EFFECTIVENESS OF POLYISOBUTYLENE AS DRAG REDUCING AGENT IN TURBULENT PIPE FLOW

A Thesis
Submitted to the College of Engineering of Nahrain University In Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Chemical Engineering

by

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ABSRACT

Drag-reduction by the use of minor amount of polymeric additives is by far the most technique to reduce the frictional resistance and to save pumping power for turbulent pipe flow.

In the present work, the turbulent drag-reduction effectiveness of polyisobutylene, type oppanol B 250 was studied in a build-up closed loop circulation system at different flowing conditions. The turbulent mode was produced via a positive displacement pump to avoid any shear degradation of polymer chains during the pumping stage. Drag-reduction results were assessed by measuring pressure drop over two test sections from the pipes.

The effect of additives concentration was investigated over a range up to 50wppm in flowing gas oil, at flow rates 2.8 to 6.0 m^3/hr in four pipes of 19.05 to 50.80 mm I.D pipe. Moreover, the effect of kerosene solvent type was also studied in 31.75 mm I.D pipe for comparison purposes.

A gradual increase of percentage drag-reduction was observed with increasing the polymer concentration and bulk velocity. The 31.75 mm pipeline shows higher drag-reduction compared to smaller pipe with 19.05 mm I.D pipe at given velocity. The drag-reduction in kerosene was slightly higher than that in gas oil due to the difference in their viscosities.

The 50wppm polymer treated gas oil shows the greatest degree of calculated, fanning friction factor reduction, approaching the maximum drag-reduction, at higher flow rates in a 31.75 mm I.D pipe. A simple fitting was used to predict the friction factor as a function of Reynolds number. The results show good agreement with the corresponding data obtained on experimental bases.

The drag-reduction results have been correlated based on modification of a theoretical model which requires knowledge of the wall shear rate, pressure drop and additive concentration. The results of the correlation showed acceptable agreement between the observed and predicted drag-reduction values.

The time dependence of drag-reduction effectiveness was studied in order to investigate the possible molecular degradation of polymer additives during the circulation of solution. The experiments were carried out by using polyisobutylene with, three different molecular weights, types oppanol B 150, 200 at concentration 50wppm and B 250 at different concentrations up to 50wppm.

It was found that the lower molecular weight polymers lost their activity faster than higher molecular weight B 250 type. Moreover, the rate of degradation is strongly dependent on pipe diameter.

The time dependence degradation behavior of the three mentioned polymers in turbulent flow was also analyzed by modifying the fractional exponential decay equation. The modified equation was found to fit the experimental data of the three polymer types better than the original equation.

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NOMENCLATURES

Symbols	***Description***	***Units***
A	Flow area (=π*D^2/4)	m^2
a,b,c	Constants in Eq. 2-13	
a_1,b_1,c_1,d_1	Constants in Eq. 4-2	
C	Polymer Concentration,	wppm
C_f	Friction Factor	
[C]	Intrinsic Concentration	
D	Pipe Diameter	m
E	Energy necessary to break one bond in Eq. 2-20	J/gmol
f	Fanning Friction Factor	
K	Exponential constant of Eq. 4-3	
K_B	Bolzman constant	
L	Test Section Length	m
le	entrance length	m
M_∞	Limiting Molecular Weight	g/gmol
Mw	Molecular weight	g/gmol
n	Fractional exponent in Eq. 4-3	
n'	Constant in Eq. 2-10	
N_A	Avogadro's number	6.0225*10^{-23}
n_f	Fractional exponent in Eq. 2-23	
P	Defining the state of polymer species	
Q	Volumetric flow rate	m^3/hr

R_F	Flory radius	m
R_N	Hydrodynamical radius	m
T	Absolute Temperature	K
t	time	min
t_{pol}	Polymer relaxation time	min
U	velocity	m/s
U^*	friction or shear velocity, defined by Eq. 2-15	m/s
U_b	bulk velocity	m/s
$U_d(t)$	The energy originating from turbulence intensity that produces degradation in Eq. 2-20	J
Δh	U-tube manometer readings	mm Hg
ΔP	Friction pressure drop	Pa

Greek Symbols

μ	Dynamic viscosity	Pa.s
f	Fanning Friction Factor process	
γ	Shear rate at the wall, defined by Eq. 2-14	m^2/s
ε	Roughness of pipe diameter	mm
η_s	Solvent viscosity in Eq. 2-17	$N.s/m^2$
Θ_p	Time scale hypothesis	s
λ	observed time scale of the relaxation	s
ν	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3
τ_w	wall shear stress	N/m^2
φ	Additive concentration	wppm

SubScript

0	at time=0
o	without polymer additives
p	with polymer additives
t	at time=t
treated	system with polymer additive
untreated	system without polymer additive
w	wall

Dimensionless Groups

De	Depora number
Pe	Peclet number
Re	Reynolds number
Re′	Generalized Reynolds number in reference (31)

Abbreviations

%DR	Percent drag reduction
2EHA	Poly(2-ethylhexylacrylate)
AAPE	Average Absolute Percent Error
CDR	Conoco Drag Reducer
GM	Guar gum
CMC	Carboxymethyl Cellulose

CTAC	Cethyltriethyl Ammonium Chloride
DR	Drag Reduction
DRA	Drag Reducing Agent
DRE	Drag Reduction Efficiency
ID	Inside Diameter
iDMA	Poly(isodecyl methacrylate)
ITP1	Irak-Turkish Pipeline,1
KWW	Kohlrausch, Williams, and Watt function
LDA	Laser Doppler Anemometer
LMA	Poly(lauryl methacrylate)
MDR	Maximum Drag Reduction
NaSaL	Sodium Salicylate
PAM	Polyacrylamide, Homopolymer
PAMH	Polyacrylamide, Hyrolysed
PDMS	Polydimethylsiloxane
PEO	Polyethylene Oxide
PIB	Polyisobutylene
PMMA	Polymethylmethacrylate
PS	Polystyrene
RDA	Rotating Disk Apparatus
STAC	Stearyltrimthyl Ammonium Chloride
TAPS	Trans Alska Pipeline System
TBS	Poly(tertiary-butyl styrene)
XG	Xanthan gum

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CHAPTER ONE
INTRODUCTION

1.1 Introduction

In the process of transferring a Newtonian fluid through a pipe, considerable energy may be expanded to overcome friction encountered in movement of the liquid. When a liquid is pumped under pressure, friction pressure is apparent as a pressure drop along the pipe. Such a pressure drop is particularly noticeable under conditions where the velocity of liquid has surpassed the critical limit for laminar flow. Drag is a term used to refer to such frictional pressure drop.

To compensate for the loss of energy due to friction, or to reduce the drag, additional energy must be consumed. Many techniques for reducing drag were suggested by many researchers for large number of applications. One of these techniques depends on suppressing turbulent eddies by using baffles with different heights in turbulent flow region. Other techniques used layers of greasy materials or bubble layers to reduce skin friction. One of the modern techniques is the addition of minute quantities of a dilute polymer solutions to liquids transported in turbulent flow through pipelines, which can lead to significant drag-reduction (DR). This phenomenon has received much attention, since its discovery more than 50 years ago. Nevertheless, detailed knowledge about the chief mechanism for the action of the polymer and its effect on turbulence is not available.

Drag reduction phenomena had been well documented in which the fluid that containing these additives requires a lower pressure drop than pure solvent to maintain the same flow rate in a pipe. This behavior can offer large economic advantages and a larger effectiveness of the pipeline transportation. Drag reduction plays an important role in different industrial application such as in petroleum transportation, fire fighting and irrigation (1), like the first large application of polymeric drag-reducer (CDR) was done by CONOCO in Trans Alska Pipeline System (TAPS). The same chemical had been used in Iraqi – Turkish pipeline in the eighties. It is worth mentioning that Iraq is one of the main countries exporting oil through a network of pipelines. These applications showed the high ability of polymers in reducing drag and increasing oil flow rate without the need for any additional pumping stations or new pipelines.

Effective polymeric DR additives are considered to be flexible, linear with a high molecular weight such as polyisobutylene. Drag reduction has promoted the use of polymeric additives in industry whenever an increase in flow rate is required, such as during maintenance of pumping equipment in pipelines. However, the usage of these polymers is limited, because of their susceptibility to flow induced shear degradation. (2,3)

The use of polymer additives to reduce drag, and consequently pumping costs, has to be carefully balanced with its degradation rate and the consequent rate of polymer renewal, the investment on injection mechanisms and quantity of polymer necessary to achieve drag reduction intensity, which may preclude its use in normal operating conditions, but not in special occasions such as maintenance of equipment. The dependence of DR efficiency is known to be a function of polymer molecular weight, polymer concentration, and the degree of turbulence. Since solvent molecules take time to establish introductions with polymer molecules, maximum drag reduction, as a function of time, is obtained when the polymer–solvent interaction reaches the state of homogeneity.

Although, the additives demonstrate a desirably high DR efficiency while so undesirable mechanical degradation under turbulent flow occurs, therefore, molecular degradation is one of the major defects in the DR application. This is because the polymeric additives are exposed to strong turbulent elongational strain and shear stresses, especially in the pump. The use of positive displacement pump of external gear type will minimize this problem. (4) The polymer chains having different molecular weight will show different time dependent resistance, since the long chain polymer experiences mid–point degradation. In this context, longer molecules are more susceptible to mechanical degradation than lighter molecules, accompanying more rapid degradation. (5)

1.2 Objectives of The Present Work:

The main objectives of the present work are:

1. To obtain experimental data which will be used to examine the effectiveness of Polyisobutylene (PIB) type (Oppanol B 250) in the petroleum fractions as drag reducing agents in the turbulent pipe flow regime. The performed experimental data aim at showing the effect of polymer concentration, solution flow rate, pipe diameter and fluid type on percent drag reduction (%DR).
2. To investigate the modification of the time scale hypothesis of turbulent flow field interaction with the polymer molecule, both for understanding of the physics of the drag reduction phenomena and to providing a reliable prediction technique for percent drag reduction results.

3. To study the DR efficiency which is to be investigated by dilute hydrocarbons solutions of PIB with three different molecular weight types (Oppanol B 150, 200 and 250) in closed re–circulation system by focusing mainly on their mechanical degradation kinetics as a function of time.
4. To modify the fractional exponential decay functions of PIB for the purpose of examining their time dependent drag reduction efficiency, and with the ultimate goal of establishing a correlation between polymer degradation and pipeline diameter.

CHAPTER TWO

THEORIES AND LITERATURE SURVEY

2.1 Introduction

Drag is a term used to refer to the frictional pressure drop per a length a of pipe, which develops when a fluid flows in a pipe line. Drag reduction is the proportional decrease in this frictional pressure drop achieved by the addition of very small amount of a drag reducing agent. These DRAs (Drag Reducing Agents) are effective only when the flow is turbulent.

The phenomenon of drag reduction by polymer additives is very interesting from a fundamental fluid dynamics point of view. The fact that such small changes in the fluid can so drastically alter the turbulent flow characteristics strongly hints at the existence of a key mechanism of turbulence transport with which polymer interface. This means that a study of polymeric drag reduction could help in gaining more knowledge about the turbulence itself.

In other words, drag reduction occurs as a result of interaction between additive molecules and coherent structures resulting from turbulent flow. Therefore, understanding and optimization of the drag reduction phenomena require a previous knowledge and understanding of turbulence in fluid flow. In addition to that, and in order to have a clear idea about the effectiveness and performance of drag reducing agents, it is essential to study the polymeric additives type used.

2.2 Turbulent Pipe Flow Characteristics

2.2.1 Turbulence

Turbulence is a fluid flow phenomenon of significant fundamental interest as well as of commercial importance for its impact in the operational performance and costs of many industrial processes and of transportation systems. It is characterized by an irregular space and time dependence of the velocity and scalar fields which is the result of vortical three–dimensional motions occuring at high Reynolds numbers, i.e. when the ratio of inertial to viscous forces is high.(6,7) Thus, it is also characterized by random motion of fluid particles in directions transverse to the direction of the main flow as shown in figure 2-1. The flow is unstable. Turbulent eddies are generated at the pipe wall and move into the core of the pipe. More energy is required to transport fluid at a given average flow velocity in turbulent flow because not all of the energy goes toward overcoming viscous resistance to motion down the pipe. Part of the energy is dissipated in the formation of the eddies current. Otherwise stated as “going around in circles”.

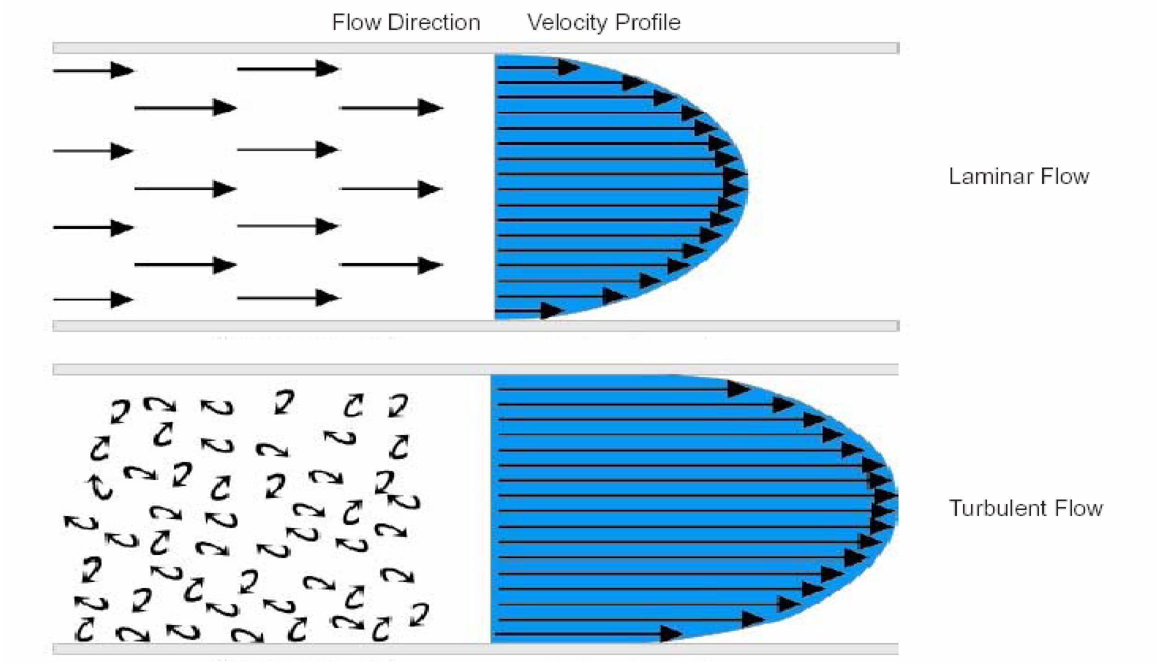


Figure 2-1 Laminar and turbulent flow velocity profile

It is this turbulence which drag reducer decrease, generally, the more turbulent flow, the more effective drag reducer becomes and consequently, greater energy utilization can be achieved.

