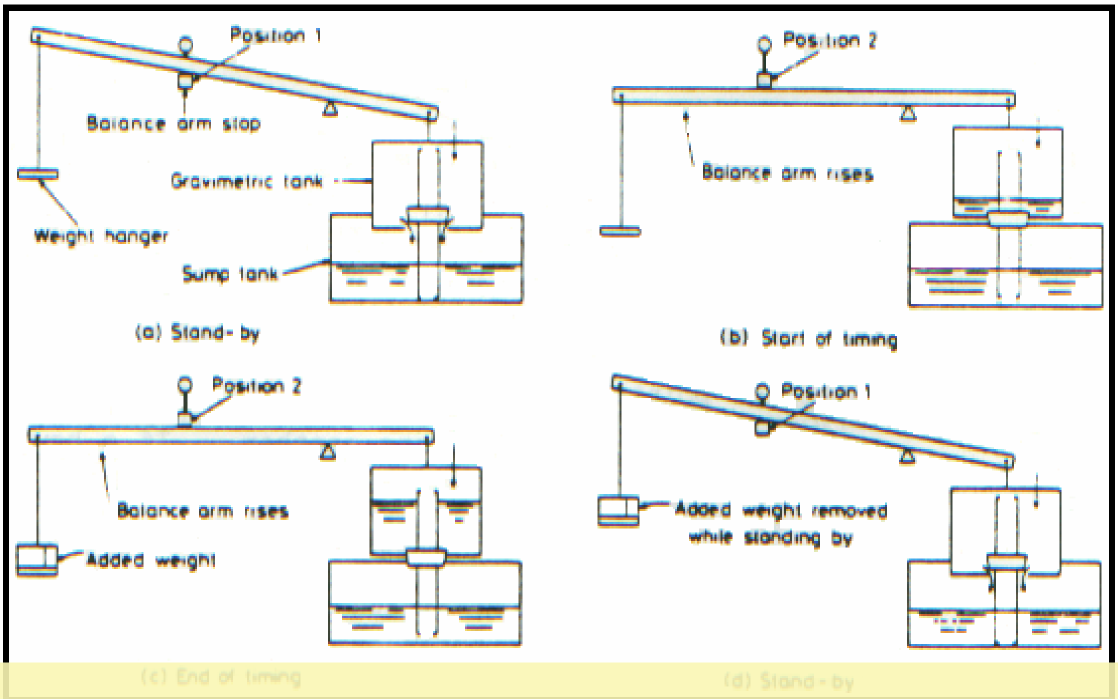


Figure 4.4: Steps in determining the mass flow rate. [24]

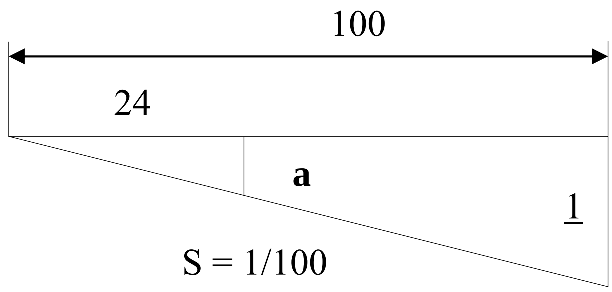
Determining Head

From flow in open channels one c [illegible] this channel is non-uniform steady flow. [illegible] is usually measured in feet, meters, or unit of pressure. Head also is a function of the characteristics of the channel or pipe through which it flows. From Fig. 4.5 the head (h) is:

$$h = \mathbf{y} - h_f + \mathbf{a} + \frac{V^2}{2g} \tag{4.19}$$

Neglecting the term $V^2/2g$ because it is too small, the sloping height **a** can be found from the triangles similarity as shown:

$$\frac{\mathbf{a}}{24} = \frac{1}{100} \Rightarrow \mathbf{a} = \frac{24}{100} = 0.24 \text{ cm}$$



Now Eq. (4.19) can be written as:

$$h = \mathbf{y} - h_f + 0.24 \qquad (4.19a)$$

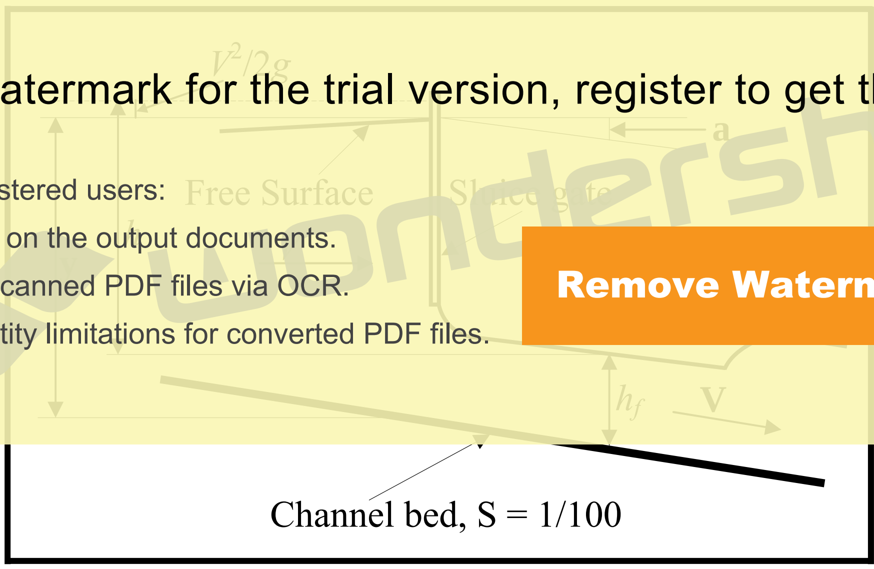


Figure 4.5: Non-uniform steady flow with sluice gate.

4.7 Series of Vanes Mounted On a Wheel

The foregoing cases of dynamic action of jet amply demonstrate the application of momentum principle. In the preceding flow-situation, the distance between the jet and the vane goes on increasing progressively, and, therefore, does not represent a practical situation. The force exerted by the impact of jet can be fruitfully utilized if the series of vanes are mounted on the periphery of a wheel as shown in Fig. 4.6.

Consider a wheel on the periphery of which a certain number of evenly spaced flat vanes are mounted. A fluid-jet of cross sectional area **A** moving with a velocity **V** strikes the bottom most plate as shown. The force exerted by the jet causes the rotation of the wheel. The flat vanes thus occupy the bottom-most position according to their turn. The number [illegible] without doing work on the plate. Thus the entire fluid mass issuing from the nozzle is considered to strike the plates.

[illegible] due to the [illegible] wheel starts moving and the second plate mounted on the wheel appears before the jet, which again exerts the force on the second plate. Thus each plate appears successively before the jet and the jet exerts force on each plate.

In this case the mass of water coming out from the jet per second is always in contact with the plates are considered. Hence mass of water per second striking the series of plates $= \rho \mathbf{AV} = \dot{m}$.

Also the jet strikes the plate with a velocity $= \mathbf{V} - \mathbf{u}$. Where $\mathbf{u}$ is the tangential velocity of the waterwheel.

After striking the jet moves tangential to the plate and hence the velocity component in the direction of motion of plate is equal to zero.

∴ The force exerted by the jet in the direction of motion of plate

$$= (\rho \mathbf{AV})[(\mathbf{V} - \mathbf{u}) - 0] = \rho \mathbf{AV}[\mathbf{V} - \mathbf{u}].$$

This is the same expression of Eq. (4.9).

Work done by the jet on the series of plates per second

= Force × Distance per second in the direction of force

$$= \rho \mathbf{A}\mathbf{V}(\mathbf{V} - \mathbf{u}) \cdot \mathbf{u} = \dot{m}(\mathbf{V} - \mathbf{u}) \cdot \mathbf{u}$$

The same equations can be used when water is hitting the blade instead of jet Fig. 4.7, but the difference is that there is waste in the water that strikes the blade, so the equations can be written as:

Water mass striking the plate per second $= \rho \mathbf{A}_a \mathbf{V} = \dot{m}_a$.

Velocity with which the water strikes the plates moving with a tangential velocity $\mathbf{u} = \mathbf{V} - \mathbf{u}$.

Force exerted on the plates by the water $= (\rho \mathbf{A}_a \mathbf{V})(\mathbf{V} - \mathbf{u})$

Work done by the water on the series of plates per second

= Force × Distance per second in

$$= \rho \mathbf{A}_a \mathbf{V}(\mathbf{V} - \mathbf{u}) \cdot \mathbf{u} = \dot{m}_a (\mathbf{V} - \mathbf{u}$$

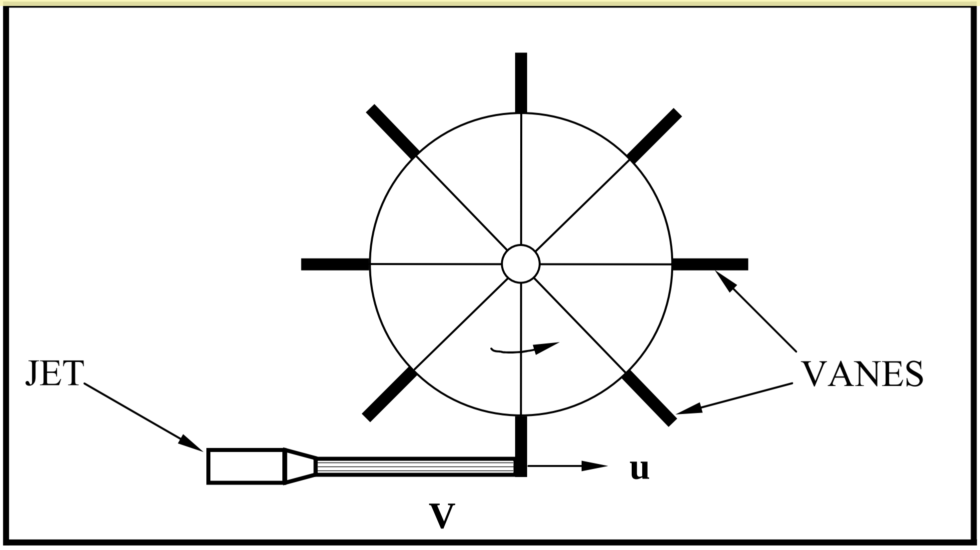


Figure 4.6: Jet striking a series of vanes. [25]

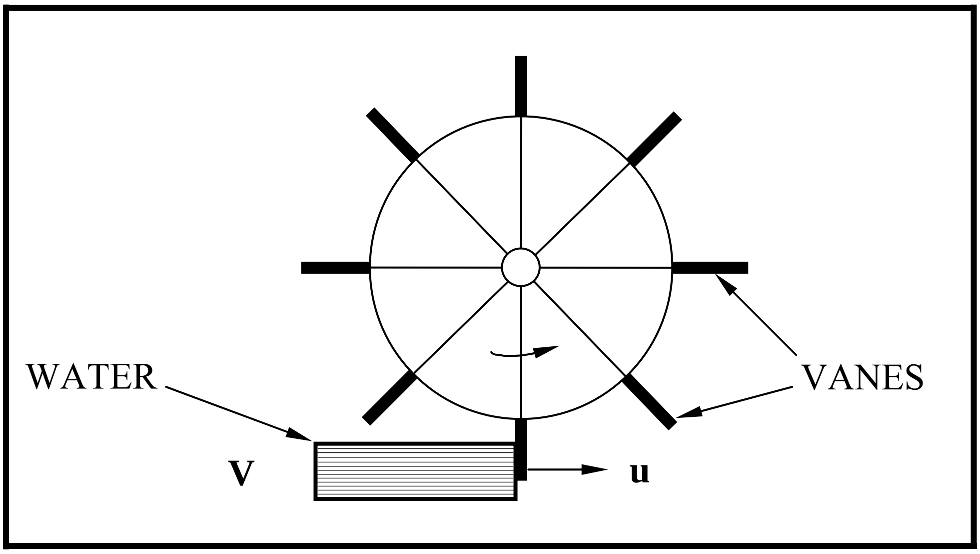


Figure 4.7: Water striking a series of vanes.