A part from a rather qualitative insight into the dynamics a complete theory of turbulence is still lacking because it is impossible to analyze in detail the non – linear equations that governs the turbulent flow.

2.2.2 Frictional Pressure Loss in Turbulent Flow:

When a liquid flows through a pipeline, a certain loss of pressure occurs due to frictional effects. This pressure loss is referred to as frictional loss or frictional pressure drop and depends upon the viscosity and density of the flowing fluid. It also depends on the roughness of the interior pipe surface, the internal diameter of the pipe and the length of the pipeline.

The qualitative effect of each of these parameters, is the frictional pressure drop will increase with increasing fluid viscosity and fluid velocity, and decrease with increasing pipe diameter. Increasing fluid density and increasing pipe wall roughness will increase the frictional pressure drop.

2.2.3 Mathematical Formula

Quantitatively, the frictional pressure drop is shown specifically in the following mathematical formula.

For estimating the type of flow in pipeline, the Reynolds number, is used, which indicates the ratio of the fluid inertia forces to viscous force

$$\mathrm{Re} = \frac{\rho u D}{\mu} \qquad (2\text{-}1)$$

Now, a fully developed turbulent flow through a straight pipe with diameter D is considered. the mean shear stress at the wall, τ_W, for Newtonian and non – Newtonian fluids and for all flow regimes is given by:

$$\tau_w = \frac{D}{4}\frac{\Delta P}{L} \qquad (2\text{-}2)$$

where $\Delta P / L$ is the constant pressure drop gradient. The wall shear stress is usually expressed in terms of the fanning friction factor f given by:

$$f = \frac{\tau_w}{\frac{1}{2}\rho\, U_b^2} \qquad (2\text{-}3)$$

with U_b is the mean velocity in the pipe and ρ is the density of the fluid.

For instance, the expressions for laminar and fully turbulent pipe flow of a Newtonian fluid are, as follows:

The individual flow regimes

- Laminar regime: for Re< 2,100, Poiseuille's law(8) is applicable.

$$f = \frac{16}{\mathrm{Re}} \qquad (2\text{-}4)$$

- Transition regime: For Re between 2,100 and 4,000 Wilson and Azad(9) derived an empirical equation for the central portion of the transition regime

$$f = 7.1 * 10^{-10} * \mathrm{Re}^2 \qquad (2\text{-}5)$$

- Turbulent regime in smooth pipe: For Re > 4,000 Blasuis(8) equation is valid:

$$f = 0.0791\,(\mathrm{Re})^{-0.25} \qquad (2\text{-}6)$$

- Von–Karman equation(8) which is an alternative to Blasius equation for the turbulent flow in smooth cylindrical pipe, and written in terms of f as follows:

$$f^{-1/2} = 4.0\log\left(\mathrm{Re}\, f^{1/2}\right) - 0.4 \qquad (2\text{-}7)$$

- Fully developed turbulent flow in rough pipe: Nikuradse(9) determined the following asymptotic expression :

$$1/\sqrt{f} = 1.737 \ln(3.707\, D/\varepsilon) \qquad (2\text{-}8)$$

2.3 Flow Increase

To compensate for the loss of energy due to friction pressure, additional energy must be consumed. Consequently, a decrease in friction loss would allow lower energy consumption or alternatively an increased flow rate under the original pumping conditions. Thus, a method where by friction loss in the flow of liquids can be appreciably reduced is desirable. Also, it is economically profitable to industrial organizations engaged in movement of large volumes of liquid at high flow rates for considerable distance.

Pipelining the liquid, requires that has being sufficiently low viscosity that line size and pumping requirements are an economic “minimum”.

There are a number of methods by which the flow increment can be achieved. Some of these are:

- The use of chemical additives known as Drag – reducing agents to liquid transported in turbulent flow through pipelines which is one of popular method to reduce the friction and to increase the flow.
- Suppressing turbulent eddies by using baffles with different heights. (1)
- Preparation of an oil / solid slurry, for oil transporting.
- Heating the liquid for viscosity reduction.
- Diluting the heavy liquid for viscosity / pour point reduction.
- Connecting the pumps in series or in parallel as required.
- Connecting re–enforcement and stand by pumping stations.

As the current study, especially interested in chemical additives, the following item will deal with them.

2.3.1 Additives

In case the flow increment is temporary, the increase in pumping stations becomes much costly; therefore it is preferred to use the chemical additives in this case to reduce the drag. At the same time, these additives can compensate for the loss of any pumping station at emergency cases.

In the past several decades, there had been a remarkable growth in the use of additives to facilitate the transportation of fluids in the pipes. These additives are able to substantially reduce the frictional loss associated with turbulent flow of fluid. By lowering the energy loss, those additives allow the pipeline fluid to move faster at any working pressure, so more can pass through the line with out mechanical expansion. On the other hand, the flow improver by additives can be able to move more products with the same amount of energy or move the same amount of fluid with less energy. This results improved system economic as illustrated in the figure 2-2.(4)

At the present time, the additives used in oil and products pipelines are themselves hydrocarbons with in minor amount and thus should have no effect on refining processes or on the chemical specification of the refined products.

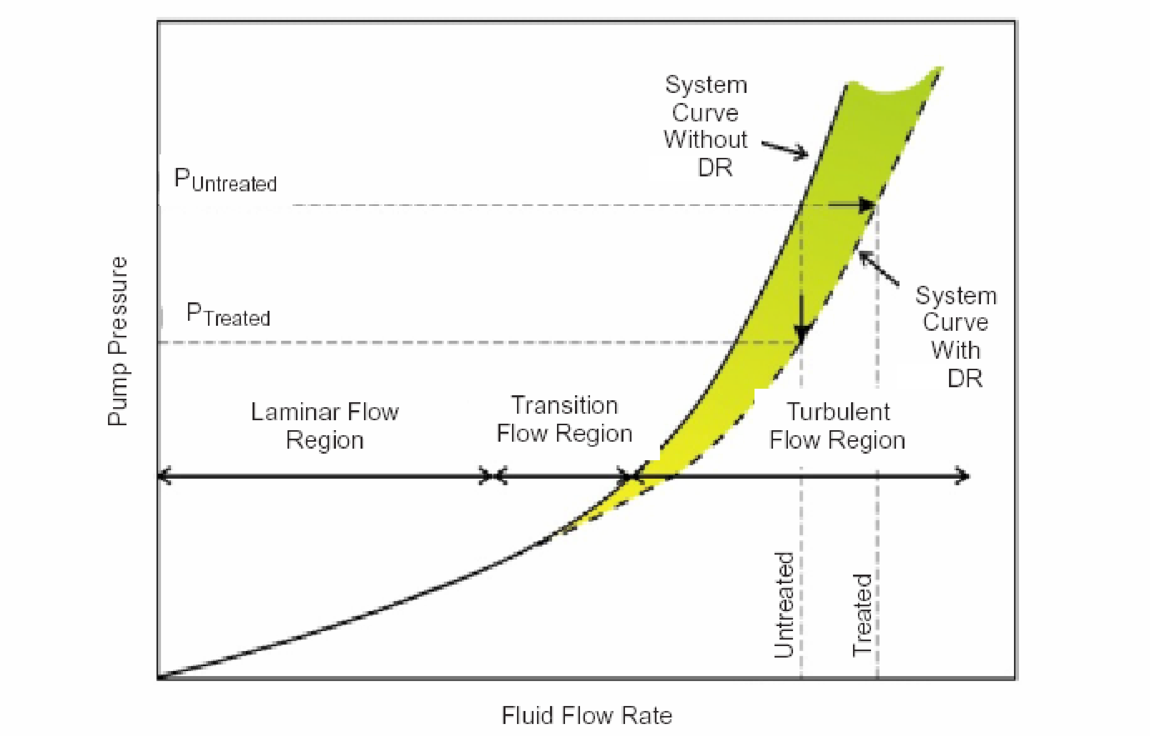


Figure 2-2: Effect of chemical drag reducers on pipeline pump pressure of flow rate

2.4 Drag Reduction Phenomena

2.4.1 Background

The frictional drag of turbulent flow through pipes can be reduced dramatically by adding a minute amount of certain long-chain polymer molecules dissolved in water or in organic solvents. The discovery of this phenomenon of turbulent drag reduction by polymer additives is generally ascribed to Toms (11). This observation was noticed by chance in the summer of 1946, when he was actually investigating the mechanical degradation of polymer molecules using a simple pipe flow apparatus. Toms observed "the really astounding thing that a polymer solution clearly offered less resistance to flow, under constant pressure, than the solvent itself"(12). Already one year earlier, Mysels had discovered that the addition of aluminum soap to gasoline lowered the resistance of the liquid to turbulent flow in a pipe. However, since this work was done under war-time restrictions, publication was delayed by several years. (13)

The phenomenon of drag reduction by polymer additives is very interesting from a fundamental fluid dynamics point of view as well. The fact that such small changes in the fluid can so drastically alter the turbulent flow characteristics strongly hints at the existence of a key mechanism of turbulence momentum transport with which the polymer interferes. It means that a study of polymeric drag reduction could help in gaining more knowledge about the turbulence itself.

Hence, polymeric drag reduction is interesting in many ways and this is reflected in the virtual explosion of research and development work in many countries on the subject during the last three decades. A vast amount of publications has appeared the majority of which concern measurements. Some of the papers are theoretical reflections, and also a respectable number of survey articles have been published. Despite this wealth of information, it cannot be said that the phenomenon is well understood. The physical mechanism responsible for the drag reduction remains largely unclear. This is caused by the fact that not only it is necessary to consider the turbulence processes that are present in the flow, but also the influence of the rheological properties of the fluid.

2.4.2 Drag Reducer Additives

Various drag – reducing additives are available, which can be classified as follows:

2.4.2.1 Suspended particles:

It is well known that the presence of suspended particles modifies the turbulent structure of the flow (14). The combination of general factors, such as sediment concentration, specific weight of solid and fluid, particle size and shape and others, can produce sub stationary changes in the behavior of the flow. The most interesting case is that of a drag reduction which can occur in pipes when the combination of factors produce a decrease of turbulent intensity. The mechanisms which produce these changes in the turbulent structure could be various, depending upon the particle and flow characteristics, and the overall effect could also vary for each particular case. A and K Zaqustin(14) presented an analysis of a mechanism in which gravity is considered as the only factor involved in the turbulence. The same approach was obtained a few years later by K. Mahmood. (15)

2.4.2.2Surfactants:

Solutions of surfactants with high enough concentrations from aggregates are called micelles. These were observed to cause drag reduction in turbulent flows of gasoline, Mysels(13). Studies of this phenomenon have been summarized by Imae et al(16), Ohlendrof et al(17), Ceyr & Bewerdroff(18). One of the most interested researchers in this field are Zakin & Lui(19), and (Zakin & Myska)(20,21).

The mechanism of drag–reduction by surfactant additives is still not well understood, but it is generally accepted that drag reduction is associated with network structures called micelles, in the surfactant solution. These network structures show elasticity and prevent the generation of turbulence and thus reduce frictional drag.

Zakin(19) investigated the effects of surfactant structure, temperature, surfactant concentration and mechanical degradation on drag reduction for several polyoxyethylene alcohol nonionic surfactants in aqueous solution. Through studying the effect of surfactant concentration, as illustrated in figure 2-3, it is shown that, at low Reynolds number, the 1.0 percent Alfonic 1214 solution with 0.4 Na_2SO_4 at 30ºC has high relative viscosity. As a result, the laminar data for this solution lie above those of the 0.5 percent solution. As the Reynolds number increases, the friction factor for the two concentrations approach each other. At about 8,000 Reynolds number, the 0.5 percent solution is subjected to shear forces which are large enough to break up the agglomerates. Rapid loss of drag reduction is seen at Reynolds number above 8,000. The 1.0 percent solution shows no break-up to a Reynolds number of about 10^4.

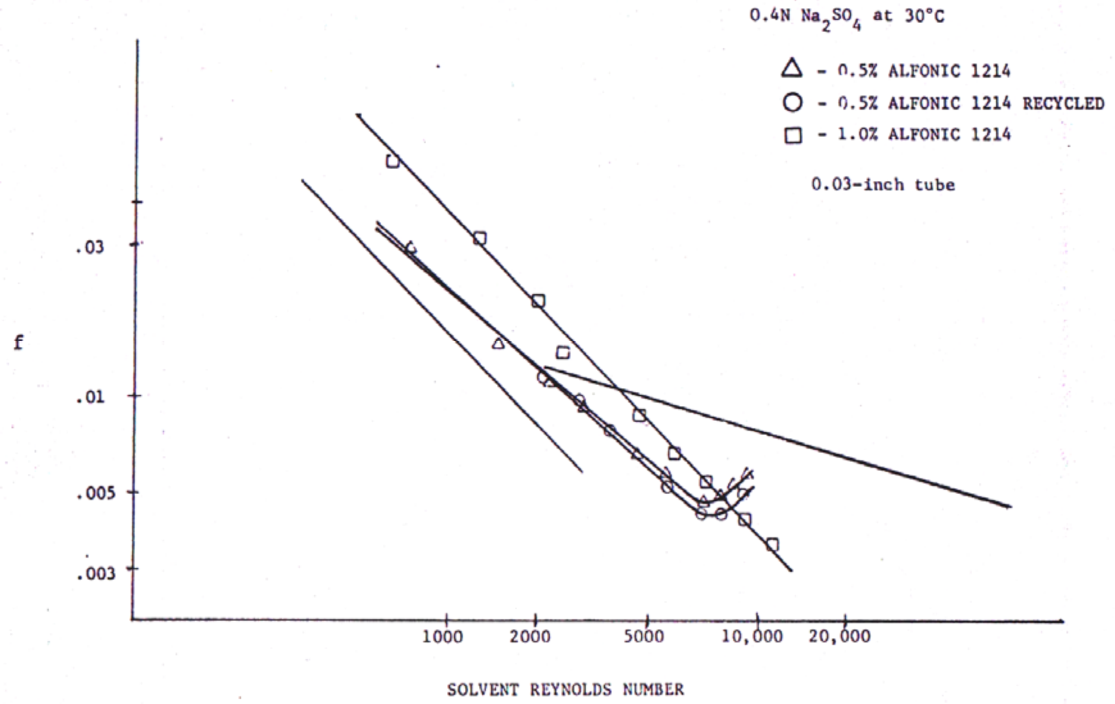


Figure 2-3: Effect of concentration on drag reduction for Alfonic 1214.