4.8 Losses and Efficiencies

All hydraulic machines convert energy from one form into another and it is a well-known fact that, in any energy conversion process, losses occur. Thus, hydraulic machines suffer from losses of energy. How small these losses are or how good a machi[illegible] indicated by its efficiency. However, hy[illegible] consisting of a number of parts through which the fluid moves and, thus, it is convenient for analytical and design purposes to consider component losses as well as their sum total and to express each component loss in the efficiency form.

Now consider these component losses one by one. First, the actual energy transfer in a rotodynamic machine occurs in its impeller (wheel). Here the fluid passes through the blade passages and either receives energy from the moving blades or imparts energy to them. In any case, there are two major sources of energy loss within the wheel. The inevitable contact between the fluid moving over solid surfaces gives rise to boundary layer development and, hence, to frictional losses, whereas the need for the fluid to change direction often results in separation and, hence, leads to separation (or shock) losses.

In this case the channel surrounds the wheel so that the fluid passes through parts of the channel before it strikes the wheel and after leaving it. Thus, losses due to difference in the heads (and possibly due to separation) occur in the channel as well. Thus if the mass flow rate through the channel is $\dot{m}$ and the loss of head in the channel is h_c, then the power loss in the channel is

$$P_c = \dot{m} g h_c \tag{4.21}$$

If the mass flow rate leaking past the wheel is denote by $\dot{m}_1$ and if h_f is the total head across the wheel, then the power loss due to the [illegible]

$$P_l = \dot{m}_l g h_f \tag{4.22}$$

If h_w is the head loss in the whee[illegible] through the wheel, then the wheel power loss is

$$P_w = \dot{m}_a g h_w \tag{4.23}$$

There are mechanical losses of energy such as in the bearings and sealing glands, which must be accounted for. It is normal practice in hydraulic machines to include within this category losses due to disc friction, some-times referred to as "windage" losses. This is the power required to spin the wheel at the required velocity without any work being done by the wheel or on the wheel by the fluid. This would be possible only if the wheel did not have any blades. Thus, windage loss accounts for the friction between the outer surfaces of the wheel rotating in the fluid surrounding it within the channel.

There is transitional loss occurs between the gears which connected between the waterwheel shaft and the generator shaft. Finally there is an electric loss within the generator.

It is now possible to consider the energy balance for the whole machine, but here to distinguish between pumps and turbines because what represents the output of one is the input of the other and vice versa.

In this case a waterwheel work as a turbine, so the energy balance equation is:

$$\underbrace{\dot{m}gh}_{\text{Fluid power input}} = \underbrace{g\left(\underbrace{\dot{m}h_c}_{\text{Channel loss}} + \underbrace{\dot{m}_1 h_f}_{\text{Leakage loss}} + \underbrace{\dot{m}_a h_w}_{\text{Wheel loss}}\right)}_{\text{Hydraulic losses}} + \underbrace{P_m}_{\text{Mechanical loss}} + \underbrace{P_{sh}}_{\text{Shaft power output}} + \underbrace{P_t}_{\text{Transitional loss}} + \underbrace{P_{g.s.}}_{\text{Generator shaft power input}} + \underbrace{P_e}_{\text{Electrical loss}} + \underbrace{P_g}_{\text{Generator power output}} \quad \text{.......................... (4.24)}$$

Having discussed all the component losses in a hydroelectric machine and the complete energy balance, it is now possible to define efficiencies.

The most important is the *overall eff*[illegible]

$$\eta = \frac{\text{Power output of the machine}}{\text{Power input to the machine}}$$

Hence, for turbine,

$$\eta = \frac{\text{Power output from the generator}}{\text{Fliud power input}} = P_g / \dot{m}gh \qquad (4.25)$$

The *channel efficiency* (η_c) accounted for the power loss in the channel. For a turbine,

$$\eta_c = \frac{\text{Fluid power supplied to wheel} + \text{Leakage loss}}{\text{Fluid power received by channel}}$$

$$= \frac{\dot{m}_a g h_f + \dot{m}_1 g h_f}{\dot{m}gh} = \frac{h_f\left(\dot{m}_a + \dot{m}_1\right)}{h\dot{m}} = \frac{h_f}{h} \qquad (4.26)$$

The *volumetric efficiency* (η_v) accounted the mass flow rate loss. For turbine,

$$\eta_v = \frac{\text{Mass flow rate through wheel}}{\text{Mass flow through machine}}$$

$$= (\dot{m} - \dot{m}_1)/\dot{m} = \dot{m}_a/\dot{m} \qquad (4.27)$$

The *wheel efficiency* (η_w) takes care of the losses in the wheel and, therefore, for turbine,

$$\eta_w = \frac{\text{Mechanical power received by shaft}}{\text{Fluid power supplied to wheel}}$$

$$= \frac{(P_{sh} - P_m)}{\dot{m}_a g h_f} = \frac{\dot{m}_a g h_a}{\dot{m}_a g h_f} = \frac{h_a}{h_f} \qquad (4.28)$$

If the mechanical loss is P_m, then the power input to the wheel is $P_{sh} + P_m$ and the *mechanical efficiency* (η_m) may be defined as:

$$\eta_m = P_{sh}/(P_{sh} + P_m) = P_{sh}/P_a$$

Let the transitional loss is P_t, the power delivered to the generator shaft is $P_{g.s.} + P_t$ and the *transitional efficiency* (η_t) is defined as:

$$\eta_t = P_{g.s.}/(P_{g.s.} + P_t) = \frac{P_{g.s.}}{P_{sh}} \quad \text{For a turbine.} \qquad (4.30)$$

The *generator efficiency* (*electrical efficiency*) (η_e) takes care of the losses in the generator and, therefore, for turbine,

$$\eta_e = \frac{P_g}{P_{g.s.}} \qquad (4.31)$$

It is now possible to show that the overall efficiency (η) is equal to the product of all the component efficiencies,

$$\eta = \eta_c \eta_v \eta_w \eta_m \eta_t \eta_e \tag{4.32}$$

By substituting into the above equation the appropriate expression as follows:

$$\eta = \frac{h_f}{h} \times \frac{\dot{m}_a}{\dot{m}} \times \frac{h_a}{h_f} \times \frac{P_{sh}}{P_a} \times \frac{P_{g.s.}}{P_{sh}} \times \frac{P_g}{P_{g.s.}}$$

This simplifies to

$$\eta = \frac{\dot{m}_a \times h_a \times P_g}{\dot{m} \times h \times P_a}$$

But, since $P_a = \dot{m}_a g h_a$, obtaining

$$\eta = P_g / \dot{m} g h$$

This is the expression (4.28) for the overall efficiency.

There is an expression for maximum efficiency of the waterwheel which is: [illegible]

[illegible] energy of the water per second = $\frac{1}{2}\dot{m}_a$ [illegible] $\frac{1}{2}(\rho A_a V)$ [illegible] $\frac{1}{2}\rho A_a$ [illegible]

Recall Eq. (4.20):

$$\text{Work done on the series of vanes per second} = \rho \mathbf{A}_a \mathbf{V}(\mathbf{V} - \mathbf{u}) \cdot \mathbf{u}$$

$$\therefore \text{Efficiency}\,\eta = \frac{\text{Work done per second}}{\text{Kinetic energy per second}}$$

$$= \frac{\rho \mathbf{A}_a \mathbf{V}(\mathbf{V} - \mathbf{u}) \cdot \mathbf{u}}{\frac{1}{2}\rho \mathbf{A}_a \mathbf{V}^3} = \frac{2\mathbf{u}(\mathbf{V} - \mathbf{u})}{\mathbf{V}^2} \tag{4.33}$$

Equation (4.36) gives the value of the efficiency of the wheel for a given water velocity **V**, the efficiency will be maximum when,

$$\frac{d\eta}{d\mathbf{u}} = 0$$

$$\frac{d}{d\mathbf{u}}\left[\frac{2\mathbf{u}(\mathbf{V}-\mathbf{u})}{\mathbf{V}^2}\right]=0$$

$$\frac{d}{d\mathbf{u}}\left[\frac{2\mathbf{u}\mathbf{V}-2\mathbf{u}^2}{\mathbf{V}^2}\right]=0$$

$$\frac{2\mathbf{V}-4\mathbf{u}}{\mathbf{V}^2}=0 \Rightarrow 2\mathbf{V}-4\mathbf{u}=0$$

$$\mathbf{V}=\frac{4\mathbf{u}}{2}=2\mathbf{u} \quad \text{or} \quad \mathbf{u}=\frac{\mathbf{V}}{2}$$

Substituting the value of $\mathbf{V}$ = 2$\mathbf{u}$ in Eq. (4.33) getting that the maximum efficiency is:

$$\eta_{\max}=\frac{2\mathbf{u}(2\mathbf{u}-\mathbf{u})}{(2\mathbf{u})^2}=\frac{2\mathbf{u}\times\mathbf{u}}{2\mathbf{u}\times 2\mathbf{u}}=\frac{2\mathbf{u}^2}{4\mathbf{u}^2}=\frac{1}{2} \quad \text{or} \quad 50\%$$

4.9 Similarity Laws

Since for all machines belonging to one family and operating under dynamically similar conditions the dime[illegible] coefficients [illegible] th[illegible] same at corresponding points of their cha[illegible] similarity laws governing the relationships between such corresponding points may be stated as follows:

$$\text{since}\, K_Q = Q/N\mathbf{D}^3 = \text{constant}, \qquad Q \propto N\mathbf{D}^3 \qquad (4.34)$$

$$\text{since}\, K_h = gh/N^2\mathbf{D}^2 = \text{constant}, \qquad gh \propto N^2\mathbf{D}^2 \qquad (4.35)$$

$$\text{since}\, K_{Pg} = P_g/\rho N^3\mathbf{D}^5 = \text{constant}, \quad P_g \propto \rho N^3\mathbf{D}^5 \qquad (4.36)$$

Chapter Five

Results and Discussion

5.1 Experimental Work

The first thing it is important to know is how many blades will give the maximum revolutions per minute (N) to the shaft at appropriate radius, so the design of the wheel allowing to change the number of blades (n) and to change the radius of the wheel (r) at each number of blades.

The following steps describe the experimental work of this project:

Step1: -

Consider the following constants which will be changed to see their effects on the results, the constants are: -

- Unloaded (no load is connected to the shaft).
- [illegible] 765 kg/s (W[illegible] total mass fl[illegible]
- [illegible] = 2 cm (Water height).
- $\theta = 90^{\circ}$ (Sluice gate angle).

Step2: -

In this step the number of blades has been changed see figures 5.1 to 5.4:

a) Number of blades $n = 9$
b) Number of blades $n = 12$
c) Number of blades $n = 18$
d) Number of blades $n = 36$

For data see Table 5.1 and for graph see Fig. 5.5. So the chosen number of (rpm) was $N = 50\,\text{rpm}$ and the chosen radius was $r = 22\,\text{cm}$ at the constants illustrated in Step1.

Step3: -

In this step the constants in Step1 has been changed one by one, the first constant changed was the cross sectional area of the water (**A**). The cross sectional area of the water (**A**) is equal to the water height (h_f) multiplied by the breadth of the channel (**b**) (*i.e.* **A**=h_f ×**b**), but (**b**) is constant (*i.e.* **b** = 7.5 cm), so the change in (**A**) depends on (h_f).

The change in water height was from h_f = 1.5 cm (**A**= 11.25 cm^2) to h_f = 2.3 cm (**A**= 17.25 cm^2). So (**A**) that gives maximum (N) was **A**= 11.55cm^2 (h_f = 1.5 cm), but the water became leaking from the channel, so the second choice was **A**= 12.75 cm^2 (h_f = 1.7 cm). For data see Table 5.2.

The second constant changed was the sluice gate angle (θ), but the water become leaking from the channel at any other (θ) accept $\theta = 90°$.

The third constant changed was the total mass flow rate of the water ($\dot{m}$). The total mass flow rate of the water ($\dot{m}$) is depending on the time (t).