Drag reduction by surfactant additives has been considered the most effective way to lower the pumping energy requirements(21,22,23) in closed–loop district heating and cooling systems.

In district heating systems, cogeneration or waste heat sources are used to heat water in a primary loop which circulates the hot water to heat-exchange stations. The heat exchanged to secondary loops provides hot water to heat nearby buildings or to heat water for household use. District heating systems conserve energy because of their use of waste heat and centralized production and distribution of heat, and their elimination of often inefficient burners in individual buildings. Thus, they reduce the amount of fossil fuel burned. District cooling systems operate in a similar manner. (21)

Among the surfactants used for drag reduction, cationic surfactants such as, cethyltrimethylammonium chloride (CTAC), $CH_3(CH_2)_{15}N(CH_3)_3Cl$, and stearyltri methylammonium chloride (STAC) $CH_3(CH_2)_{17}N(CH_3)_3Cl$, and sodium salicylate (NaSal) have been most widely used as the drag–reducing additives.

Under the suitable conditions of surfactant/counterion chemical structures, ratios, concentrations and temperature, they form rod-like micelles. The resulting microstructure imparts viscoelasticity to the solution. The microstructure is mechanically degraded when passing through a high shear pump such as a centrifugal pump. (21)

The disadvantage of this type of additives is that, the surfactant drag reducing additives require higher concentration (i.e. 2000 ppm), if it is compared with high molecular weight polymeric additives (about 50 ppm) this will lead to a higher economic cost.

2.4.2.2 Polymers

The polymeric drag reduction has shown much promise in reducing the energy requirement of crude oil and water transport through pipes than other types of drag reducing agents. This implies that fluid containing dilute polymer solutions, which posses a linear flexible structure and very high molecular weight, requires a lower pressure drop than pure solvent to maintain the same flow rate in a pipe.

When polymeric drag reducer is mixed with fluid in a pipeline, it changes the flow characteristic and reduces the turbulence. By reducing turbulent in the flow, polymer drag reducer directs more energy to moving additional fluid through the system. Studies have shown that the number of turbulent bursts originating at the pipe wall and strength of turbulent eddies are reduced by addition of polymeric drag reducer. It should be emphasized that polymeric drag reducer does not work by being absorbed into or coating the walls of the pipes, as some have thought, whereas it is dissolved into and becomes part of the fluid, not the pipe.

The performance of polymeric drag reducers in a variety of crude oils seems to vary quite substantially, with greatest effectiveness being found in the low viscosity crude oils such as Kirkuk crude oil of the Middle East. The variability in performance in crude oils is primarily a function of the viscosity of the crude, as weak as polymer chemical composition. Since a few amount of polymer solution, in part per million is added, Many investigators have been used this type of drag reducer for its high economics.

A review of polymer types in the literature during the past half century with their solvents is illustrated in table 2-1.

Table 2-1 : Review of polymer types in the literature

Author	Solvent used	Polymer species	Mwt $*10^{-6}$
Toms, 1948(11)	Chlorobenzene	PMMA	2.3
Shover and Merrill, 1959(24)	Water	CMC	-
Shin , 1965(25)	Water Water	PEO PEO	4.7 0.6
Gadd, 1965(26)	Water	PEO	4
Elata et.al., 1966(27)	Water	CGM	0.5
Pruitt et.al., 1966(28)	Water 0.6 m K_2SO_4	PEO PEO	0.8 0.8
Rodriguez et.al., 1967(29)	Cyclohexane	PIB	0.93
Virk et.al., 1967(30)	Water	PEO	.69
Hershy & Zakin, 1967(31)	Cyclohexane Benzen Toluene	PIB PIB PMMA	0.72 0.46 1.5
Liaw, 1968(32)	Benzen Toluene	PEO PDMS	3.1 10.7
Whittsitt et.al., 1968(33)	Water	GGM	0.22
Patterson & Florez, 1969(34)	Cyclohexane	PIB	0.5
Seyer & Metzu(35)r	Water	PAMH	3
Virk & Baher, 1970(36)	Water	PAM	4.7

Virk, 1971(37)	Water	PAM	12.5
Zakin & Hunston, 1978(38)	Benzene Toluene	MPS MPS	7.1 4.1
Marlin D and Jiten , 1980(39)	Kerosene	TBS Poly (tetra butyl styrene)	5.5
Marlin D and Jiten , 1980(39)	1,1,1,trichloroe tethane Kerosene Kerosene Kerosene	IDMA IDMA LMA 2EHA	20 20 14 15
Zakin, 1980(40)	Toluene Toluene Toluene	7MPS 4MPS 2MPS	7.1 4.1 2.4
Burger, 1980(41)	Crude oil Diesel	CDR CDR	- -
Munstedt, 1981(42)	Oil Oil	Oppanol B 200 Oppanol B 100	4 2
Robert & Sellin , 1983(43)	Water Water water	PEO PAM PAM	4 >1 1
Backtiyarove, 1983(44)	Water	PAM	>4
Horn et al, 1985 (45)	Crude Oil	FLO™	-
Shao,& Lin, 1993(4)		PAM	4.7
Emad, 1996(46)	Gas oil Water	CDR CMC	

	Water Water	XG PAM	4.7
Kim et.al., 2000(47)	Benzene Chloroform Toluene	PS PS PS	1.54
Kim, 2001(48)	Water Water	PEO Xanthum gum	5
Choi , 2004(49)	Water Water	PEO PEO	4 5
Jovonovic et al, 2005(50)	Diesel oil	Fortum	25
Jacqueline Brazin, 2006(51)	Water	PEO	8

2.4.3 Parameters Affecting

2.4.3.1 Polymer Concentration

The effect of polymer concentration on %DR have been studied by Kim(48) at a constant rotational speed, and found that this effect is related to two competitive mechanisms. Initially, %DR increases as the concentration increases due to an increase in the number of available drag reducers. However, as the polymer concentration increases further, the solution viscosity drastically increases, leading to a decrease in the turbulent strength, i.e., reduction of Reynolds number and an increase in the frictional drag. Therefore, one anticipates that there exists a critical concentration at which the drag reduction is maximized. The same anticipation was found by Virk(30), who demonstrated that the %DR increases initially with increasing concentration but tends to a constant, maximum value of %DR at high concentration. To illustrate this point, figure 2-4 shows %DR of PEO as a function of polymer concentration at 2040 rpm.

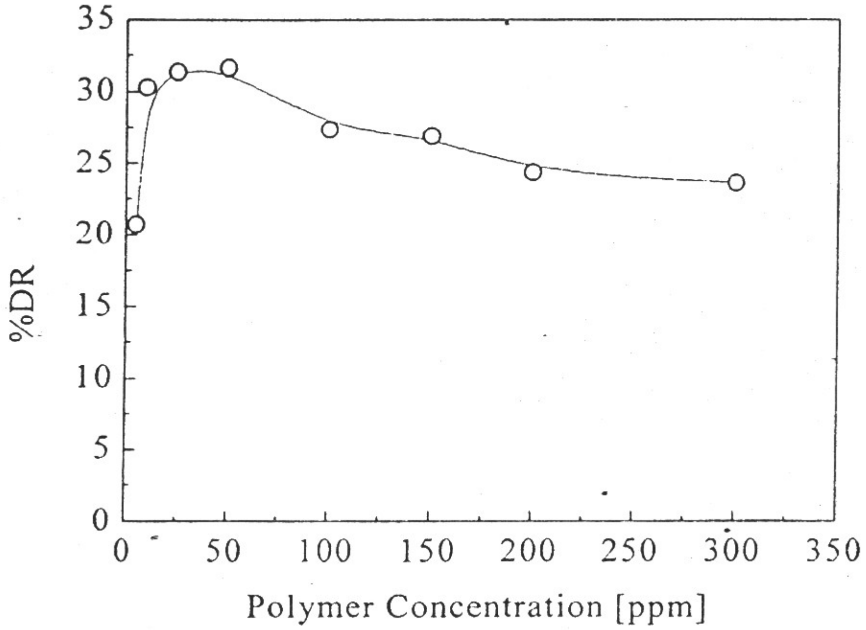


Figure 2-4: %DR of PEO 345 vs. polymer concentration at 2040 rpm and 25°C.

Another observation had been found by Sellin(43) where suggested that the core–injection of concentrated polymer solutions results in a different type of drag reduction than that obtained with dilute homogeneous polymer solution.

In addition, the effect of concentration on %DR is variable according to the nature of polymer. The flexible polymer like PEO and PAM, which are synthetic polymers, cause maximum drag reduction (≅ 55%) in turbulent pipe flow at the concentration of few 10 wppm. On the other hand, rigid polysaccharides, from natural resources, like guar gum, xanthan gum, carboxymethyl Cellulose, require much higher concentration ≥ 500 wppm to cause maximum drag reduction (≅ 45%).(52)

2.4.3.2 Type of solvent

Polymers are more efficient drag reducer in a good solvent than in a poor solvent. The effect of polymer – solvent interactions or the nature of the solvent on the extent of drag reduction were studied, by comparing pressure drop measurements of solutions of polyisobutylene L-80(PIB) in a good and in a poor solvent. Cyclohexane at 25°C is a good solvent for polyisobutylene and polymer–solvent contacts, leading to expanded conformations of polymer molecules in solution. Benzene at 24°C, is a poor solvent for polyisobutylene. It is at the ideal temperature and there is no preference for polymer–solvent contacts over polymer–polymer contacts, the molecules in this solution are not expanded. Thus, for approximately equal concentrations of the same polymer, considerably more drag reduction is obtained when the molecules have expanded rather than unexpanded conformations. (31)

Another work has been done by Conoco. It was found out that lighter crude oil causes higher drag reduction than heavier crude, using larger pipes at 8 ft/sec, as illustrated in figure 2-5 below.

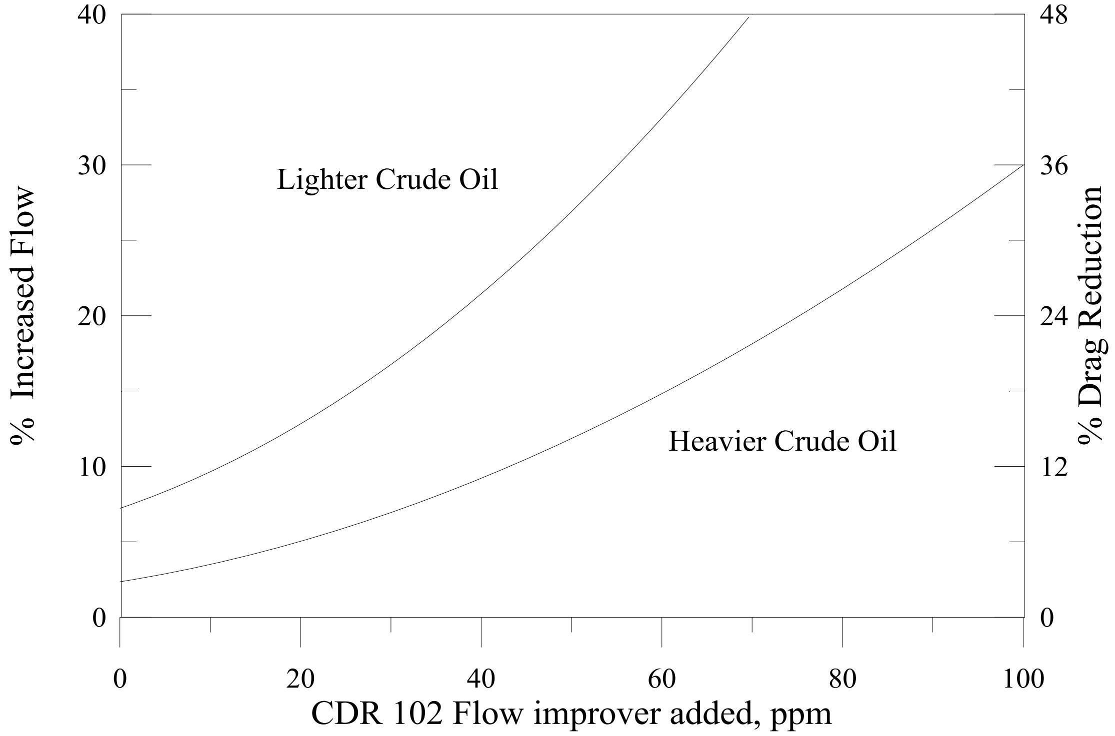


Figure 2-5: Solvent type effect on % DR and % flow increase.

2.4.3.3 Type of polymer

The physical properties of polymer type has a great effect on drag reduction phenomena such as molecular weight, polymer structure and polymer composition.

- **Molecular weight of polymer:**

High molecular weight polymers have been in use for more than 25 years in pipelines around the world. This approach to handle pipeline throughput problems was developed by a Conoco scientist many years ago.

Although the original idea was for use as a fracturing fluid additive, the high molecular weight polymer in a kerosene-like solvent was subsequently identified as an effective friction – reducing agent for crude oil pipelines. Additional tests with high performance Conoco Drag Reducer (CDR) has shown that product pipelines can also use the product at effective levels of treatment with no detrimental effect to the transported product.

Virk(53) correlated onset of DR with polymer radius of gyration which is a function of both polymer molecular weight and polymer-solvent interaction.

Zakin(40) showed that a minimum molecular weight is required before a polymer can effectively reduce drag. The minimum is defined in terms of (MC), the critical (Mw), at which chain entanglements becomes important in polymer melts. (MC) is unique for each polymer.

Furthermore, turbulent drag reduction with PEO in a Rotating Disk Apparatus (RDA) was investigated with two different molecular weights. A higher molecular weight of PEO (Mw = $5*10^6$ g/mol) showed less mechanical degradation than that of a lower molecular weight (Mw = $4*10^6$ g/mol) at the same concentration as shown in figure 2-6. (49)

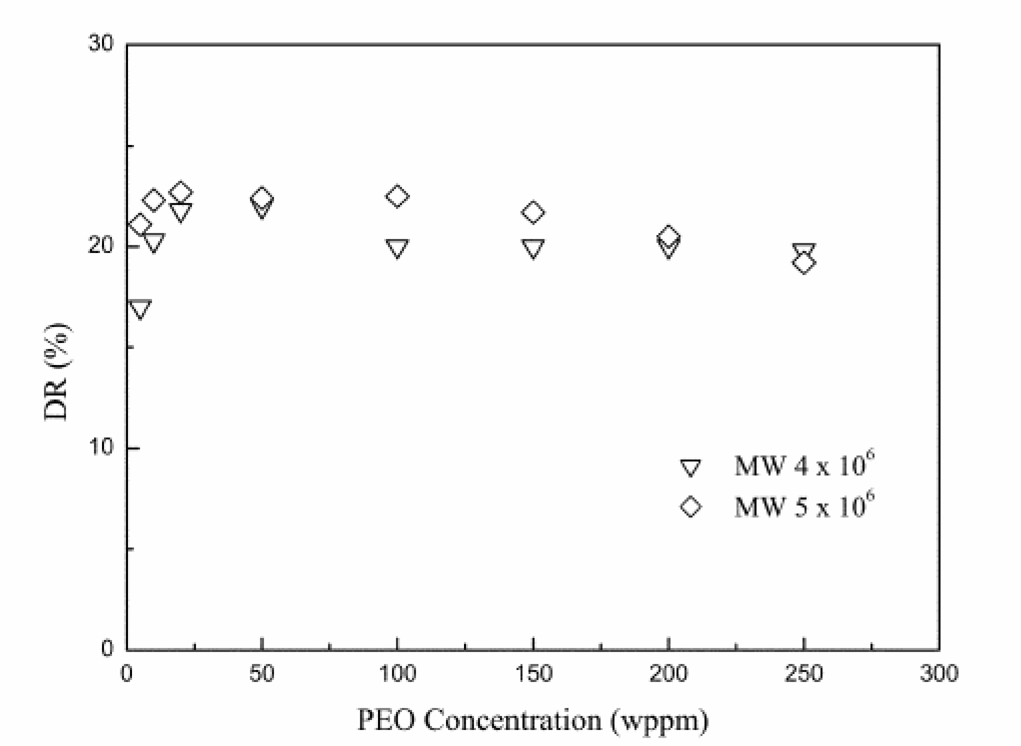


Figure 2-6: Drag reduction efficiency vs. PEO concentrations of two molecular weights.

- **Polymer structure and composition**

The chemical nature of the polymer is important in terms of its relation to other DR parameters. The molecular linkages in the polymer backbone affect shear stability, chain flexibility, intermolecular association and polymer-solvent interaction, which in turn affect DRE (Drag Reduction Effectiveness). Polymer-molecular composition and architecture can be tailored to provide desired combination of the above properties. Morgan(54) had shown that slight modification of polymer chemical composition can dramatically alter drag reduction effectiveness (DRE).

In the first place, linear, high molecular weight polymers are most effective in reducing drag.

Furthermore, the experiments by Virk & Wagger(55) , in 1990 , showed that the initial polymer conformation has large influence on the drag reduction. Sasaki(56), found that the drag reduction ability decreases when the polymers become more flexible. Also, Sasaki(56), showed that increasing the elasticity of a drag-reducing fluid (by adding a micro-gel to a polymer solution) has an adverse effect, rather than an enhancing influence on drag reduction.

2.4.3.4 Diameter of Pipe

One of the most interesting factors in the study of the drag reducing fluid is the question of the “diameter effects”. This term in the turbulent pipe flow of drag reducing solutions is the additional dependence of the friction coefficient (C_f) on the pipe diameter, which is not fully taken into account by the Reynolds number as it is for Newtonian fluids. For practical applications, this problem means that it is not possible to predict the C_f on a large diameter pipe given the C_f measurements readily made on a small laboratory–scale pipe. Evidently, this problem is particularly significant for large system, where it is not feasible to perform drag-reducing tests on large pipes, and therefore, smaller laboratory pipes need to be used to scale the problem.

Several studies have produced satisfactory models and correlations that have been partially successful in predicting the C_f for some polymers, however, they are usually too computationally involving and cumbersome to use. (57)

Mansour et al(58) had studied the effect of diameter for Iraqi and Saudi crude oils, and they concluded that drag reduction increases with increasing pipe diameter. This finding agrees with the works of Berman(59), who found that in a large pipe, where the persistence time of the strain field as higher, DR increased, compared with a smaller pipe size.

Robert et al(43) showed that, the small pipe results indicated lower drag reduction as compared with large pipes.

2.4.4 Applications

The drag reduction effect is extremely interesting from a practical point of view. Liquids are mostly transported through pipes and a drag reduction, by adding a small amount of polymers, can offer large economic advantages and a larger effectiveness of this transportation. The first account of field trials was published by Bord, & Rossi in 1971(60). They were concerned with the use of drag reducing additives in the pipeline transportation of waxy crude, and they found that there are no unexpected side-effects of these additives that would militate against their commercial use.

Also in 1971 Lescarboura et al(61), published the results of a test run with a polymeric drag reducer in a 200 mm diameter crude oil pipeline. The test segment was 45 km long. At the normal flow velocity in the 200 mm pipe of about 2 m/sec, drag reductions of 16, 21 and 25 % were obtained at polymer concentrations of 300, 600 and 1000 ppm. A series of tests were run to determine the effect of flow velocity on drag reduction and this was found to decrease with the velocity. In none of these tests did the polymer appear to degrade or has less effectiveness because of turbulent shear in the pipes.

The most spectacular success in polymer applications for drag reduction has been the use of oil-soluble polymers in the trans-Alaska pipeline system. The use of Conoco chemical Co. (CDR) drag reducer has proved practical as a temporary replacement for unconstructed pumping stations, where as a result the flow rate had been increased by 32,000 m^3/day. The polymer, in this case, was injected downstream of the pumping stations; polymer concentrations were of the order of 10 wppm. (41)

Another commercial application of CDR was in Kirkuk-Turkish Pipeline (ITP1) through 1982-1987. An injection of 15wppm of CDR by nitrogen gas to IT1 pipeline, about $3.7*10^5$ BPD flow increment had been achieved. Through commercial use and field tests, Conoco had identified many practical pipeline situations in which CDR has been an efficient and economical solution to pipeline problems. These are:-

- Pressure Limitations
- Seasonal Demand
- Pump Capacity Limitation
- Changing Crude Viscosity
- Offshore Production
- Emergencies
- Wax Build-up

In addition to a drag reduction, the polymer also causes a reduction in heat transfer, which is advantageous in maintaining low oil viscosity(62). Also, in sewerage pipes and storm-water drains polymers have been used to increase the flow rates so that the peak loads do not result in overflowing; if only relatively infrequent use is required, this can be much cheaper than constructing new pipes(43). Another application is the increase in the range and coherence of water jets from firefighting hoses, but this idea has not been widely exploited.(1)

2.5 Theory

Since the discovery of the drag reduction effect by chemical additives, several theories for the phenomena have been proposed.

The first explanation of polymeric drag reduction was given by Oldroyd(63), who offered a wall effect hypothesis for Toms data(11). Oldroyd proposed the existence of an abnormally mobile laminar sublayer whose thickness was comparable to molecular dimensions and which caused apparent slip at the wall. Toms latter showed that slip at the failed to explain his data(64).

Savins(65) showed that a slip velocity could be calculated from experimental results. He also indicated that the anomalous diameter effects were so noticeable in Dodge's CMC data(66), as well as in those of later investigators and were qualitatively explained by a slip hypothesis. Astarita's analysis(67) had indicated, however that the wall slip effects were not sufficient large to explain the literature.

Dodge(66) measured friction factors in pseudoplastic solutions. His resultant friction factor equation was a generalization of the Nikuaradse's measurements on water as expressed by equation 2-9

$$\sqrt{1/f} = 4.0\log(\mathrm{Re}) - 0.4 \qquad (2\text{-}9)$$

The friction factor of Dodge resultant, can be expressed as follows:-

$$\sqrt{1/f} = \frac{4.0}{(n')^{0.75}}\log\left[\mathrm{Re}'(f)^{1-n/2}\right] - 0.4/(n')^{1.2} \qquad (2\text{-}10)$$

Equation (2-10), is reduced to equation (2-9) when $n'=1.0$

In addition to that, Dodge(66) suggested viscoelastic effects as an explanation of the failure of his CMC data to fit equation (2-10), and most investigators have proffered this hypothesis. (67,68,69,70,65,71))

Shaver measured the velocity profile in drag–reducing fluid(72). Although his correlation predicts larger values of velocity deficiency in a non–Newtonian fluid than in water at any radial position, the conclusion that the profiles are therefore steeper is not warranted. At the same time, it was reported that, the velocity profiles in drag reducing fluids compared with water or some other Newtonian fluid are not available for data. (68,71)

Another conjecture, discussed first by Shaver and Mirrill(24), is that drag reduction may be a result of the non–Newtonian viscosity gradient. Since the shear rate is maximum at the tube wall and zero at the tube center, a turbulent vortex must encounter an increase in viscosity in a pseadoplastic liquid. However, this theory fails to explain the absence of drag reduction in the highly shear thinning Canbopol and Attagel solutions of Dodge(66) or the presence of drag reduction in dilute (and apparently Newtonian) polymer solutions of Toms(37), Hershey(73), and others.

Astarita(67) suggested that turbulence in viscoelastic fluids was less dissipative and offered some order of magnitude calculations to support his proposal. Hershey and Zakin(73) proposed that turbulence suppression begins at a critical Reynolds number which is reached when a characteristic time of the flow is of the same order as the longest relaxation time of the polymer solution. Using relaxation time estimated from a modification of the theory of Zimm(74) and reciprocals of the shear rate at the wall as a measure of the characteristic flow time, they obtained good predictions of the start of turbulence suppression in their experimental pipe flow data. At about the same time Fabula, Lumely, and Taylor(69) offered a similar proposal. Elata et. al.(27,75),had used a similar approach.

Hershey and Zakin(31) suggested that drag reduction in the pipe flow of polymer solutions is shown to be of two types which apparently occur by two separate mechanisms. In turbulent flow, drag reduction is probably caused by viscoelastic effects. The other type of drag reduction occurs when the laminar region is extended to high Reynolds numbers. It is followed by a transition region and a turbulent region in which the drag is not affected.

Gadd(26) reported that weak solution of Polyox and guar gum, shows normal stress differences, although they are not shear–thinning and have viscosity close to that of water.

Another kind of wall effect was proposed by Elperin et.al. (76). They suggested that an adsorbed layer of polymer molecules could exist at the pipe wall during flow and this could lower the viscosity, create a slip, damp turbulence and prevent any initiation of vortices at the wall. However, from later experiments it had become clear that the adsorption of the additives on surface could in fact be an experimental artifact, but it cannot be the reason for drag reducing effect.

The structure of turbulence during drag reduction had been studied to the extent of a few turbulent intensity profiles and kinetic energy spectra. (30,35,77)

Virk et.al. (30) postulated that the onset of drag reduction occurs at a well–defined wall shear stress related to the random coiling effective diameter of the polymer. Also, it has been experimentally found that a so – called maximum drag reduction asymptote exists (Virk et.al. (30). For each Reynolds number a lower bond for the friction factor that can be reached exists, irrespective of the solvent-additive system that is used. The empirical relation for this asymptote, which is also known as "Virk asymptote" is:

$$\frac{2}{\sqrt{f}} = 19.0 \log\left(\frac{1}{2}\mathrm{Re}\sqrt{f}\right) - 32.4 \tag{2-11}$$

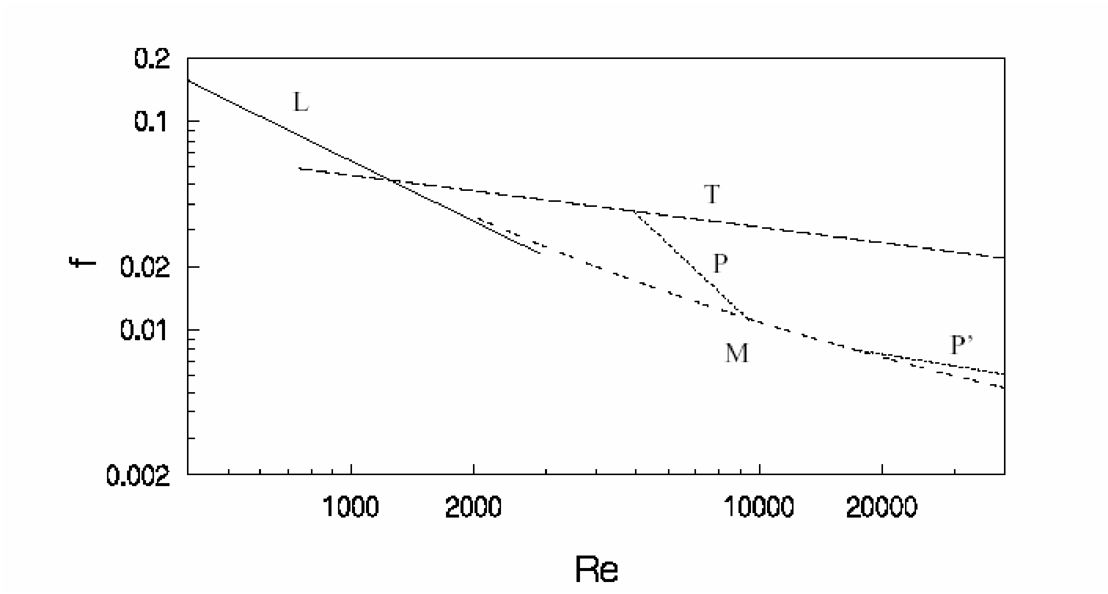


Figure 2-7: The friction factor as a function of the Reynolds number in a pipe flow: possible drag reduction trajectories.

The possible friction behavior of drag reducing polymer solutions in a pipe has been sketched as in figure 2-7. The plot contains, the laminar friction law (L), the turbulent friction law (T), and Virk asymptote (M). The lines denoted by P and P' show the possible behavior of two specific polymer solutions.

When increasing Re, the following trajectories are possible:

L → T →P →M, L → M, L → M → P'.

The exact positions of the lines P and P' depend on parameters already listed in the previous paragraph. Virk and Wagger(55), in (1990), found that the most common trajectories, is L → T → P →M, for an initially coiled conformation. However, when the polymers were extended initially, the trajectories were L → M → P'. It means that in the latter case there is no drag reduction onset number, but the flow becomes drag reduced as soon as it becomes turbulent.

Other studies have used the empirical equation of Virk(30) and Little(78) to describe the variation of drag reduction DR with concentration C where MDR, the maximum drag reduction, and [C], the intrinsic concentration, are empirical constants characteristic of each polymer solvent system and flow field.

$$\frac{DR}{MDR} = \frac{C}{[C] + C} \tag{2-12}$$

In later studies, Lumely⁽⁷⁹⁾, had shown that the shortest dynamically significant length in turbulent flow, at the onset of drag reduction, is of the order of 10^3 times the size of radius of gyration of the polymer molecules. Lumley(79,80) and Landahl(81,82) had proposed a molecular elongation phenomena. Such an extension should result in extremely larger elongational viscosities which may cause a reduction in the turbulent energy production.