The change in time was t = 88 s ($\dot{m}$=0.341kg/s) to t = 17 s ($\dot{m}$=1.765kg/s). So the choice was $\dot{m}$=1.765kg/s (t = 17 s) which gives the maximum (rpm). For data see Table 5.3.

The last constant changed was the unloading (*i.e.* connect load to the shaft of the waterwheel); the load was a DC generator that connected to the waterwheel shaft. The DC generator has a maximum capacity of 300 W and number of revolutions per minute n = 3000 rpm.

The required number of revolutions per minute was n = 100 rpm, and after using chain, belt, and gears the waterwheel could not reach it.

The alternative was an AC generator with a maximum capacity of 6 W and voltage of 12 V. By using gears with a ratio of 80:16, the resulting voltage (***V***) was 1.5 V and the resulting current (I) was 0.12 A.

The power of the generator can be define as the current I multiplied by the voltage ***V*** and the power factor $\cos\phi$, so the power generator P_g is:

$$P_g = \mathrm{I}\boldsymbol{V}\cos\phi$$

Neglecting the effect of the power factor, because the load that connected to the generator is only a bulb. So the generator power is become:

$$P_g = \mathrm{I}\boldsymbol{V} = 0.12 \times 1.5 = 0.18 \text{ W}$$

<u>Note</u>**:** - This value at $\dot{m} = 1.765\,\text{kg/s}$, **A**= 12.75 cm^2, $\theta = 90^\circ$, $r = 22\,\text{cm}$ and $n = 36$ blade.

To find the other values of the generator power at different mass flow rates $\dot{m}$ and cross sectional areas **A**, the generator loss must be calculated from the above value of generator power, so the generator loss (electrical loss) is equal:

$$P_e = P_{g.s.} - P_g$$

This value of the electrical loss is very important to calculate the generator power P_g and the total efficiency η of different mass flow rates $\dot{m}$ and cross sectional areas **A**.

Using similarity laws to predict the performance of the waterwheel after assuming some waterwheel diameter at different heads and the results are illustrated in Tables 5.6 to 5.8.

5.2 The Effect of Increasing Blades

Fig. 5.5 shows that the higher number of blades at constant radius of wheel gives higher value of velocity, which has more benefit power to turn the wheel (*i.e.* the energy of the water converted to the blades without west).

The equations of the exponential fitting for Fig. 5.5 are:

$$N_9 = 208.45e^{-0.0746r}$$

$$N_{12} = 152.38e^{-0.0584r}$$

$$N_{18} = 134.24e^{-0.0502r}$$

$$N_{36} = 140.02e^{-0.047r}$$

5.3 The Effect of Increasing the Radius

The effect of increasing the radius of the wheel (r) with wheel velocity is shown in Fig. 5.5 for different number of blades (n) which show that the wheel velocity will decrea[illegible] constant rate of flow and constant numbe[illegible] power is constant and it is equal to the velocity radius multiplication.

Extrapolations of the radius are illustrated in tables 5.6 to 5.8 which show that increasing the diameter of the waterwheel at fixed water head the output generated power increased because the number of revolutions per minute was decreased and the water mass flow rate was increased.

5.4 The Effect of Mass Flow Rate

The mass flow rate ($\dot{m}$) effected on the parameters of the system which shown in Fig. 5.6 to 5.8.

Fig. 5.6 shows the variations of the system efficiencies with mass flow rate. The volumetric efficiency (η_v) and the wheel efficiency (η_w) are fixed at different mass flow rates because it depends on the flow geometry only. The transitional efficiency (η_t) is fixed because of the losses rate is assumed to be fixed. The channel efficiency (η_c) decreased because the total head (h) is increased due to increasing in mass flow rate ($\dot{m}$) with keeping the water head (h_f) fixed. The mechanical efficiency (η_m) is increase due to increasing in flow velocity (**V**). The electrical efficiency (η_e) is increased alternatively with small rate of the mass flow rate because the velocity (**V**) is increased. The overall efficiency (η) is the multiplication of all efficiencies and has the alternative feature from the mechanical efficiency (η_m) and the channel efficiency (η_c).

The increase in the velocity of the wheel when increasing the mass flow rate is due to the increase in water velocity with keeping the cross sectional area constant which is shown in Fig. 5.7.

The performance curves (Generator power P, Overall efficiency [illegible] and Total head h verses the total mass flow rate $\dot{m}$) was plotted in Fig. 5.8 the generator power increased with the total mass flow rate due to increasing in flow momentum. The total [illegible] rate, which is a [illegible] pheno[illegible]

5.5 The Effect of the Cross Sectional Area

The effects of channel flow cross sectional area on the parameters of the system are shown in Fig. 5.9 to 5.11.

Fig. 5.9 shows the variations of the system efficiencies with channel cross sectional area. The channel efficiency (η_c) increased because the total head (h) is decreased due to increasing in water height (h_f) with keeping total mass flow rate constant. The volumetric efficiency (η_v) increased because of the actual mass flow rate ($\dot{m}_a$) is increased and the increasing in the volumetric efficiency is small because the loss mass flow rate is increased too. The wheel efficiency (η_w) increased due to the increasing in the actual head (h_a) with the increasing in the water head (h)

because the difference between them is constant. The mechanical efficiency (η_m) is increased due to decreasing in flow velocity (**V**). The transitional efficiency (η_t) is fixed (The same resin of the above section). The electrical efficiency (η_e) is decreased because the velocity (**V**) is decreased. The overall efficiency (η) is the multiplication of all efficiencies and has the alternative feature from the mechanical efficiency (η_m) and the channel efficiency (η_c).

The decrease in the velocity of the wheel when increasing the channel cross sectional area is due to the decrease in water velocity with keeping the water mass flow rate fixed which is shown in Fig. 5.10.

The curves (Generator power P_g, Overall efficiency η, and Total head h verses the channel cross sectional area **A**) were plotted in Fig. 5.11 the generator power decreased with the channel cross sectional area due to decreasing in flow momentum. The total head decreased with the channel cross sectional area, which is also a fare clear phenomenon.

r (cm)	N (rpm) for			
	n = 9 blades	n = 12 blade	n = 18 blade	***n = 36 blade***
22	40	42	45	***50***
24	35	37	40	45
26	30	34	36	41
28	26	30	33	38
30	22	26	30	34

Table 5.1: Number of revolutions per minute at different number of blades and radiuses.

h_f (cm)	**A**=h_f × **b** (cm^2)	h (cm)	N (rpm)
1.5	11.25	16.34	66
1.7	***12.75***	***15.54***	***57***
1.8	13.50	08.44	56
2.0	15.00	03.24	50
2.5	17.25	02.5[illegible]	41

Table 5.2: Number of revolutions per minute at different [illegible]ional areas.

t (sec)	m = w/t (kg/s)	[illegible]	[illegible]
88	0.341	01.70	04
67	0.448	03.54	10
58	0.517	04.54	13
54	0.556	05.54	15
49	0.612	06.54	17
37	0.811	09.54	25
29	1.035	11.54	33
25	1.200	12.54	39
21	1.429	13.54	47
19	1.579	14.54	52
18	1.667	15.04	54
17	***1.765***	***15.54***	***57***

Table 5.3: Number of revolutions per minute at different mass flow rate.

$\dot{m}$ (kg/s)	N (rpm)	h (m)	η_c	η_v	η_w	η_m	η_t	η_e	η	P_g (W)
0.341	04	0.0170	1.00000	[illegible]	0.8823[illegible]	0.10827	0.972	0.80628	0.05457	0.00310
0.448	10	0.0354	0.48023	0.72970	0.8823[illegible]	0.19428	0.972	0.89204	0.05209	0.00810
0.517	13	0.0454	0.37445	[illegible]	0.8823[illegible]	0.22945	0.972	0.90859	0.04884	0.01125
0.556	15	0.0554	0.30686	[illegible]	0.8823[illegible]	0.23184	0.972	0.90953	0.04048	0.01223
0.612	17	0.0654	0.25994	0.72941	0.8823[illegible]	0.26146	0.972	0.91978	0.03911	0.01536
0.811	25	0.0954	0.17820	0.72945	0.8823[illegible]	0.30123	0.972	0.93037	0.03124	0.02371
1.038	33	0.1154	0.14731	0.72933	0.8823[illegible]	0.38752	0.972	0.94588	0.03378	0.03970
1.200	39	0.1254	0.13557	[illegible]	0.8823[illegible]	0.43134	0.972	0.95137	0.03481	0.05139
1.429	47	0.1354	0.12555	[illegible]	0.8823[illegible]	0.53387	0.972	0.96071	0.03752	0.07122
1.579	52	0.1454	0.11692	[illegible]	0.8823[illegible]	0.63576	0.972	0.96701	0.04497	0.10100
1.667	54	0.1504	0.11303	[illegible]	[illegible]	0.86840	0.972	0.97585	0.05991	0.14700
1.765	57	0.1554	0.10940	[illegible]	0.8823[illegible]	0.99631	0.972	0.97895	0.06672	0.18000

Table 5.4: The results of computer p[illegible] for fixed cross sectional area (**A**= 12.75 cm^2).

A (cm^2)	N (rpm)	h (m)	η_c	η_v	η_w	η_m	η_t	η_e	η	P_g (W)
11.25	66	0.1634	0.08568	0.70878	0.85714	1.00000	0.972	0.99350	0.07100	0.20087
12.75	57	0.1554	0.10940	0.72918	0.88235	0.99270	0.972	0.98361	0.06680	0.18000
13.50	55	0.0844	0.21327	0.73484	0.88889	0.96900	0.972	0.97061	0.08792	0.12900
15.00	50	0.0324	0.61728	0.74391	0.90000	0.95056	0.972	0.96121	0.17397	0.09760
17.25	41	0.0230	1.00000	0.75467	0.91304	0.96728	0.972	0.94394	0.16898	0.06729

Table 5.5: The results of computer program for fixed water mass flow rate ($\dot{m}$ = 1.765 kg/s).

D (m)	N (rpm) for					
	h =0.1554 m	h =1 m	h= 2 m	h =3 m	h =4 m	h =5 m
0.44	57	145	205	250	289	323
0.6	42	106	150	164	212	237
0.8	31	80	113	138	159	178
1.0	25	64	90	110	127	142
1.2	21	53	75	92	106	109
1.4	18	45	64	79	91	102
1.6	16	40	56	69	80	89
1.8	14	35	50	61	71	79
2.0	13	32	45	55	64	71

Table 5.6: Number of rpm (N) at different extrapolation waterwheel diameter and head.

D (m)	$\dot{m}$ (kg/s) for					
	h =0.1554 m	h =1 m	h= 2 m	h =3 m	h =4 m	h =5 m
0.44	1.765	4.490	6.348	7.741	8.949	10.002
0.6	3.298	8.323	11.778	14.447	16.646	18.609
0.8	5.770	14.889	21.031	25.684	29.592	33.129
1.0	9.088	23.264	32.716	39.986	46.165	51.618
1.2	13.191	33.291	47.110	57.789	66.583	68.467
1.4	17.954	44.886	63.838	78.799	90.769	101.741
1.6	23.823	59.557	83.380	102.736	119.114	132.514
1.8	29.680	74.199	105.998	129.318	150.518	167.478
2.0	37.805	93.058	130.862	159.943	186.115	206.472

Table 5.7: Total mass flow rate ($\dot{m}$) at different extrapolation waterwheel diameter and head.

D (m)	P_g (W) for					
	h =0.1554 m	h =1 m	h= 2 m	h =3 m	h =4 m	h =5 m
0.44	0.180	2.963	8.374	15.187	23.461	32.753
0.6	0.340	5.458	15.467	28.549	43.667	61.008
0.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1.0	0.921	15.450	42.965	78.445	[illegible]	[illegible]
1.2	[illegible]	21.833	[illegible]	[illegible]	[illegible]	189.920
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	108.530	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2.0	4.143	61.799	171.859	313.778	494.395	675.009

Table 5.8: Shows the generated power (P_g) at different extrapolation waterwheel diameter and head.