Another approach to correlating drag reduction with turbulent bulk flow parameters is the time scale hypothesis. Lumely(79) had calculated that the characteristic time scale of the turbulent flow field, υ/U^{*2} , is of the order of the molecular relaxation time of a monodesperse polymer sample

Berman and Gorge(83) investigated the time scale hypothesis experimentally in regard to the onset of drag reduction. Their results support the contention that the onset of drag reduction is related to a time frame interaction of the turbulence with the polymer molecules. Berman and Gorge indicated that the relaxation times of polydisperse polymer sample should be described by a distribution function rather than a single value. Consequently, by increasing the characteristic time of the turbulence, more of the distribution of relaxation times should be affected, thus increasing the drag reduction.

Chorn(84) used the above approach to increase the level of drag reduction for a given polymer concentration in a 2 – 6 cm pipe by increasing the solvent viscosity and hence the value of υ/U^{*2} for a given Reynolds number.

Ting(85) observed that the onset data for drag reduction shows a qualitative correlation between the parameters describing the polymer and the flow conditions at onset.

Achia et.al. (86) had measured axial and transverse length scales of the near wall region and found them to be significantly increasing with drag reduction.

Various approaches to an explanation of drag reduction have been taken, such as reduced energy(34), modified transient shear response(87), boundary layer thickness(35), and resistance to extensional flow(88). The approaches range from purely hypothetical to essentially rearrangement of turbulent flow data. However non of them have resulted in a method of qualitatively predicting the pressure drop for a given solution from fundamental measurable physical properties of these solutions.

Burger(41) had correlated the drag reduction results in the Trans–Alak Pipeline (TAP). The results were obtained by using the CDR drag – reduction additive. This additive is a polymerized straight – chain α-olefin monomer of one of more pure hydrocarbons above six carbon atoms. It was supplied as a 10 to 11 % by weight solution in a Sadlerochit crude oil, with 27° API gravity. The drag reduction experiments were performed typically at nominal polymer concentrations of 5, 10 and 20 wppm, with different pipe diameters, 1, 2 and 14″. Correlation was based on an extension of a theoretical model of turbulent viscoelastic flow presented by Savin and Syer(89). The functional form of the model requires a knowledge of the wall shear rate, the friction factor, and the additive concentration as independent variables. The characteristic time was found to relate to the drag – reduced shear rate, γ_p, and the additive concentration, φ, in wppm as follows:

$$\Theta_P = a\varphi^b \gamma_p^C \qquad (2\text{-}13)$$

where γ_p: represents shear rate at polymer additive, and calculated as:

$$\gamma_p = \frac{U_p^{*2}}{\upsilon} \qquad (2\text{-}14)$$

and U_p^*: represents the friction or shear velocity and can be obtained as follows:

.

$$U^* = \sqrt{\frac{\tau_w}{\rho}} \qquad (2\text{-}15)$$

The constant a, b, and c were found by linear regression.

Burger(41) found that, the time scale hypothesis was to be adequately correlating the levels of drag reduction, and concluded that, the drag reduction data for specific polymer-solvent systems must be correlated separately due to potential differences in the ineractions of the polymer and solvent.

Morever, Motier and Priluski(90) have extended the Burger work, and through linear regression, have determined the corresponding exponents for determining the characteristic time. The correlation is only partly successful in predicting performance in the various crude oils. They studied the injecting of a polymer solution with relatively high concentration into a pipe flow by means of a suitable injection system. Injected polymer solution does not quickly mix with the mean flow. Heterogeneous flow conditions are maintained over a considerably long distance from the polymer injection station. It is well–known that the injection of polymer solution into a turbulent pipe flow causes a significant drag reduction.

The examination of the drag reduction phenomena in details with on the role of molecular parameters on the onset and flow rate dependence has been investigated. In which, the researcher concluded that the experimental studies of drag reduction using “nearly monodisperse” polystyrene samples and gel penetration chromatography analysis have shown details of the relationship between the molecular weight distribution of the polymer and the experimentally measured drag reduction onset behavior and flow rate dependence.(40)

Robert et. al.(43) improved the ability to predict the behavior of drag reducing polymer additives in industrial applications (Pipelines) and better understanding of the scaling laws for such fluid flows was required. Scaling of Newtonian fluid had been done by increasing the variables friction coefficient C_f to be a function of the flow Reynolds number, Re, rough pipes, the relative wall roughness, ε/d. With dilute solutions of drag reducing polymers, the additional parameters were added to (1) $D/\sqrt{t_{pol}\upsilon}$, as a dimensionless ratio between the pipe diameter d, the solution viscosity ν, and the polymer relaxation time. This variable grouping is regarded as the characteristic time of the polymer solvent pipe system. (2), C, is the concentration of the polymer in the solution, (3), P, defining the state of the polymer species used including the distribution of different molecular weights present and its degree of dissolution. All these parameters gave a functional relationship for the friction coefficient:

$$C_f = f\left[\mathrm{Re}, d\sqrt{t_{pol}\upsilon}, C, P, \varepsilon/D\right] \tag{2-16}$$

This approach has been demonstrated to be unsatisfactory for drag reduction flows.

McComb and Rabie(91) observed a thickening of the elastic sublayer, an enlargement of integral scale of autocorrelation, a decrease of high–frequency energy spectra and an increase of bursting time. The same observations have also been reported for the premixed drag reducing flow. The difference in turbulence structure between polymer injection and premixed drag–reducing system had not been clarified.

Backiyarove and Oliver(44) studied the effect of using low concentration of polymeric drag reducing agents (Polyacrylamide) and concluded that the effects of the drag reducing agents used depend greatly on the method of solution preparation. These low concentrations are provided on additional inside into speculation as the mode of interaction between turbulence in the boundary layer and the molecules themselves.

Ron Darby et. al. (92) used the generalized friction factor for drag reducing polymer solutions of three different concentrations both freshly prepared and shear degraded, in a wide range of tube size, then to be reduced to the usual friction factor vs solvent Reynolds number correlation for Newtonian fluids in smooth tubes. They suggested that, the viscous and elastic (time constant) parameter of the solutions which are required for the generalized correlation can be obtained directly from a knowledge of the apparent viscosity function of the solution.

Horn et al(45) investigated the validity of using F10TM polymer in high viscous fluid (crude oil), as a drag-reducer. Their experiments were performed with a 2″ pipe in the 200 ft long circulating loop system. The results showed that, at a Reynolds number of 2370, just into the transition region, a 1 % drag reduction was observed. As the Reynolds number increased above 2960, the percent drag reduction increased to 25 %. They concluded that drag reduction is possible in fluids of high viscosity. Also, high Reynolds number is not a requirement for effective drag reduction, which can occur in flow systems that are in fact only partly turbulent.

Usui, et. al. (93) studied the injection of concentrated polymer solutions. Measurements were made for the radial distribution of fluctuating velocities by means of video image analyser. It was suggested that, the wall turbulence structure might be controlled by suppressing the large scale turbulent motion in the turbulent core region.

The turbulent intensities and Reynolds stresses were measured in a mixing layer and pipe flow by Laser Doppler Anemometer (LDA). The results showed that polymer additives do not simply suppress the turbulent fluctuation as was expected. The turbulent structures were changed rather than suppressed. (4)

A simple and accurate correlation, DR, vs U_b was proposed, and it proved to be successful in correlating the diameter effect problem for some polymer and surfactant solutions. (57)

The study of Sreenivaanf and White(94), criticized the scenario that the drag reduction comes from the elongational viscosity which is increased greatly by "coil stretch" transition under the time criterion. The investigators used the elongational viscosity by arguing the "coil stretch" which does not occur in turbulent flow. In the mean time, Tabor and de Genne(95), thought that the elastic energy stored in polymer molecules causes drag reduction (elastic theory). That is, the polymer molecules absorb the small scale turbulence energy by prohibiting the turbulent cascade, which results in drag reduction.

Following that, the kinetic and elastic energy transport equations were derived, in order to investigate the effect of elasticity on drag reduction. It was shown that the polymer stores the elastic energy from the flow in the sublayer and then releases it again in the sublayer when the relaxation time is short (no drag reduction). However, when the relaxation time is long enough (drag reduction), the elastic energy is transported to and released in the buffer layer. Therefore the drag reduction occurs when the turbulent velocity scale is larger than the characteristic velocity scale of the polymer solution. (96)

After that, L'vov et. al.(97) proposed that the polymer stretching gives rise to a self–consistent effective viscosity that increases with the distance from the wall. Such a profile reduces the Reynolds stress (i.e. the momentum flux to the wall) more than it increases the viscous drag; the result is drag reduction. Since polymers tend to stretch in a turbulent flow, thus increasing the bulk viscosity, it appears contradictory that they should reduce the drag.

Javanovic et. al.(50) had shown a conceptual scenario of the mechanism of polymer drag reduction depending on the interaction between a polymer and turbulence which is essentially at the molecular level of the former. This interaction involves modification of the molecular structure of a polymer by turbulent motions in the near–wall region. Figure 2-8 shows a scenario where, under very special circumstances, turbulence in the near–wall region forces rolled–up chains of a polymer partially to unroll and stretch in the mean flow direction.

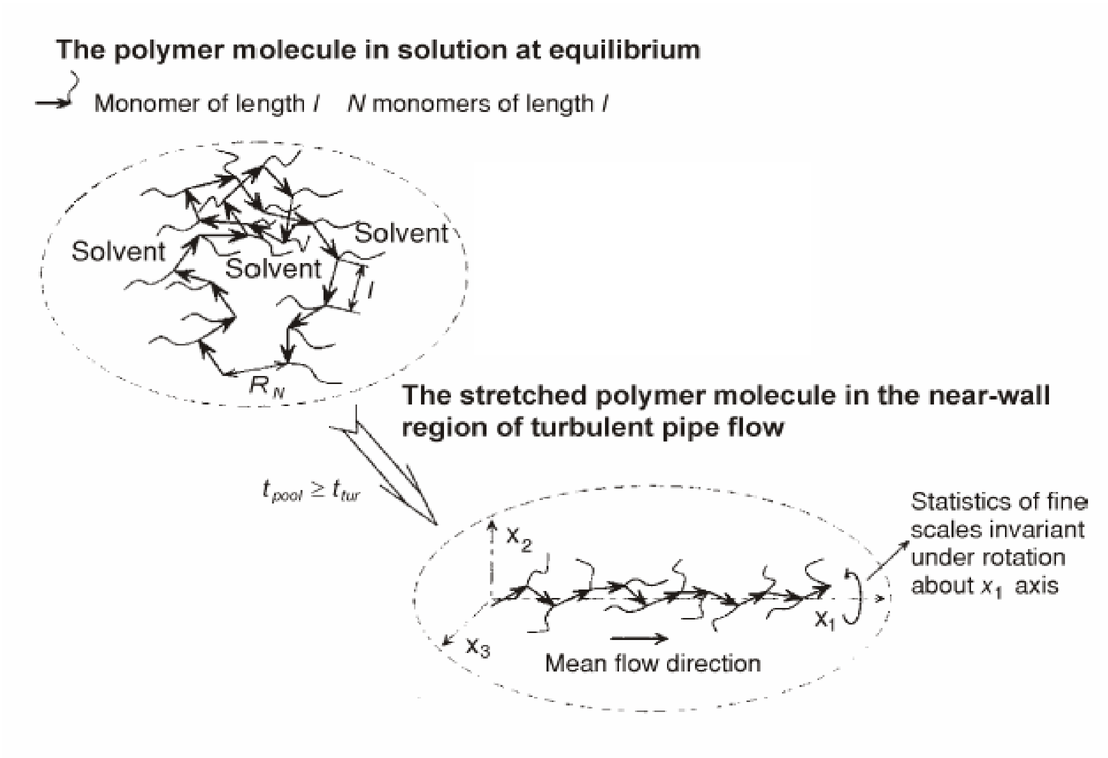


Figure 2-8: Behavior of a polymer in solution at equilibrium (top) and its response to stretching by turbulent motions at small scales very close to the wall (bottom). Here R_H and R_F are hydro dynamical and Flory radius, respectively.

$$R_F = N^{3/5}\, l$$

$$(t_{Zimm})_{pol} = \frac{\eta_s R_F^3}{k_B T} \qquad (2\text{-}17)$$

η_s – the solvent viscosity
k_B – Bolzmann constant
T – absolute temperature

In the unrolled state, polymer chain dictate characteristic length scales associated with the fine structure of turbulence. These scales are elongated in the stream wise direction and are therefore strongly anisotropic. In the most extreme case, polymer chains from a filament structure with a length – scale arrangement which is almost ax symmetric around the axis aligned with the mean flow. Hence it is reasonable to assume that the chief mechanism of DR is related to the ability of the activated polymer to re – structure turbulence at small scales by forcing them to satisfy constraints imposed by local ax symmetry.

Recently, an experimental investigation of drag reduction using the rod-like polymer scleroglucan was completed. Drag reduction of approximately 10-15% were obtained. Increasing the additive concentration did not increase the drag reduction and shifted the spatial drag reduction profile downstream. Decreasing the velocity, or decreasing the Peclet number, reduced the drag reduction effectiveness. (98)

Closing this brief review, it is conducted that the explaining theories for drag reduction may be divided into three major categories. In the first place, an explanation in which the increase in extensional viscosity for the polymer solution is the main ingredient. Second, a theory that stresses the importance of anisotropic effect is introduced by the extended polymer molecules. And finally, a proposed explanation in which elastic effects is responsible for drag reduction.