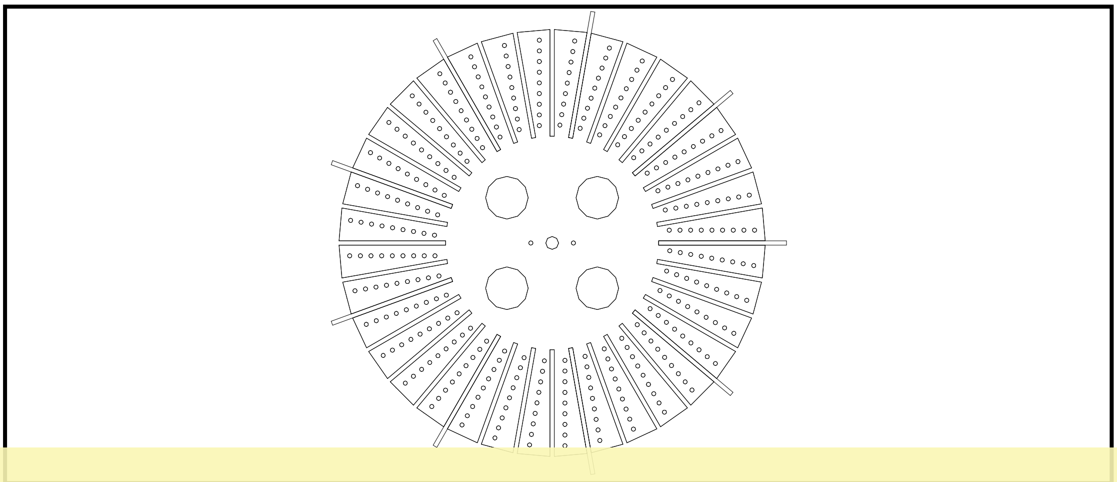


Figure 5.1: Waterwheel sketch for n = 9 blades and r = 22 cm.

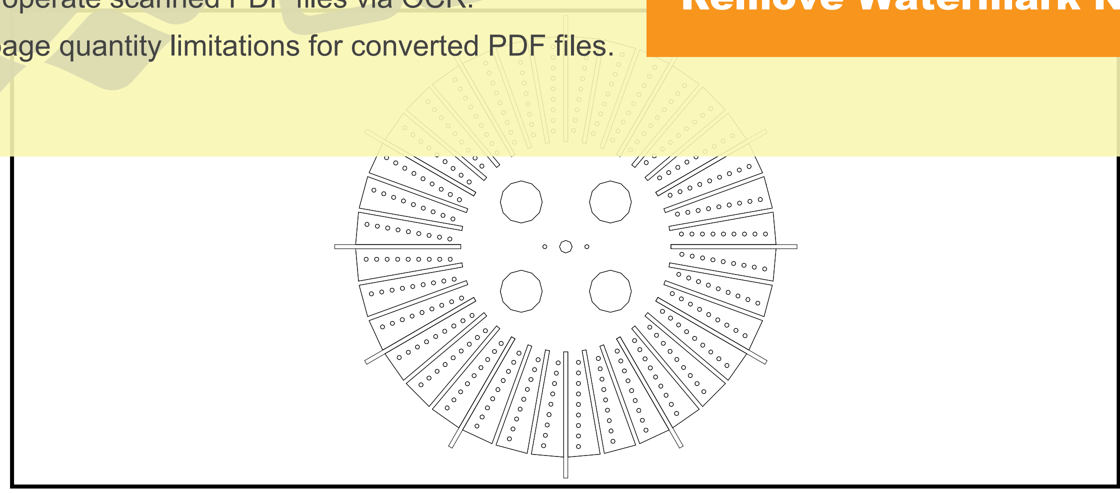


Figure 5.2: Waterwheel sketch for n = 12 blade and r = 22 cm.

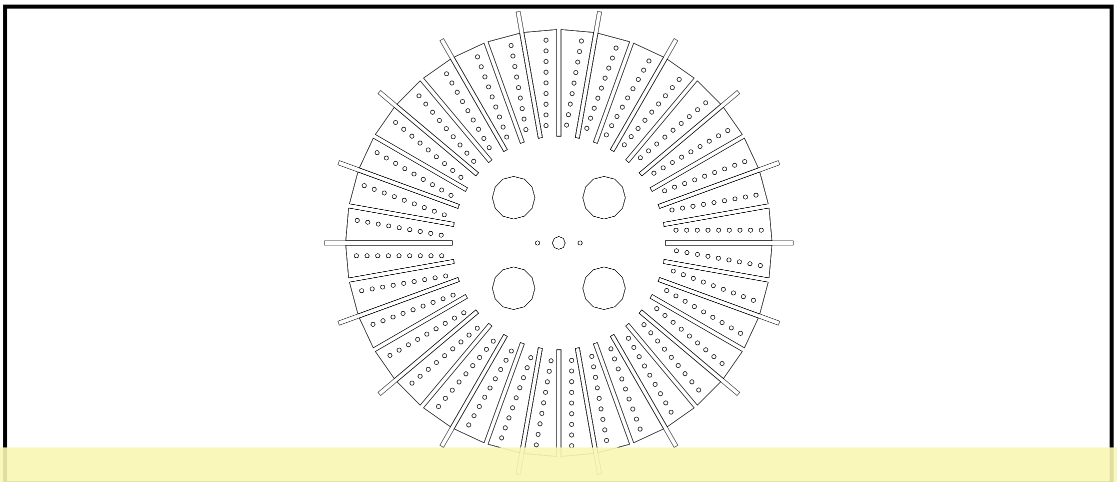


Figure 5.3: Waterwheel sketch for n = 18 blade and r = 22 cm.

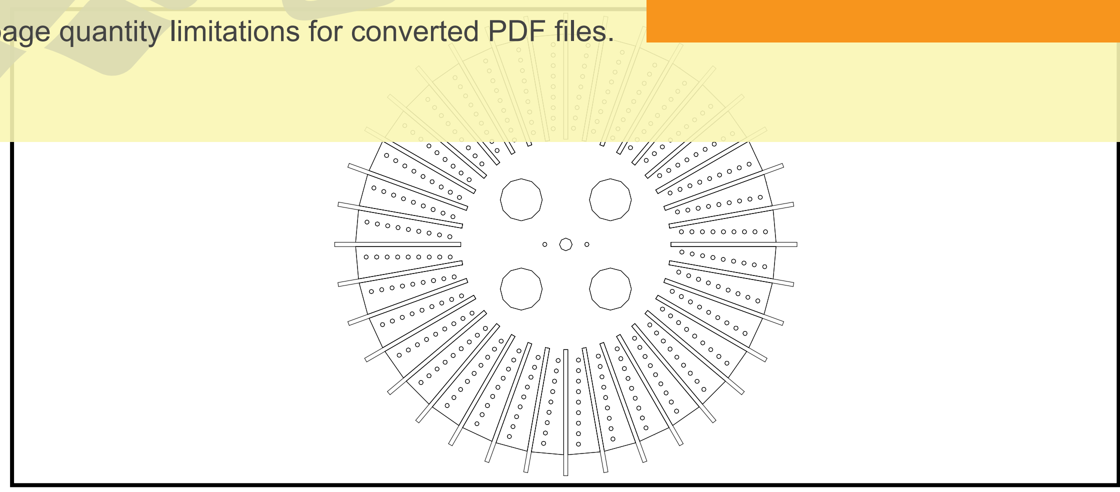


Figure 5.4: Waterwheel sketch for n = 36 blade and r = 22 cm.

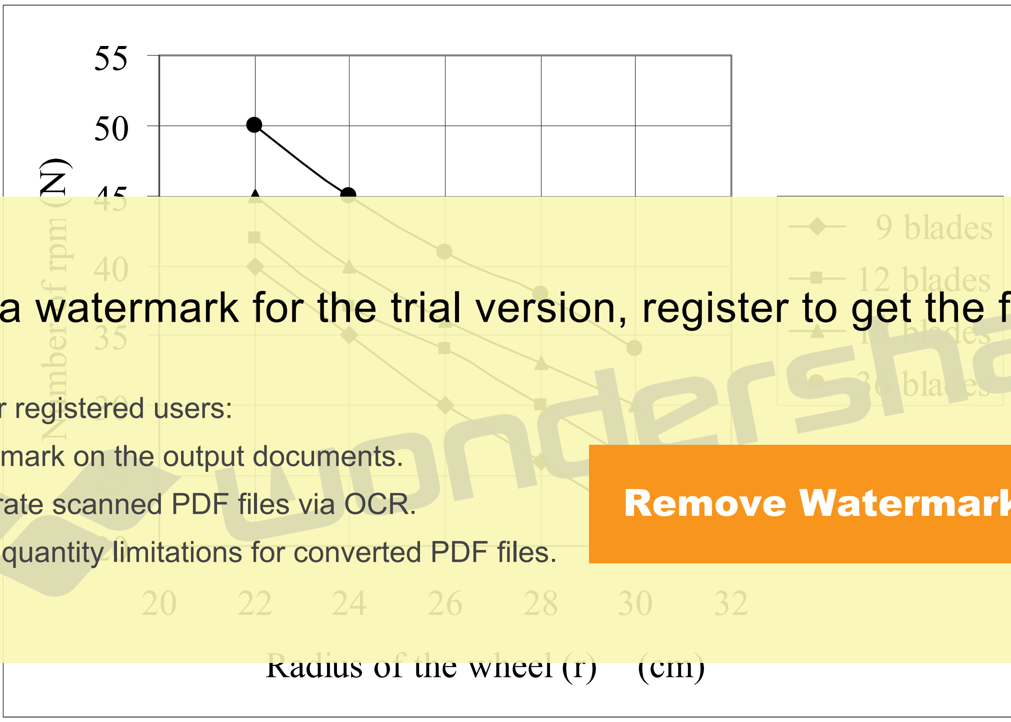


Figure 5.5: The number of revolutions per minute against the radius of the wheel at different number of blades and constant mass flow rate($\dot{m} = 1.765$kg/s).