2.6 Polymer Degradation

Degradation hampers the practical usage of polymers for turbulent drag reduction application. Degradation is a deleterious process, to degrade a substance is to impair it in respect to some physical property or to reduce its complexity, in which the activation energy of polymer chain scission is exceeded by the mechanical action on the polymer chain, thus bond rupture occurs. In turbulent flow, molecules undergo scission when fully extended; decreasing the polymer chains molecular weight. As previously described, the molecular weight of a polymer is a large factor in determining its drag reduction efficiency. Scission of molecules therefore decreases their ability to reduce the wall shear stress. Gadd(26) was one of the first researchers, who investigated the phenomenon of polymer degradation by using solutions of polyethylene oxide. The grade used was Union Carbide 'Polyx WSR301', with a molecular weight of about $4*10^6$, in addition to guar gum solution with a concentration not more than 60 ppm. He supposed that the turbulence mechanically breaks up the long 'Polyx' molecules so that they lose their effectiveness. Another possibility is that the mechanical action renders the molecules susceptibility to oxidation. On the other hand, with guar gum solution, little or no mechanical degradation seem to occur. Paterson(99) had also reported the degradation phenomenon. Referring again to figure 2-9, it is apparent that as the value of Reynolds number increases, the polymer solutions reach a maximum drag reduction efficiency then begin to approach the Prandtl-Karman line, which represents the flow of pure solvent

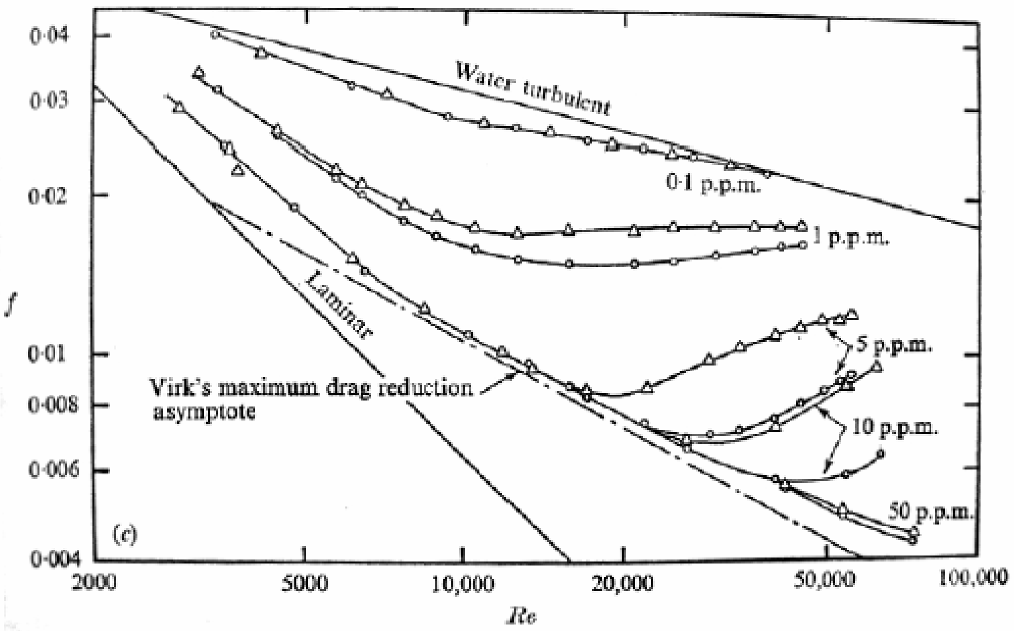


Figure 2-9: Friction factor plot for drag reduction and degradation of PEO MW=$5*10^6$ g/mol, in a 6.29 mm ID pipe.

Many mechanical shear degradation experiments have been performed under turbulent flow conditions. Zakin and Hunston(38) monitored DR efficiency in a capillary tube, which is very sensitive to changes in polymer molecular weight at extremely low concentrations. On the other hand, Culter et al. (100) pointed out that much of degradation in turbulent flows through capillary tubes occurs at the entrance. To reduce the entrance effect, Horn and Merrill(101) installed a conical funnel at the entrance of the tube from the feed solution reservoir.

Using gel permission chromatography, Merill et al(101) were able to establish that molecules under scission high probability in the middle of the chain. $9*10^5$ MW polystyrene in chloroform was used to measure the MW distribution of the polymer before and after the molecules were subjected to extensional flow(101). In figure 2-10, two peaks of molecular weights are indicated, one at $9*10^5$ g/mol and one at half the molecular weight, $4.5*10^5$ g/mol.

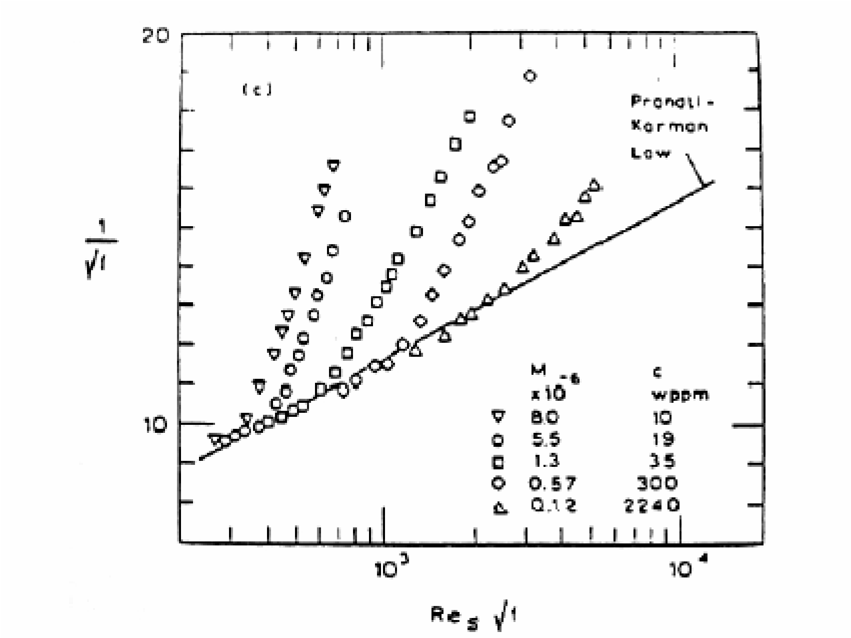


Figure 2-10: Effect of molecular weight on drag reduction pipe ID 8.46 and 9.45 mm, PEO

The mechanical degradation of high molecular weight polymers such as PEO and PIB under turbulent flow was investigated by various conditions of temperature, polymer concentration, and fluid flow rate. Since the long chain polymer experiences midpoint degradation, the polymer chains have different time dependent resistance. In other words, longer molecules are more susceptible to mechanical degradation, accompanying more rapid degradation. (5)

Several correlations between *DR* efficiency and mechanical degradation were published(102,103,104). Brostow and his coworkers have developed a model from a statistical mechanical approach(103) and have investigated the validity of their model based on computer simulations. The drag reduction *DR* efficiency and mechanical degradation were related to macromolecular conformation in solution. The DR efficiency is proportional to the molecular weight of the polymers. The drag reduction DR efficiency ratio was expressed as:

$$DR(t)/DR(0) = M(t)/M_0 \qquad (2\text{-}18)$$

Where

DR (t); percent drag reduction at time t

DR_0; percent drag reduction at time 0

M (t); effective number-average molecular mass at time t

M_0 ; effective number-average molecular mass at time 0

More mechanical degradation was observed in a poor solvent than in a good solvent under the same flow conditions(102). A limiting molecular weight M_∞ can be defined by $M_\infty \equiv \lim_{t\to\infty} M(t)$. M_∞ becomes smaller in the poor solvent than in good solvents for a given polymer. Brostow et al. (102,103) noted that the points on the chain where change of direction occurs are more vulnerable to chain scission. Depending on their specific location, some of them might be protected from degradation by their surroundings, while others will undergo scission during flow. The average number of points per chain of the latter kind are denoted by W, and

$$M_\infty = \frac{M_0}{1+W} \tag{2-19}$$

Here, *W* is proportional to the number of breakable sequences having two different orientations and changing extended-to-compact or compact-to-extended conformations. For a polymeric drag reducing agent, *W* can also be related to the drag reducer concentration C, the energy $U_d(t)$ originating from turbulence intensity that produces degradation, and the energy *E* necessary to break one bond. (103)

$$W = \frac{M_0 U_{d(\infty)}}{C N_A E} \tag{2-20}$$

Where N_A is Avogadro's number.

By introducing the single exponential model (with *h* as the decay constant), the following relationship could be obtained: (103)

$$DR(t)/DR(0) = 1/(1 + W(1 - e^{-ht})) \tag{2-21}$$

A large value of *h* indicates fast degradation, and a large value of W implies a low shear-stability. Kim(47) adopted the theoretical model for molecular degradation proposed by Brostow et al.(103) to their experimental data and obtained an excellent fit by using equation 2-21, for monodesperse polystyrene polymer.

A single-relaxation decay model was adopted to explain a time-dependent relative drag reduction efficiency which is related to mechanical degradation as given in equation 2-22. The empirical equation associated with a slow relaxation time of the polymer solution. (105,106)

$$DR(t)/DR(0)=\exp(-t/\lambda_s) \tag{2-22}$$

The $1/\lambda_s$ quantifies the loss rate of drag reduction activity on the rate of degradation. Despite the successful applicability for this single exponential especially in describing short time degradation behavior, it is not difficult to conjecture the inadequacy of this model. Recently Choi,(49) has investigated the drag reduction efficiency by dilute aqueous solutions of polyethylene oxide with two molecular weights in a rotating disk system (RDS) and found that equation 2-22 does not fit the experimental data relatively well. Therefore, to improve the fitting, a fractional exponential form, often called the Kohlrausch, William, and Watt (KWW) function, has been modified from the single exponential decay function as shown in Eq. 2-23. This equation has been used to describe the second order nonlinear relaxation behavior.

$$DR(t)/DR(0)=\exp(-t/\lambda_F)^{1-n} \tag{2-23}$$

λ_F, is an observed time scale of the relaxation process and n is a functional exponent . The degree of non-exponentially considers the breadth of the distribution of relaxation time. Choi, (49) applied equation 2-23 and had shown that the relative drag reduction effectiveness was fitted better with equation (2-23) than equation (2-22).

2.7 Factors affecting the Degradation

2.7.1 Solvent Type

The type of solvent used to dissolve the polymer is important in degradation kinetics. The degree of mechanical degradation has been reported to be higher in poor solvents than those in good solvents. (107)

In a good solvent, the polymer chain prefers interactions with the solvent to those with other polymer molecules, thus it extends in solution to maximum solvent polymer interaction. In poor solvents, the polymer chain coils upon itself to minimize solvent-polymer interaction. Since polymers remain more tightly coiled in poor solvents, the subsequence degradation under shear stress is lower than that for polymers in good solvents.

Kim, et al. (47) demonstrated the above phenomenon by examining the degradation of polystyrene dissolved in benzene, chloroform and toluene, with benzene being the best solvent and toluene being the worst. Figure 2-11, shows that polymeric degradation which is much smaller for benzene than for toluene, as indicated by molecular weight measurements. Both chloroform and toluene show intermediate degradation.

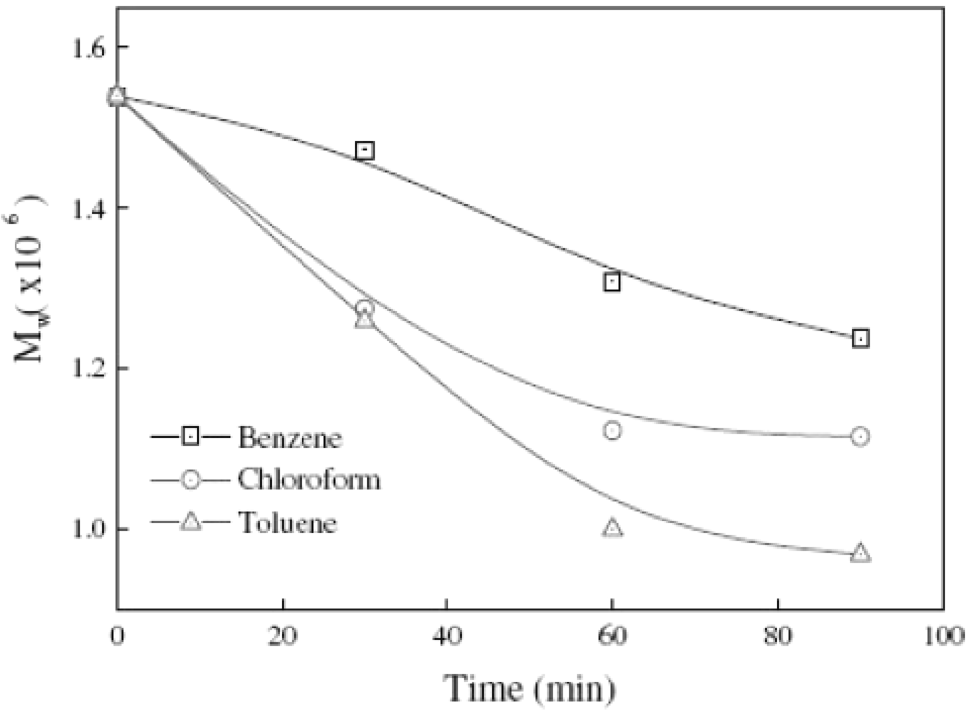


Figure 2-11: Change in molecular weight of polystyrene dissolved in various solvents undergoing shear stress as a function of time(47)

2.7.2 Type of Pump

Polymers are continuously subjected to deformation, especially in the pump, which cause the scission of the polymers and this might dramatically occurs when the re-circulation system was used experimental set-up.

If a centrifugal pump is used, the higher molecular weight polymer will be degraded rapidly due to its exposure to high mechanical shear. Whereas using the rotary pumps, especially the type of external gear pump, reduces the polymer degradation. In the external gear pump, figure 2-12, intermeshing gears rotate with close clearance inside the casing. Liquid interring the section line is caught in the spaces between the teeth and the casing and is carried around to the top of casing and forced out through the discharge. Thus, the effectiveness of high molecular weight polymer as a drag reducer lasts for a longer time. On the other hand, the concentrated additive was injected with gear pumps to minimize mechanical degradation. (4)

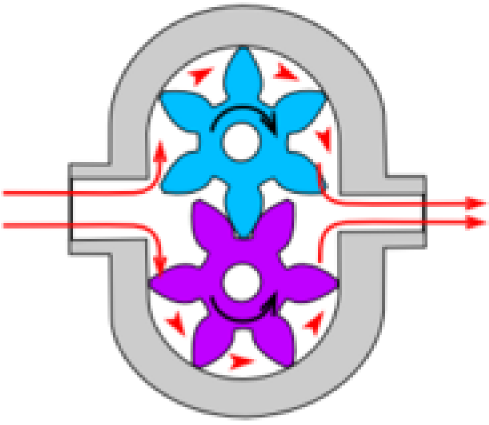


Figure 2-12: Gear pump.

2.7.3 Mechanical Configuration

Pipes configuration varies from straight line to inclined line and/or right angle and others. The best shape to reduce the degradation of high molecular weight polymer is the straight line shape. Therefore the pipeline operating system prefers this shape through the pipelining, unless the geography of the area obliges them to use other shapes. Figure 2-13 illustrates the effectiveness of mechanical configuration on drag reduction. (42)

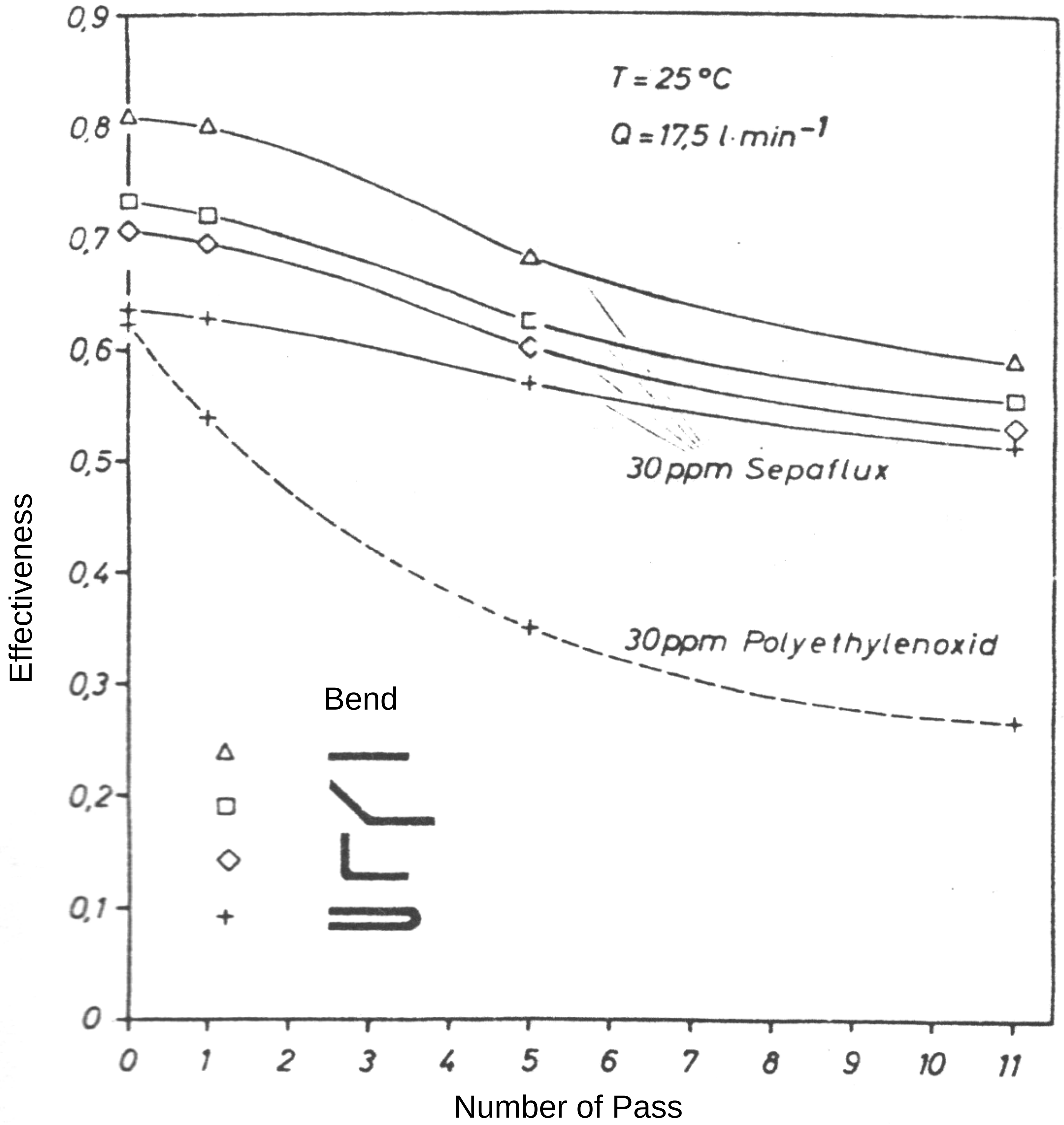


Figure 2-13: Effect of mechanical configuration on polymer effectiveness.

2.7.4 Thermal and Radiation

The effect of the thermal degradation on turbulent drag reduction efficiency was studied, for water soluble polyethylene oxide (PEO) with two different molecular weights. It was found that the susceptibility of PEO to degradation increases dramatically with increasing temperature. Figure 2-14 shows the effect of temperature on percent drag reduction,(%DR) examined with 50 ppm PEO at three different temperatures (25ºC, 40ºC, 60ºC). The initial drag reduction efficiency value was 29.39% at 25ºC, 26.7% at 40ºC and 25.3% 60ºC, respectively. (49)

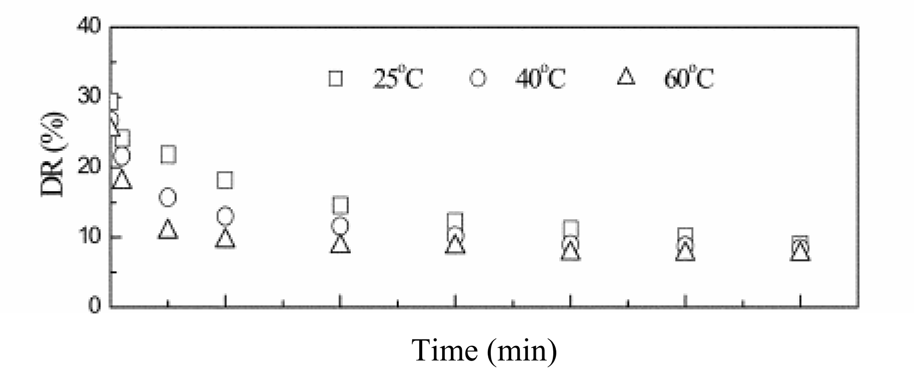


Figure 2-14: Effect of temperature on % DR.

The same effect had been obtained by Kim(48) in his experimental investigation for PEO (344) at different temperatures, and was found that the %DR of the PEO solution decreases with temperature increase.

Radiation had been demonstrated through an experiment. Samples of guar gum solution left for three days, out of strong light, gave the same results as samples tested with 1hr of mixing, but a sample which had been exposed to sunlight over a period of 3 days showed considerable degradation. Evidently, the sun light has some action on the guar gum molecules, either a direct photochemical one, or by promoting bacterial action. (26)

2.7.5 Aging

All materials are subjected to aging, process of long-term degradation, but not at the same rate or affected on the same manner. The wide variation in susceptibility (or resistance) of polymers to degradation by aging, depends on their chemical composition and structure.

Many investigators have studied this field, but recently Javanovic et al. (50) prepared a solution of 10 wppm of a FORTUM polymer, mixed with

Diesel oil. As shown in figure 2-15, drag reduction decreased fast within the first 2 hours. With an additional of 10 wppm polymer a maximum drag reduction percent, (%DR) of 70 % could be observed. The effect had completely vanished after continuous operation for 7.5% hour. The highest value of percent drag reduction, (%DR) with a 5 wppm polymer concentration was around 50%. For this concentration of polymer, the effect had disappeared 4 hour after the beginning of the measurement.

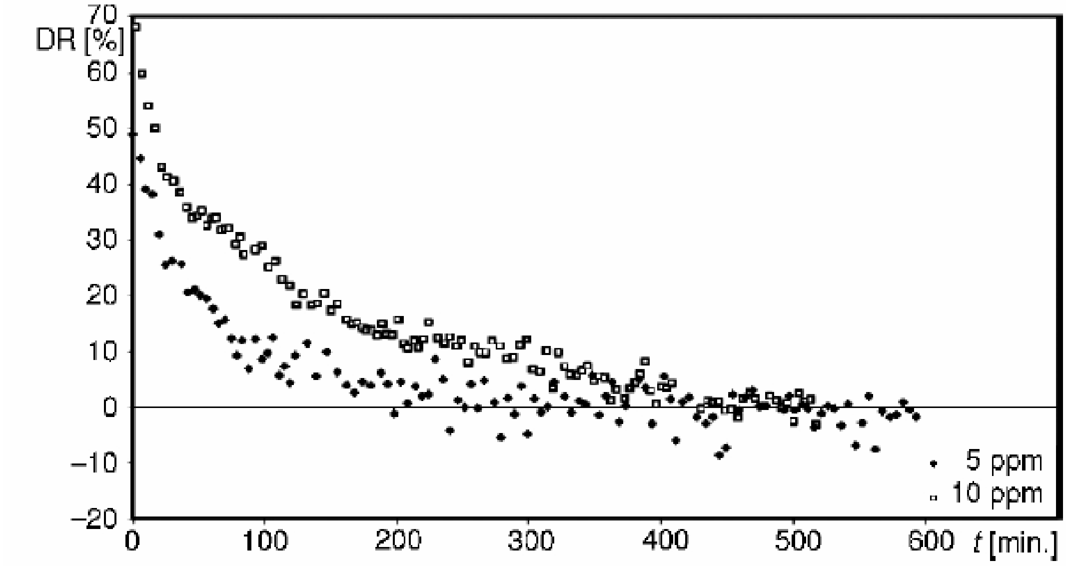


Figure 2-15: DR for different concentration of FORTUM polymer.

CHAPTER THREE
EXPERIMENTAL WORK

3.1 Materials

Light gas-oil and kerosene obtained from AL-Dura Refinery had been used in this work as pipelining liquids. Their general characteristics obtained from AL-Dura Refinery, are listed in table 3-1.

Table 3-1: Properties of gas oil & kerosene

Properties	Gas-oil	Kerosene
Sp. Gr. at 25ºC	0.811	0.776
API-gravity	43	50.8
Flash point, ºC	60	41
Viscosity at 25ºC (cst)	3.13	1.41
Color	+30	0.5
Initial boiling pt. ºC	158	150
End pt. ºC	364	260

Polyisobutylene (PIB) types Oppanol B150, 200 and 250 were acquired from BASF Company, Germany, to be used as drag-reducing additives in this work. These polymers covered three different molecular weights of $2.5*10^6$, $4.1*10^6$ and $5.9*10^6$ g/mole. Their properties are listed in Table 3-2.

Table 3-2: Oppanol B types Properties

Properties		Oppanol B type		
		150	200	250
Consistency		Rubber like	Rubber like	Rubber like
Viscosity of solutions in isoocatan at 20 ^{o}C	Conc. g/cm^3	0.001	0.001	0.001
	Staudinger Index (Jo)	416-479	551-661	> 770
Volatile matter (105 ^{o}C, to h) wt %		0.01	0.01	0.005
Glass Temperature (^{o}C)		-61	-61	-
Weight average Mw (GPC)		2,500,000	4,100,00	> 5,900,00
Viscosity average (Mv(1))		2,600,000	4,000,00	> 5,900,00
Stabilizer content (ppm)		250-500	250-500	250-500
Ash content (ppm)		<100	<100	<100
Area of application		Sealants, adhesives, anti-misting	Drag reduction oil spills	Drag reduction oil spills

3.2 Preparation of polymeric solutions

Reformate, supplied from AL- Dura Refinery, was used to dissolve the three Oppanol B polymer types. This solvent has high ability of dissolving high molecular weight PIB in comparison with other locally available petroleum products. Its general characteristics are, about 58ºAPI gravity at 25ºC, Initial boiling point 40ºC, End point about 186ºC and an octane number of 91 by research method.

The method of solution preparation adapted in this study was to make 2% by weight concentration in a separate container. Thus, 10 gram of corresponding Oppanol type was placed in a one liter conical flask and mixed with 650 ml of reformate under laboratory temperature. The container was placed in an electrical shaker, at 100 rpm. The shaker was used instead of stirring device to avoid polymer molecular degradation; hence the shaker has no sharp edge that could expose the polymers to high shear force. The shaker was started at 40 rpm and increased by 10 rpm after every 24 hours. A homogenous solution was obtained, after 2 days for Oppanol B 150, 3 days for 200 and 5 days for 250 types. The solution was allowed to stand at least 24 hours at room temperature prior to its use as drag reducer, in a re-circulation closed loop system.

3.3 Circulation Closed Loop System

3.3.1 Determination of the entrance length

The boundary layer forms in the inlet of the pipe and grows in thickness until it fills the flow area, or until it extends to the center of the pipe. The velocity profile will not change downstream beyond this point, and the flow is said to be fully developed. A considerable distance is required for the velocity profile to develop from the fairly uniform velocity distribution at the pipe entrance. This region where the velocity profile is developing is known as the entrance length, which depends on the pipe diameter.

The following different relationships are suggested to calculate the minimum entrance length for turbulent flow:

Cebci (108)

$$le = \frac{(\mathrm{Re})(d)}{20} \tag{3-1}$$

Brodkey (109)

$$le = 0.693(\mathrm{Re})^{0.25}(d) \tag{3-2}$$

Desissler (110)

$$le = 50(d) \tag{3-3}$$

Therefore the entrance length for the present work, based on Eq.(3-3), according to the pipe diameter is given in table (3-3).

Table 3-3: Entrance length for the used pipes

	D (m)	$le(m)$
1	0.019	0.95
2	0.0254	1.27
3	0.03175	1.5875
4	0.0508	2.54

The design of the experimental set up was carried out by using pipe diameters, 0.019, 0.0254, 0.3175 and 0.0508 m.

3.3.2 Design and Constitution

A closed circulation loop system was designed to ensure studying the effects of some important factors in polymer effectiveness towards drag-reduction, such as polymer concentration, pipe diameter, test section, flow rate as well as the pipe configuration.

In designing the re-circulatory pipe flow system, the following considerations were taken into account:-

- The availability of tools and necessary instruments such as pump, pipes and measuring devices.
- Avoiding the use measuring devices that cause a high mechanical shear in the flow
- The availability to obtain a high flow rate in the circulation loop (Re>4000)
- Taking into consideration that the closed loop system can be easily operated with accurate control on the parts of rig.

The circulation loop system as shown in figure (3-1) constitutes the following major parts, which were supplied from local marketing.

1- Reservoir (item No.1): Considered as a feed tank of the solvent for the whole loop, with the dimensions (100*70*70cm) and capacity of 0.49 m^3. The reservoir is made of galvanized metal. Its temperature is controlled by a thermometer.
2- External gear pump (item No.2): The gear pump type has the specifications, 50.8 mm diameter, rating speed 1440rpm, total head 6m and motor:3 phase, 11.6A, 5.5kw. This type of pump was used to avoid polymer mechanical degradation and thus reduces the drag-reducing capability.
3- By-pass (item No.3): A by-pass tube of about 2m length and 50.8 mm diameter was installed to control and adjust the desired flow rate.

4- Float flow meter (item No.4): of a diameter 50.8mm and flow indication range (0.6-6m^3/hr).

5- Pipes: Four seamless carbon steel pipes of various inside diameters (50.8, 31.75, 25.4 and 19.05mm) were used to perform the flow measurements.

6- Test Section (item No.5): Three pressure tappings on each pipe (1.5 mm ID) are located in the downstream and upstream of the test section. The test Sections are 2 and 3m long and they were placed away from the entrance according to the pipe diameter as shown in table (3-2). The reason to do this is to restrict the measurement in the fully developed region. No bent or joint or gauge pressure or any connection exists in the test section to minimize the stresses outside the sections.

7- Recycling Pipe (item No.9): To return the liquids to reservoir.

8- Accessories:

I. U-tube manometers and an inverted manometer (item No.6): To measure the pressure drop between two points. It consists of glass tube of (8mm diameter). The U-tube manometers filled of mercury are used for moderate flow rate, and the inverted one is used for high flow rates.