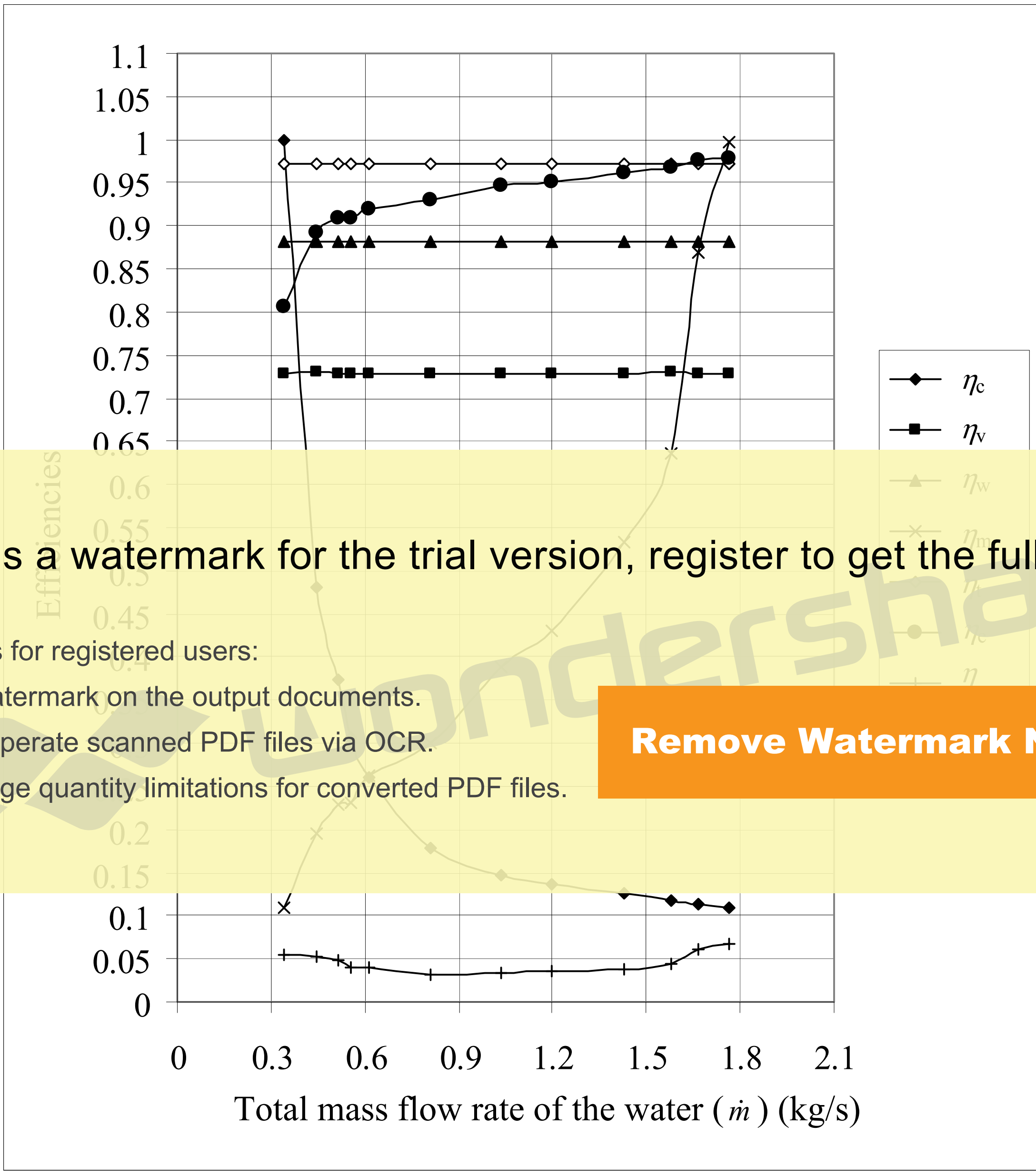


Figure 5.6: The efficiencies against the total mass flow rate at constant cross sectional area **(A**= 12.75 cm^2), number of blades (n = 36 blade), and wheel radius (r = 22 cm).

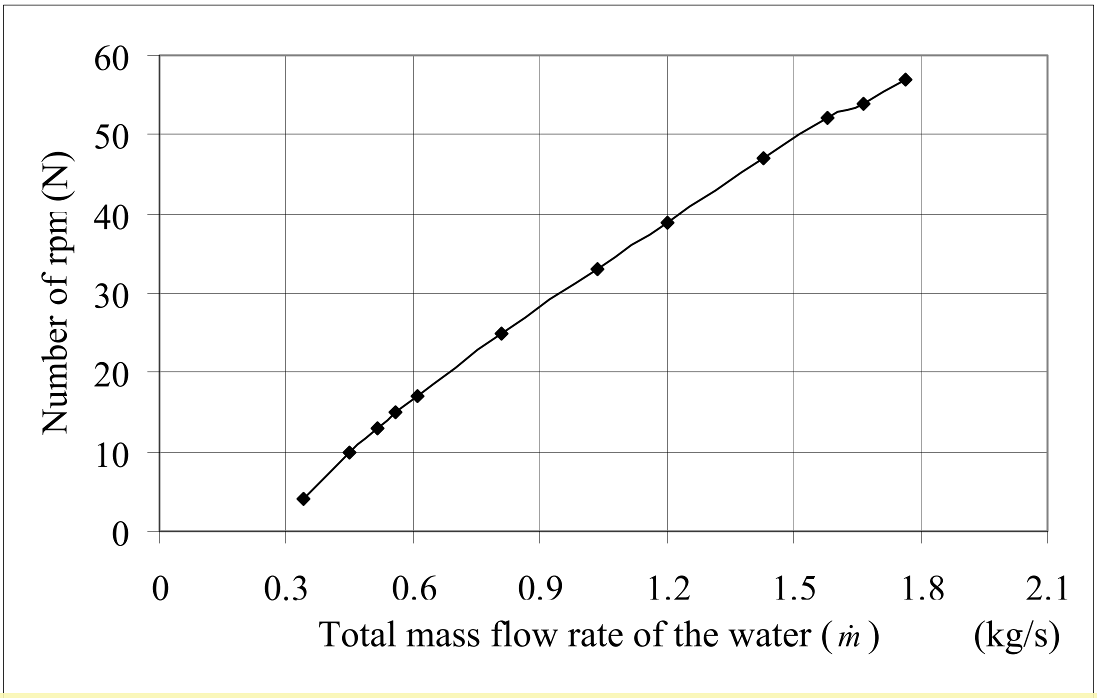


Figure 5.7: The number of rpm against the total mass flow rate at constant cross sectional area (**A**= 12.75 cm^2), number of blades (n = 36 blade), and wheel radius (r = 22cm).

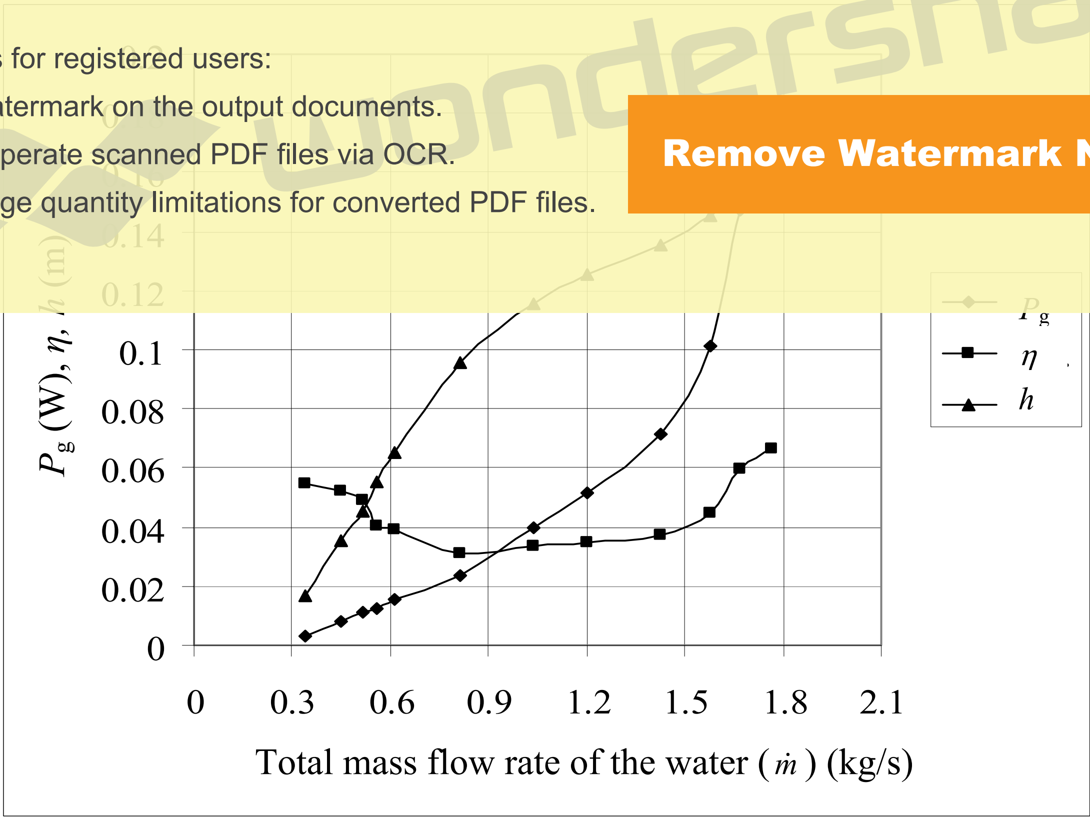


Figure 5.8: The generator power, total efficiency, and total head against the total mass flow rate at constant cross sectional area **(A**= 12.75 cm^2), number of blades (n = 36 blade), and wheel radius (r = 22 cm).

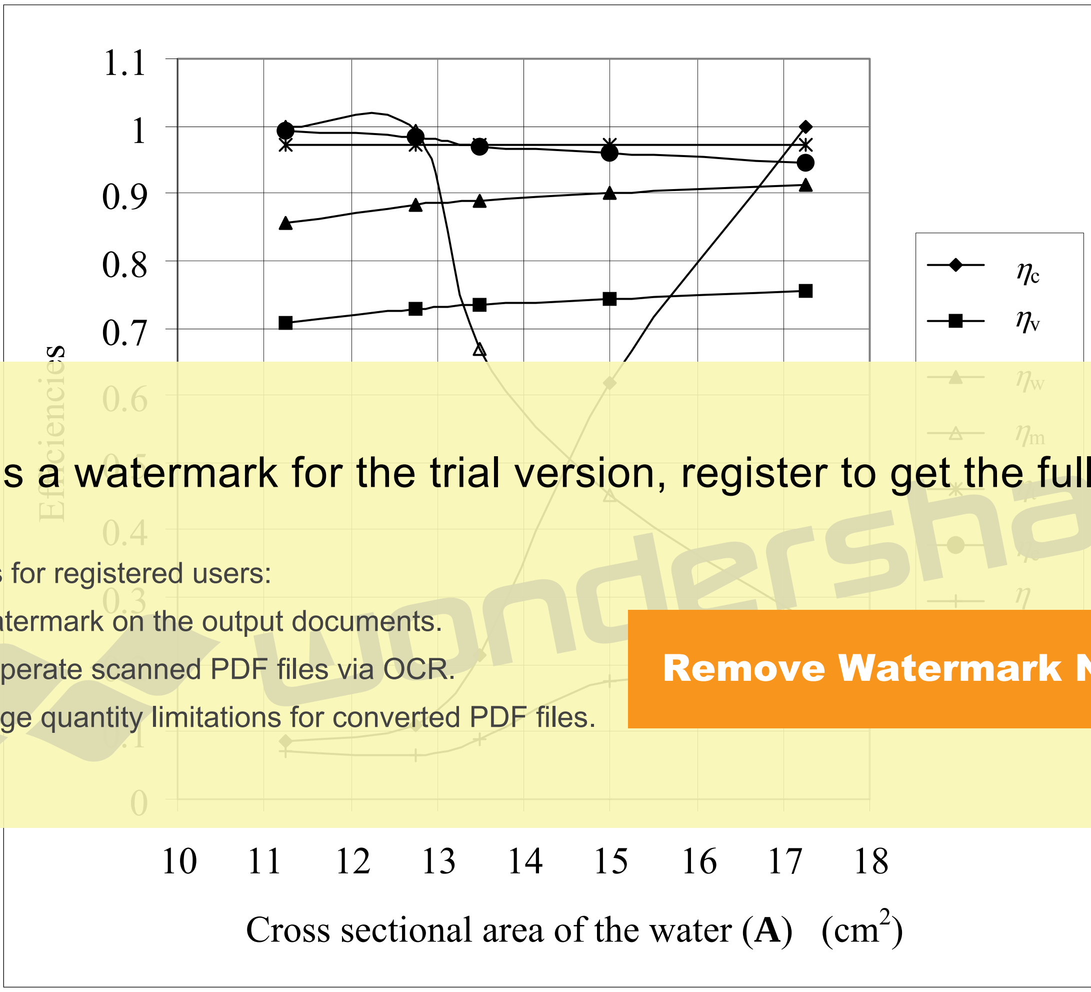
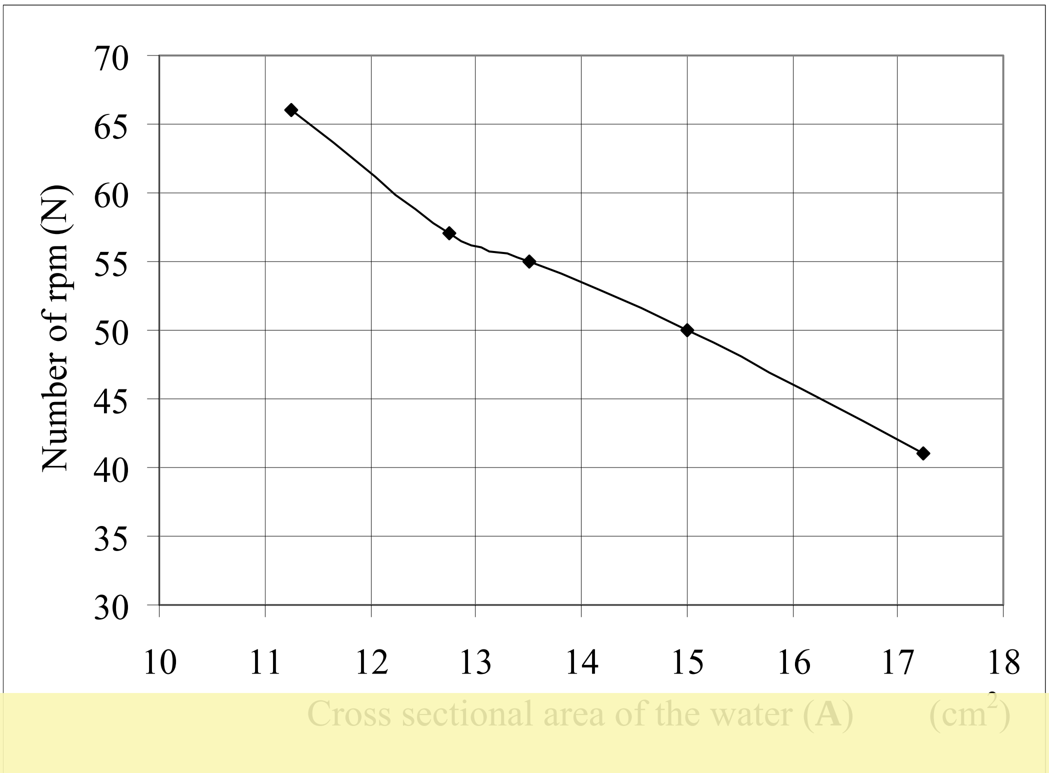


Figure 5.9: The efficiencies against the cross sectional areas at constant total mass flow rate ($\dot{m} = 1.765$kg/s), number of blades (n = 36 blade), and wheel radius (r = 22 cm).



[illegible] constant total mass flow rate ($\dot{m}$=1.765kg/s), number of blades (n = 36 blades), and wheel radius (r = 22 cm).

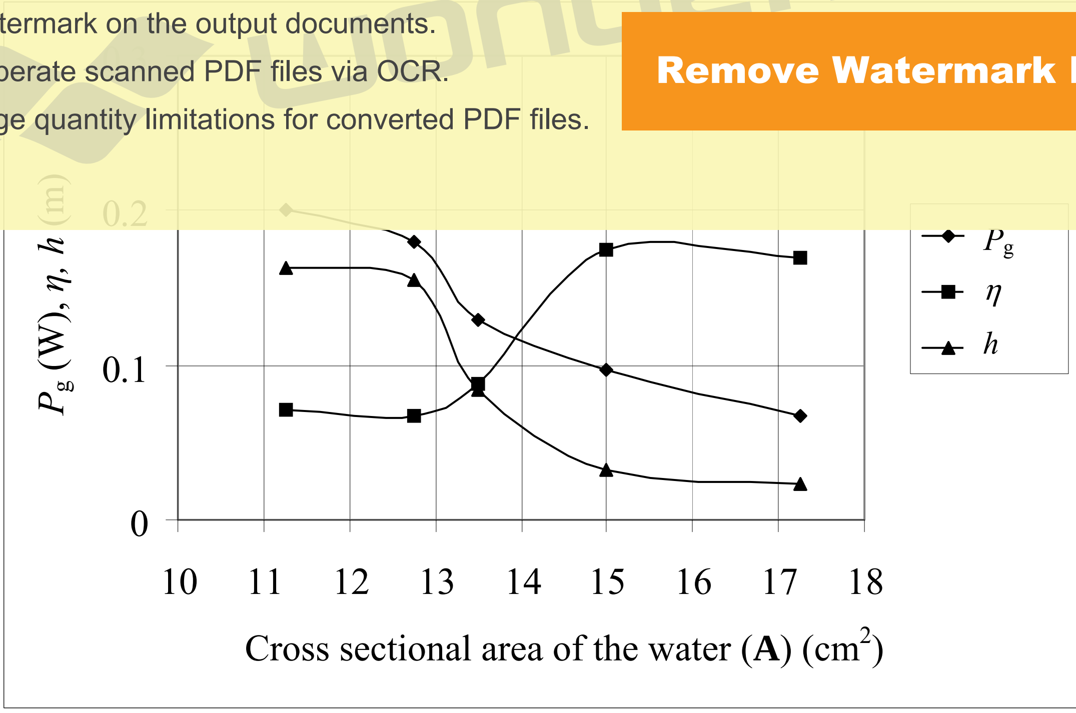


Figure 5.11: The generator power, total efficiency, and total head against the cross sectional areas at constant total mass flow rate ($\dot{m}$=1.765kg/s), number of blades (n = 36 blade), and wheel radius (r = 22 cm).

Chapter Six

Conclusions and Recommendations

6.1 Conclusions

The following has been concluded from the constructed undershot waterwheel generated power system:

1. The increasing of the number of blades (9-36 blades) at fixed radius of waterwheel gives increasing in the number of revolutions per minute (22-50 rpm) which represented by the exponential curve fitting equations.
2. The increasing of the water mass flow rate (0.341-1.765 kg/s) at fixed channel cross sectional area (12.75 cm^2) of the undershot waterwheel generated power system shows increased in the following the generator output power (0.0031-0.18 Watt), the mechanical efficiency (10.8%-99.6% [illegible] [illegible]%-97.9%) and the channel efficiency [illegible] 10.9%). The following were fixed volumetric efficiency 72.9%, wheel efficiency 88.2%, and transitional efficiency 97.2%.
3. The increasing of the channel cross sectional area (11.25-17.25 cm^2) at fixed water mass flow rate (1.765 kg/s) of the undershot waterwheel generated power system shows decreased in the following the generator output power (0.201-0.067 Watt), the mechanical efficiency (100%-26.7%) and the electrical efficiency (99.4%-94.4%) and increased in the following the channel efficiency (8.6%-100%), volumetric efficiency (70.9%-75.5%), and wheel efficiency (85.7%-91.3%). The transitional efficiency was fixed at 97.9%.

4. The maximum generated power obtained from the constructed undershot waterwheel generated power system at n = 36 blade, r = 22 cm, $\dot{m} = 1.765\,\text{kg/s}$ and **A** = 12.75 cm^2 was P_g = 0.18 Watt.
5. The maximum overall efficiency of the constructed undershot waterwheel generated power system at n = 36 blade, $\dot{m} = 1.765\,\text{kg/s}$, r=22 cm and **A** = 12.75 cm^2 was η = 6.69%.
6. The overall efficiency was affected by the channel efficiency and the mechanical efficiency as shown in figures 5.6 and 5.9.
7. The theoretical extrapolation of the waterwheel diameter (0.44-2 m) and the water head (0.1554-5 m) gives that the output generated power was increased (0.18-675 Watt).

6.2 Recommendations for Future Work

The recommendations for future include the following suggestions:

1. Using the extrapolation of the undershot waterwheel generated power system to use it for larger wat[illegible]
2. Using other materials to construct th[illegible] aluminum.
3. Using curved blades instead of flat blades and makes a comparison between the results of this system with that of the curved blades.
4. Using the seasonal valleys and the Tigris, Euphrates branches as the water supply network for tasting the extrapolated waterwheels.

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دراسة تصميمية لمنظومة كهرومائية صغيرة

رسالة

مقدمة الى كلية الهندسة في جامعة النهرين وهي جزء من

متطلبات نيل درجة ماجستيرعلوم في الهندسة الميكانيكية

قبل المهندس

سنان سمير توفيق

(بكالوريوس 2001)

رمضان 1425هـ

تشرين الأول 2004 م

شكر و تقدير

اتقدم بعظيم شكري وفـائـق امتنـاني لاستـاذي الفـاضـل **(أ. د. خليل أنجاد)** المشرف على اعداد هذا البحث لما ابداه من مساعدة كبيرة وجهود مخلصة من اجل انجاز هذا البحث بصورته الحاليـة هـذه الحصيلة وهذا الجهد، ارجو من ا عز وجل ان يمن عليه بدوام الصحة كما اوجه شكري وعرفاني الى رئيـس قسم الهندسـة الميكـانيكيـة **(أ. د. هشام توفيق)** وجميع الاساتذة والمدرسين في القسم.

الى من دلّني على طريق المعرفة واناره لي ... أبي.

[illegible]

الى من شجعني للأستمرار في درب العلم الشائك ... أخوتي.

[illegible] الدكتوراه (علي [illegible]) [illegible] الكبيرة التي قدمها لي .

وختاماً اقدم شكري الجزيل الى كل اصدقائي وزملائـي فـي مرحلـة البحث, **أحمد جميل**, **حسام**, **فادي**, **سيف**, **أسامة** و الى الصديق العزيـز المهندس **زياد يوسف توفيق**.

الخلاصة

دراسة لتصميم و صنع منظومة صغيرة هيدرومائية لتوليد الطاقة الكهربائية باستخدام باستخدام نموذج مصغر لتوربين ناعور الجريان التحتي الذي تم وضعهُ في القناة الهيدروليكية وتوجد هناك بوابة منزلقة تعمل كأنها سد صغير.

أن تصميم الناعور لـهُ القدرة على تغيير عدد ريشهِ و الريش يمكن أن تكون اطول أو اقصر وهذا يعطي للناعور قطراَ اكبر أو اصغر.

زيادة كتلة تدفق الماء (0.341-1.765 كغم/ثا) بثبوت المقطع العرضي للقناة (12.75 سم^2) لمنظومة توليد القدرة الكهربائية بواسطة الناعور توضح زيادة في التالي القدرة الخارجة (0.0031-0.18 واط) و الكفاءة الميكانيكية (%10.8-%99.6) و الكفاءة الكهربائية (%80.6-%97.7) وكفاءة القناة قلة (%100-%10.9). الكميات التالية كانت ثابتة الكفاءة الحجمية 72.9% و كفاءة الناعور 88.2% و كفاءة النقل 97.2% [illegible] (1.765) [illegible] 11.25-17.25 [illegible] كغم/ثا) لمنظومة توليد القدرة الكهربائية بواسطة الناعور توضح نقصان في التالي القدرة الخارجة (0.201-0.067 واط) و الكفاءة الميكانيكية (%100-%26.7) و الكفاءة الكهربائية (%99.4-%94.4) والكميات التالية قد زادة كفاءة ألقناة (%8.6-%100) و ألكفاءة الحجمية (%70.9-%75.5) و كفاءة الناعور (%85.7-%91.3) زادة. كفاءة النقل كانت ثابتة على97.2%.

الكفاءة الكلية كانت تساوي 6.69% وارتفاع الماء كان يساوي 15.45سم و القدرة الخارجة كانت تساوي 0.18 واط و هذه القيم وجدة عندما كان عدد الريش يساوي 36 و نصف قطر الناعور يساوي 22سم و كتلة الماء المتدفق تساوي 1.765كغم/ثا و المقطع العرضي للقناة يساوي 12.75سم^2.

أن الزيادة النضرية لقطر النـاعور (0.44-2 م) و ارتفـاع المـاء ادة الـى زيـادة فـي القدرة الخارجة (0.18-675 واط).

Appendix (A)
Cases of Study and Sample of Calculations

1. At constant cross sectional area ($\mathbf{A}=12.75\ \text{cm}^2$)

Having the values:

- The density of the water $\rho=1000\,\text{kg/m}^3$.
- The height from channel bed to the free surface $\mathbf{y}=17\text{cm}$.
- The total head across the wheel $h_f=1.7$ cm.
- The wheel radius $\text{r}=22\ \text{cm}$.
- The time measured $\text{t}=17\ \text{s}$.
- The number of revolutions per minute $\text{N}=57$ rpm.

Before calculating losses and efficiencies there are some values must be calculated first, like: $\dot{m}$, **V**, $r_\circ$, **u**, $\dot{m}_a$, $\dot{m}_1$, h and h_c.

From Eq. (4.18) the total mass flow rate can be calculated:

$$\dot{m}=\frac{m}{t}=\frac{30}{17}=1.765\ \text{kg/s}$$

$$\mathbf{V}=\frac{\dot{m}}{\rho\mathbf{A}}=\frac{1.765}{1000\times12.75\times10^{-4}}$$

$$=1.384\,\text{m/s}$$

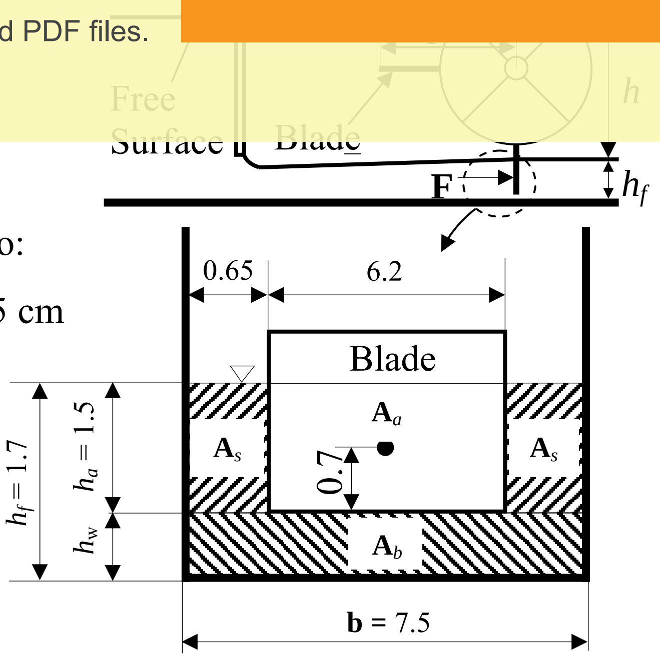
From figure $r_\circ$ is equal to:

$$r_\circ=r-0.75=22-0.75=21.25\ \text{cm}$$

$$\mathbf{u}=\frac{2\pi\ \text{N}}{60}\times r_\circ$$

$$=\frac{2\times\pi\times57}{60}\times21.25\times10^{-2}$$

$$=1.269\ \ \text{m/s}$$



Descriptions drawing for Channel cross sectional area.

Note: All dimensions in (cm).

From figure above:

$$\dot{m}_a = \dot{m} - \dot{m}_l$$

$$\dot{m}_l = \dot{m}_b + \dot{m}_s$$

$$\dot{m}_b = \rho \mathbf{V} \mathbf{A}_b = 1000 \times 1.384 \times 7.5 \times 0.2 \times 10^{-4} = 0.208 \, \text{kg/s}$$

$$\dot{m}_s = 2\rho \mathbf{V} \mathbf{A}_s = 2 \times 1000 \times 1.384 \times 0.65 \times 1.5 \times 10^{-4} = 0.270 \, \text{kg/s}$$

$$\dot{m}_l = 0.208 + 0.270 = 0.478 \, \text{kg/s}$$

$$\dot{m}_a = 1.765 - 0.478 = 1.287 \, \text{kg/s}$$

From Eq. (4.19a) the total head can be calculated:

$$h = y - h_f + 0.24 = 17 - 1.7 + 0.24 = 15.54 \, \text{cm}$$

$$h_c = h - h_f = 15.54 - 1.7 = 13.84 \, \text{cm}$$

After calculating these values, it is [illegible] efficiencies [illegible]

From Eq. (4.16) the power of water can be calculated:

$$P_{P.E.} = \dot{m} g h = 1.765 \times 9.81 \times 15.54 \times 10^{-2} = 2.691 \, \text{W}$$

Recall Eq. (4.24) the power loss in channel is:

$$P_c = \dot{m} g h_c = 1.765 \times 9.81 \times 13.84 \times 10^{-2} = 2.396 \, \text{W}$$

Eq. (4.22) calculates the power loss due to leakage:

$$P_l = \dot{m}_l g h_f = 0.478 \times 9.81 \times 1.7 \times 10^{-2} = 0.07972 \, \text{W}$$

From Eq. (4.23) the power loss in the wheel is:

$$P_w = \dot{m}_a g h_w = 1.287 \times 9.81 \times 0.2 \times 10^{-2} = 0.02525 \, \text{W}$$

From Eq. (4.20) the power output from shaft is:

$$P_{\text{sh}} = \dot{m}_a (\mathbf{V} - \mathbf{u}) \cdot \mathbf{u} = 1.287(1.384 - 1.269) \times 1.269 = 0.188 \text{ W}$$

The value of the transitional loss can be taken from Table **A-1**:

$$P_{\text{t}} = 0.028 P_{\text{sh}} = 0.028 \times 0.188 = 0.005264 \text{ W}$$

The power delivered to the generator shaft is equal:

$$P_{\text{g.s.}} = P_{\text{sh}} + P_{\text{t}} = 0.188 - 0.005264 = 0.183 \text{ W}$$

From experimental work the generator power is:

$$P_{\text{g}} = \text{IV} = 0.12 \times 1.5 = 0.18 \text{ W}$$

Overall efficiency can be calculated from Eq. (4.25):

$$\eta = P_{\text{g}} / \dot{m} g h = \frac{0.18}{2.691} = 0.06689 \times 100\,\% = 6.689\,\%$$

... calculated from ...

$$\eta_{\text{c}} = \frac{h_f}{h} = \frac{1.7}{15.54} = 0.1094($$

Volumetric efficiency is calculated by using Eq. (4.27):

$$\eta_{\text{v}} = \frac{\dot{m}_a}{\dot{m}} = \frac{1.287}{1.765} = 0.72918$$

Wheel efficiency can be calculated from Eq. (4.28):

$$\eta_{\text{w}} = \frac{h_a}{h_f} = \frac{1.5}{1.7} = 0.8823$$

Mechanical efficiency is calculated by using Eq. (4.29):

$$\eta_{\mathrm{m}} = \frac{P_{\mathrm{sh}}}{P_a} = \frac{\dot{m}_a(\mathbf{V}-\mathbf{u})\cdot\mathbf{u}}{\dot{m}_a g h_a} = \frac{0.188}{1.287\times 9.81\times 1.5\times 10^{-2}} = 0.99270$$

Transitional efficiency is calculated from Eq. (4.30):

$$\eta_{\mathrm{t}} = \frac{P_{\mathrm{g.s.}}}{P_{\mathrm{sh}}} = \frac{0.183}{0.188} = 0.97340$$

Generator efficiency can be calculated from Eq. (4.31):

$$\eta_{\mathrm{e}} = \frac{P_{\mathrm{g}}}{P_{\mathrm{g.s.}}} = \frac{0.18}{0.183} = 0.98361$$

From Eq. (4.32) the overall efficiency can be also calculated:

$$\eta = 0.10940\times 0.72918\times 0.88235\times 0.99270\times 0.97340\times 0.98361$$
$$= 0.06690\times 100\% = 6.690\%$$

The other values (Head, Efficienc[illegible] [illegible] by using computer program (M[illegible] in appendix (**B**) for constant cross sectional areas.

The results of this computer program is illustrated in Table 5.4 and plotted in Figures 5.6 to 5.8.

2. At constant total mass flow rate ($\dot{m} = 1.765$ kg/s)

Having the values:

- The density of the water $\rho = 1000\,\text{kg/m}^3$.
- The height from channel bed to the free surface $\mathbf{y} = 10\text{cm}$.
- The total head across the wheel $h_f = 1.8$ cm.
- The breadth of channel $\mathbf{b} = 7.5\,\text{cm}$.
- The wheel radius $\text{r} = 22\,\text{cm}$.
- The number of revolutions per minute $\text{N} = 55$ rpm.

Before calculating losses and efficiencies there are some values must be calculated first, like: **A**, **V**, r∘**, u**, $\dot{m}_a$, $\dot{m}_1$, h and h_c.

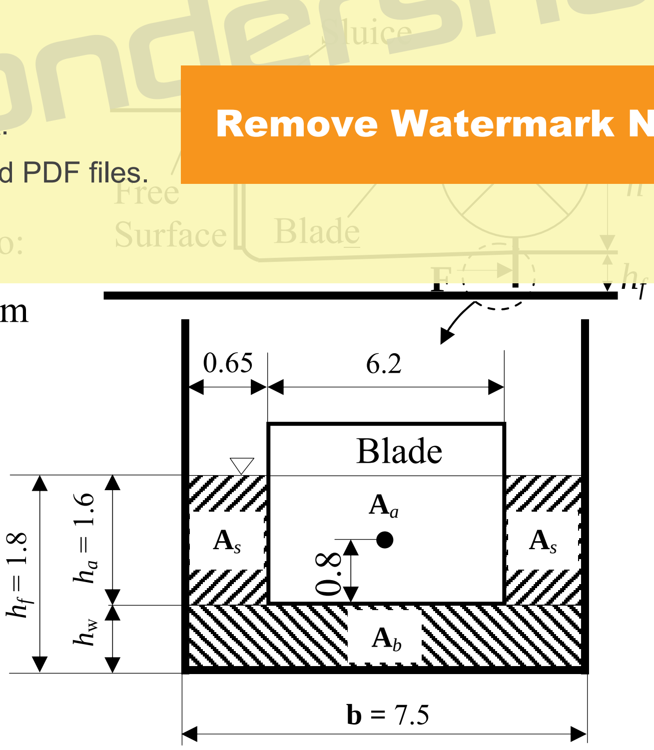
$$\mathbf{A} = \mathbf{b} \times h_f = 7.5 \times 1.8 = 13.5\,\text{cm}^2$$

$$\mathbf{V} = \frac{\dot{m}}{\rho \mathbf{A}} = \frac{1.765}{1000 \times 13.50 \times 10^{-4}} = 1.307\ \text{m/s}$$

From figure r∘ is equal to:

$$r_\circ = r - 0.75 = 22 - 0.8 = 21.2\ \text{cm}$$

$$\mathbf{u} = \frac{2\pi\ \text{N}}{60} \times r_\circ = \frac{2 \times \pi \times 55}{60} \times 21.2 \times 10^{-2} = 1.221\ \ \text{m/s}$$



Descriptions drawing for Channel cross sectional area.

Note: All dimensions in (cm).

From figure above:

$$\dot{m}_a = \dot{m} - \dot{m}_l$$

$$\dot{m}_l = \dot{m}_b + \dot{m}_s$$

$$\dot{m}_b = \rho \mathbf{V} \mathbf{A}_b = 1000 \times 1.307 \times 7.5 \times 0.2 \times 10^{-4} = 0.196\,\text{kg/s}$$

$$\dot{m}_s = 2\rho \mathbf{V} \mathbf{A}_s = 2 \times 1000 \times 1.307 \times 0.65 \times 1.6 \times 10^{-4} = 0.272\,\text{kg/s}$$

$$\dot{m}_l = 0.196 + 0.272 = 0.468\,\text{kg/s}$$

$$\dot{m}_a = 1.765 - 0.468 = 1.297\ \text{kg/s}$$

From Eq. (4.19*a*) the total head can be calculated:

$$h = \mathbf{y} - h_f + 0.24 = 10 - 1.8 + 0.24 = 8.44\,\text{cm}$$

$$h_c = h - h_f = 8.44 - 1.8 = 6.64\ \text{cm}$$

After calculating these values, it is [illegible] losses and efficiencies.

From Eq. (4.16) the power of water can be calculated:

$$P_{P.E.} = \dot{m}gh = 1.765 \times 9.81 \times 8.44 \times 10^{-2} = 1.461\,\text{W}$$

Recall Eq. (4.21) the power loss in channel is:

$$P_c = \dot{m}gh_c = 1.765 \times 9.81 \times 6.64 \times 10^{-2} = 1.150\ \text{W}$$

Eq. (4.22) calculates the power loss due to leakage:

$$P_l = \dot{m}_l g h_f = 0.468 \times 9.81 \times 1.8 \times 10^{-2} = 0.08264\,\text{W}$$

From Eq. (4.23) the power loss in the wheel is:

$$P_w = \dot{m}_a g h_w = 1.297 \times 9.81 \times 0.2 \times 10^{-2} = 0.02545\,\text{W}$$

From Eq. (4.20) the power output from shaft is:

$$P_{sh} = \dot{m}_a(\mathbf{V} - \mathbf{u}) \cdot \mathbf{u} = 1.297(1.307 - 1.221) \times 1.221 = 0.136 \text{ W}$$

The value of the transitional loss can be taken from Table **A-1**:

$$P_t = 0.028 P_{sh} = 0.028 \times 0.136 = 0.00381 \text{ W}$$

The power delivered to the generator shaft is equal:

$$P_{g.s.} = P_{sh} + P_t = 0.136 - 0.00381 = 0.132 \text{ W}$$

From experimental work the generator power loss is equal:

$$P_e = 0.003 \text{ W}$$

The generator power output is equal:

$$P_g = P_{g.s.} - P_e = 0.132 - 0.003 = 0.129 \text{ W}$$

Note: The value of the generator [illegible] experimental [illegible] because the experi[illegible] h_f = [illegible] cm (**A**= 13.75 cm²) and because of the first case of study takes h_f =1.7 cm, so to show different values this case of study takes h_f =1.8 cm (**A**= 13.50 cm²).

Overall efficiency can be calculated from Eq. (4.25):

$$\eta = P_g / \dot{m}gh = \frac{0.129}{1.461} = 0.08830 \times 100\,\% = 8.830\,\%$$

Channel efficiency is calculated from Eq. (4.26):

$$\eta_c = \frac{h_f}{h} = \frac{1.8}{8.44} = 0.21327$$

Volumetric efficiency is calculated by using Eq. (4.27):

$$\eta_v = \frac{\dot{m}_a}{\dot{m}} = \frac{1.297}{1.765} = 0.73484$$

Wheel efficiency can be calculated from Eq. (4.28):

$$\eta_w = \frac{h_a}{h_f} = \frac{1.6}{1.8} = 0.88889$$

Mechanical efficiency is calculated by using Eq. (4.29):

$$\eta_m = \frac{P_{sh}}{P_a} = \frac{\dot{m}_a(\mathbf{V}-\mathbf{u})\cdot\mathbf{u}}{\dot{m}_a g h_a} = \frac{0.136}{1.297\times 9.81\times 1.6\times 10^{-2}} = 0.66805$$

Transitional efficiency is calculated from Eq. (4.30):

$$\eta_t = \frac{P_{g.s.}}{P_t} = \frac{0.132}{0.136} = 0.97059$$

Generator efficiency can be calculat[illegible]

$$\eta_e = \frac{P_g}{P_{g.s.}} = \frac{0.129}{0.132} = 0.97727$$

From Eq. (4.32) the overall efficiency can be also calculated:

$$\eta = 0.21327\times 0.73484\times 0.88889\times 0.66805\times 0.97059\times 0.97727$$
$$= 0.08827\times 100\% = 8.827\%$$

The other values (Head, Efficiencies and Generator power) are calculated by using computer program (MATLAB 6.1), which illustrated in appendix (**C**) for constant mass flow rate.

The results of this computer program is illustrated in Table 5.5 and plotted in Figures 5.9 to 5.11.

Sample of Calculations

Having:

- Waterwheel diameter $\mathbf{D}_1 = 0.44$ m.
- Total head $h_1 = 0.1554$ m.
- Number rpm $N_1 = 57$ rpm.
- Total mass flow rate $\dot{m}_1 = 1.765$ kg/s.
- Generated power $P_{g1} = 0.18$ W.

Assuming that $\mathbf{D}_2 = 2$ m and $h_2 = 2$ m

Recall Eq. (4.35),

$$gh_1 / N_1^2 \mathbf{D}_1^2 = gh_2 / N_2^2 \mathbf{D}_2^2$$

From this equation N_2 is equal to:

$$N_2 = \sqrt{N_1^2 \frac{h_2}{h_1} \left(\frac{\mathbf{D}_1}{\mathbf{D}_2} \right)^2} = \sqrt{(57)^2 \times \frac{2}{0.1554} \times \left(\frac{0.44}{2} \right)^2} = 45 \text{ rpm}$$

From Eq. (4.34) the mass flow rate (

$$Q_1 / N_1 \mathbf{D}_1^3 = Q_2 / N_2 \mathbf{D}_2^3 \Rightarrow \dot{m}_1 / \rho N_1 \mathbf{D}_1^3 = \dot{m}_2 / \rho N_2 \mathbf{D}_2^3$$

$$\dot{m}_2 = \dot{m}_1 \frac{N_2}{N_1} \left(\frac{\mathbf{D}_2}{\mathbf{D}_1} \right)^3 = 1.765 \times \frac{45}{57} \times \left(\frac{2}{0.44} \right)^3 = 130.862 \text{ kg/s}$$

From Eq. (4.36) the generated power (P_{g2}) can be calculated as:

$$P_{g1} / \rho N_1^3 \mathbf{D}_1^5 = P_{g2} / \rho N_2^3 \mathbf{D}_2^5$$

$$P_{g2} = P_{g1} \left(\frac{N_2}{N_1} \right)^3 \left(\frac{\mathbf{D}_2}{\mathbf{D}_1} \right)^5 = 0.18 \times \left(\frac{45}{57} \right)^3 \times \left(\frac{2}{0.44} \right)^5 = 171.859 \text{ W}$$

Table A-1: Practical values for N_z and N_v for different designs [28].

Drive	Gears	N_z [% of N_1]	N_v [% of N_1]	Remarks
Turbine gearing:	Quenched & tempered and			
Parallel axis	machined	0,3· · ·0,5	2· · ·2,8	Sliding bearings and spray lubrication
Parallel axis	Case-hardened and ground	0,2· · ·0,33	1,9· · ·2,6	(Sliding bearings and spray lubrication)
Planetary	Shaved and nitrided	0,3· · ·[illegible],6	1· · ·1,6	Pinion without bearings
Automobile gearing:				
Parallel axis	Case-hardened and ground	0,6· · ·[illegible],4	2,5· · ·3	Rolling bearings, splash lubrication
Spiral bevel	Case-hardened and [illegible]	[illegible]	3	(Rolling bearings, splash lubrication)
Hypoid	Case-hardened and [illegible]	[illegible]	4· · ·6	
Worm gearing $i = 5$	worm hardened [illegible] ground; wheel [illegible] bronze	[illegible]	5· · ·10	Rolling bearings, splash lubrication
Worm gearing $i = 11$	(worm hardened [illegible] ground; wheel [illegible] bronze)	[illegible]		(Rolling bearings, splash lubrication)
Worm gearing $i = 23$	(worm hardened [illegible] ground; wheel [illegible] bronze)	[illegible]	34· · ·48	

Note: N_v represents P_t and N_1 represents P[illegible]

Appendix (B)

Computer Program for Constant Cross Sectional Area

Computer Program Notations

p = Density of water (ρ).
m = The hanging mass multiplied by the arm.
r = Wheel radius (r).
b = Breadth of channel (**b**).
hf = Total head across the wheel (h_f).
t = Time (t).
M = Total mass flow rate ($\dot{m}$).
V = Velocity of water (**V**).
Ro = Active radius (r_o).
N = Number of revolutions per minute (N).
U = Tangential velocity of wheel (**u**).
hb = The head below the blade.
Mb = Mass flow rate losses from below ($\dot{m}_b$).
Ms = Mass flow rate losses from sides ($\dot{m}_s$).
Ml = Total loss of mass flow rate ($\dot{m}_s$).
Ma = Actual mass flow rate ($\dot{m}$).
Y = Height from channel bed to the free
h = Total head (h).
Ec = Channel efficiency (η_c).
Ev = Volumetric efficiency (η_c).
Ew = Wheel efficiency (η_w).
g = Gravitational acceleration (g).
Em = Mechanical efficiency (η_m).
Et = Transitional efficiency (η_t).
Ee = Electrical efficiency (η_e).
E = Overall efficiency (η).
Pg = Power output from generator (P_g).

```
p=0.1;
m=30;
r=22;
b=7.5;
hf=1.7;
t=[88 67 58 54 49 42 37 29 25 21 19 18 17];
M=m./t
V=M/(p*b*hf)
Ro=r-0.75
N=[4 10 13 15 17 21 25 33 39 47 52 54 57];
U=((2*3.14*N)/60)*Ro*0.01
hb=0.2;
Mb=p*V*b*hb
Ms=2*p*V*0.65*1.5
Ml=Mb+Ms
Ma=M-Ml
Y=[3.16 5 6 7 8 9 11 13 14 15 16 16.5 17];
h=Y-hf+0.24
Ec=hf./h
Ev=Ma./M
Ew=[0.8824 0.8824 0.8824 0.8824 0.8824 0.8824 0.8824 0.8824 0.8824
0.8824 0.8824 0.8824 0.8824]
g=9.81;
Em=(Ma.*(V-U).*U)./(Ma*g*1.5*0.01)
Et=(((Ma.*(V-U).*U)-(Ma.*(V-U).*U*0.02[illegible]
Ee=(((Ma.*(V-U).*U)-(Ma.*(V-U).*U*0.028))-(0.003))./((Ma.*(V-
U).*U)-(Ma.*(V-U).*U*0.028))
E=(Ew).*(Ec).*(Ev).*(Em).*(Et).*(Ee)
Pg=E.*M*g.*h*0.01
```

Appendix (C)
Computer Program for Constant Total Mass Flow Rate

Computer Program Notations

p = Density of water (ρ).
m = The hanging mass multiplied by the arm.
r = Wheel radius (r).
b = Breadth of channel (**b**).
hf = Total head across the wheel (h_f).
t = Time (t).
M = Total mass flow rate ($\dot{m}$).
V = Velocity of water (**V**).
Ro = Active radius (r_o).
N = Number of revolutions per minute (N).
U = Tangential velocity of wheel (**u**).
hb = The head below the blade.
Mb = Mass flow rate losses from below ($\dot{m}_{[illegible]}$).
Ms = Mass flow rate losses from sides ($\dot{m}_s$).
Ml = Total loss of mass flow rate ($\dot{m}_s$).
Ma = Actual mass flow rate ($\dot{m}_{[illegible]}$).
[illegible] = [illegible] to the fre[illegible]
[illegible] = Total head ([illegible]).
Ec = Channel efficiency (η_c).
Ev = Volumetric efficiency (η_c).
Ew = Wheel efficiency (η_w).
g = Gravitational acceleration (g).
Em = Mechanical efficiency (η_m).
Et = Transitional efficiency (η_t).
Ee = Electrical efficiency (η_e).
E = Overall efficiency (η).
Pg = Power output from generator (P_g).

```
p=0.1;
m=30;
r=22;
b=7.5;
t=17;
hf=[1.5 1.7 1.8 2 2.3];
M=m/t
V=M./(p*b.*hf)
ro=(hf-0.2)/2
Ro=r-ro
N=[66 57 55 50 41];
U=((2*3.14*N)/60).*Ro*0.01
hb=0.2;
Mb=p*V*b*hb
ha=hf-0.2
Ms=2*p*V*0.65.*ha
Ml=Mb+Ms
Ma=M-Ml
Y=[17.5 17 10.5 4.36];
h=Y-hf+0.24
Ec=hf./h
Ev=Ma./M
Ew=ha./h
g=9.81;
Em=[illegible](V-U).*U)./(Ma.*g.*ha*0.01)
Et=((Ma.*(V-U).*U)-(Ma.*(V-U).*U*0.028))./(Ma.*(V-U).*U)
Ee=(((Ma.*(V-U).*U)-(Ma.*(V-U).*U*0.028))-(0.003))./((Ma.*(V-U).*U)-(Ma.*(V-U).*U*0.028))
E=(Ew).*(Ec).*(Ev).*(Em).*(Et).*(Ee)
Pg=E.*M*g.*h*0.01
```