II. Ball type valves (item No.7): Can be opened and closed in one quarter of a turn only, in order to control the flow in the pipes.

III. Gauge pressure (item No.8): Two gauge pressures were installed before and after the test sections.

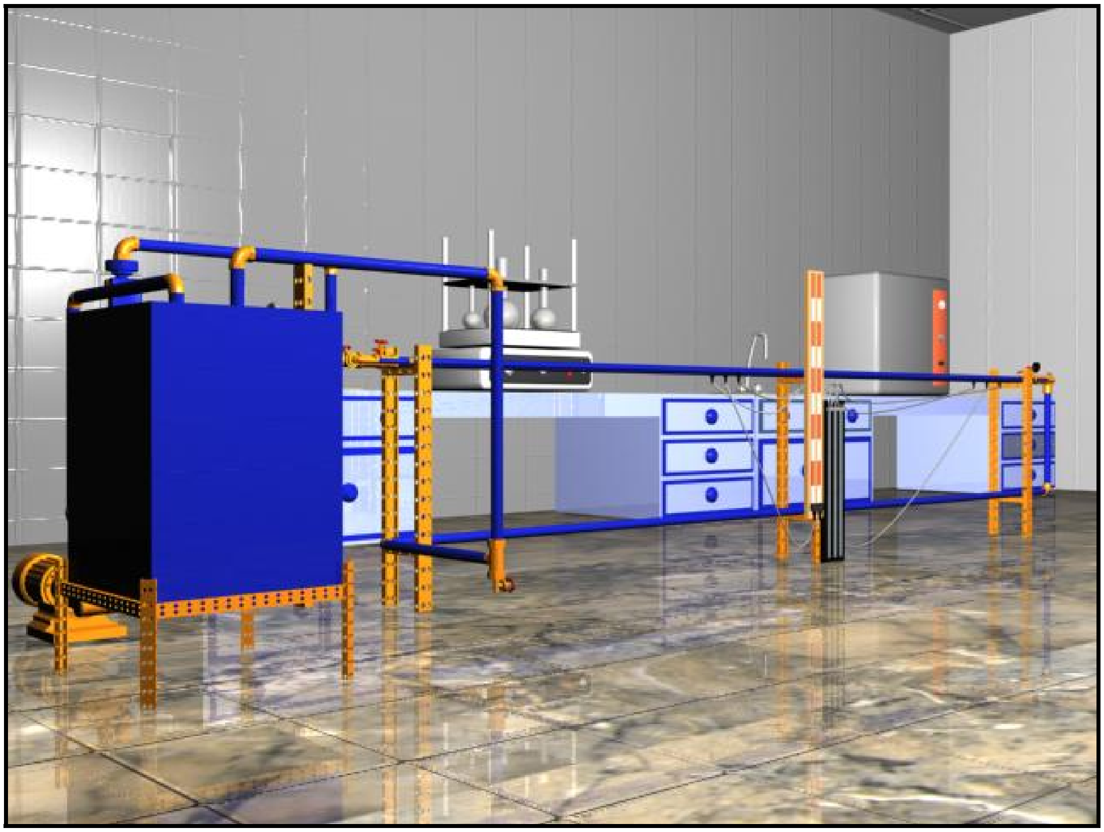


Figure 3-2: Experimental rig showing closed loop circulation system

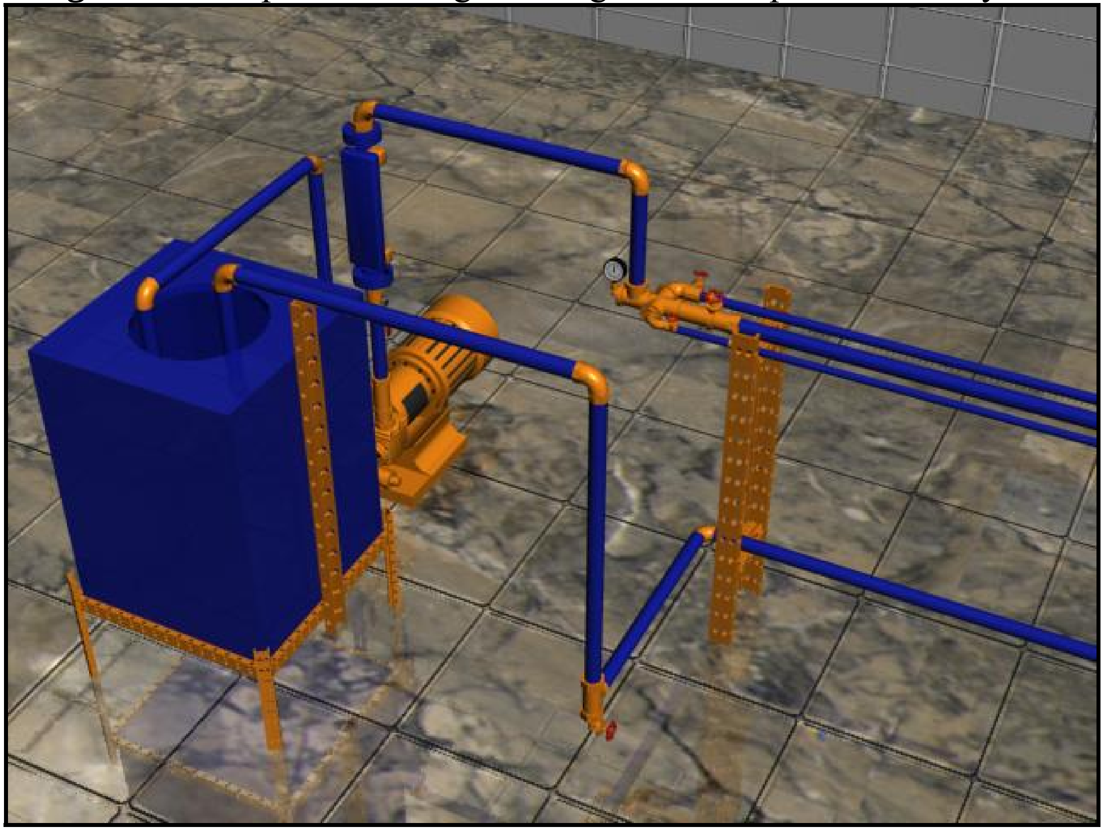


Figure 3-4: Experimental rig showing storage tank and piping system

3.3.3 Construction

At the beginning of constructing the piping the system reservoir was raised above the ground by 35cm for drainage purposes, and then connected to a gear pump, which was connected to a flow meter and a by-pass line. The pipes were connected after being arranged into equal length sections. After that, all the parts were connected to each other by suitable joints.

The installation of the system was based upon dividing it into parts connected by joints in order to treat any leak that might occur at the beginning of the operating procedure without having to disassemble the all parts of the system.

Three U-tube manometers were fixed and connected to the pressure tapings fitted in the pipes by using a 5mm rubber tubes. The fitting of pressure tapings in the pipes needed accuracy and careful handling. Furthermore, the following points were taken into consideration.

- Pressure tapings were made of brass with dimensions of 1.5mm ID, 6mm OD and 20mm length.
- Pressure tapings were fitted to the pipes with a depth exactly equal to the thickness of the pipe, in order to avoid mechanical shear that might occur in the solvent flow.

After connecting and assembling all parts, the re-circulatory pipe flow was cleaned by circulating gas-oil for 2 hours. Some leaks were noticed due to high pressure at high flow rates especially in small pipes and were treated by tightening the joints for several times until the leak was completely eliminated.

3.3.4 Flow Meter Calibration

A 50 liter capacity tank was used to calibrate the float flow meter. The tank was filled with gas-oil and the time of filling was recorded by stopwatch. The results of calibration are shown in figure (3-4)

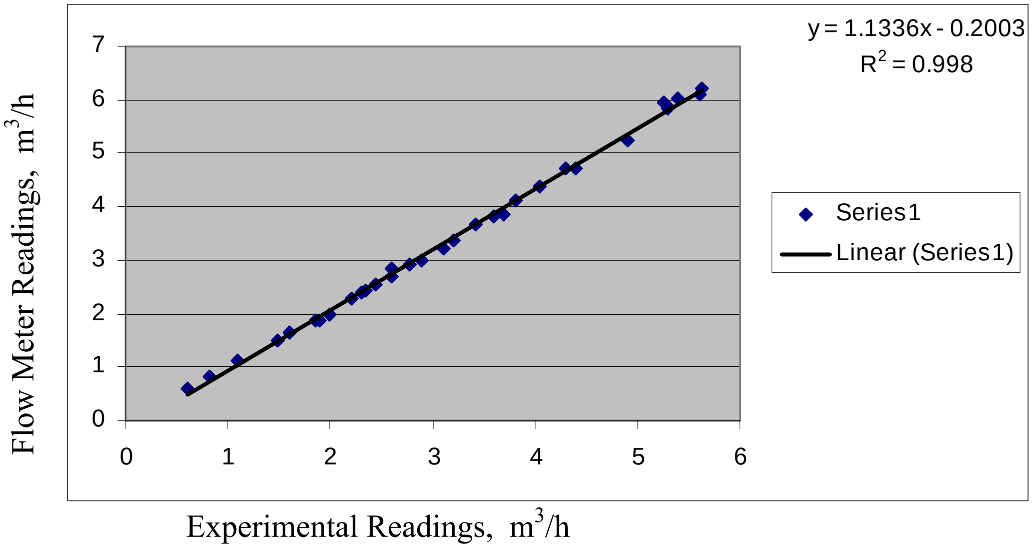


Figure 3-5: Flow meter calibration.

As shown in figure (3-4) the measured and actual data are identical. Therefore the measurements were taken directly from flow meter.

3.4 Experimental Procedure

The following steps were performed in each experiment.

1- The reservoir was filled with 125-140 liter of corresponding fluid gas-oil or kerosene.

2- In order to guarantee a homogeneous mixture it was decided to prepare it outside the installation. The required amount of concentrated oppanol B solution was mixed with 900ml solvent, gas-oil or kerosene. This mixture was stirred slowly by a shaker for 24 hours prior to use. Since the polymer is sensitive to mechanical straining, all these steps were performed very carefully and slowly.

3- To avoid any error in manometers readings, bubbles were allowed to flow away by controlling the pressure tapings

4- The prepared solution of polymer mentioned in step 2 was added to the reservoir accurately.

5- The external gear pump had been operated after ensuring that the fluid is allowed to flow through only one of the four pipes by closing the other valves.

6- After 15-20 minutes circulation, the reading of the manometers was recorded.

7- Flow rate was controlled and changed in the test section by controlling valves 1 and 2.

8- Steps (2-7) were repeated upon any change in concentration, flow rate, molecular weight and pipe diameter.

9- For degradation experiments purposes, steps (2-7) were repeated and manometers reading was taken every 15-20 minutes until the effectiveness of polymeric additive became noticeable

3.5 Experimental Calculations

3.5.1 Velocity and Reynolds number Calculations

The average velocity and flow rate of the fluid flow were measured as follows:

The flow rate was read directly from the float flow meter in (m^3/hr), and the volumetric average velocity for each pipe was calculated by dividing the volumetric flow rate by the flow area(A):-

$$u = \frac{Q}{A} = \frac{Q}{\frac{\pi}{4} D^2 3600} \tag{3-4}$$

Where: u in m/sec, Q in m^3/hr and D in m

The Reynolds number was calculated by using equation 2-1 with kinematic viscosity of flowing liquid, for each run as follows

$$\mathrm{Re} = \frac{uD}{\upsilon} \tag{2-1}$$

Where ν is in m^2/sec and $\upsilon = \frac{\mu}{\rho}$ (3-5)

3.5.2 Frictional pressure drop

The loss of head in mmHg (Δh) was measured by U-tube manometer. (Δh) represent the drop between the upstream and downstream points in the test section and it was converted to Pascal unit ($\Delta h_{\text{readed}} \times 1.01325 \times 10^5$Pa/760mmHg). The frictional pressure drop can be found as follows:-

$$f = \frac{\Delta h * 133.3}{2} \frac{1}{\rho u^2} \frac{D}{L} \tag{3-6}$$

Where *f*; fanning friction factor= 4×skin friction factor

3.5.3 Percentage drag-reduction calculations

The effectiveness of a drag-reducer is expressed in terms of percent drag-reduction. At a given flow rate, the percent drag-reduction is calculated from the following equation:-

$$\%DR = \frac{(\Delta p)_{untreated} - (\Delta p)_{treated}}{(\Delta p)_{untreated}} \times 100 \qquad (3\text{-}7)$$

$(\Delta p)_{\text{untreated}}$=frictional pressure drop in the pipe without a polymer.

$(\Delta \text{p})_{\text{treated}}$=frictional pressure drop in the pipe when the polymer is added to the fluid.

3.5.4 Percent Throughput Increase

The relationship between percent drag-reduction and percent throughput increase (%*FI*) can be estimated using the following equation :- (63)

$$\%FI = \left\{ \frac{1}{\left(1 - \frac{\%DR}{100}\right)^{0.55}} - 1 \right\} \times 100 \qquad (3\text{-}8)$$

Where %*DR* is obtained from equation (3-7). The throughput increase equation (3-8) gives the amount of flow increase which is available in a given pipeline if all of the drag-reduction is converted to flow increase.

CHAPTER FOUR
RESULTS AND DISSCUSION

Part One

4.1 Laboratory Screening Apparatus

A laboratory circulation closed loop system was designed and constructed to investigate the effectiveness of various drag-reducing additives in petroleum fractions under turbulent pipe flow. Since turbulent flow is necessary for drag reduction to occur, the system was designed for high Reynolds numbers. The turbulent flow was produced by positive displacement Gear-pump to avoid mechanical degradation of the high molecular weight polymers. The gear pump was chosen to pump such flammable hydrocarbons.

The flow system consists of four pipes of different diameters, 19.05, 25.4, 31.75 and 50.80 mm, to investigate the effect of diameter in addition to flow rate on drag-reduction effectiveness. Since, the Reynolds number and velocity of flowing liquids depend on pipe diameters, it was possible to vary the flow rates, from 2.8 to 6.0m^3/hr, hence different values of Reynolds number and velocities were obtained, as shown in table 4-1. The maximum achieved Reynolds numbers are 11568, 18509, 23137 and 30849 for pipes of inside diameters 50.8, 31.75, 25.4 and 19.05mm respectively under the experimental conditions, as discussed in part 4.2.3.

Table 4-1: Ranges of Reynolds number and velocity at minimum and maximum flow rates

I.D pipe (mm)	Min Re	Max Re	Min u (m/s)	Max u (m/s)
19.05	14396.076	30,849	2.7302091	5.8504481
25.4	10797.057	23,137	1.5357426	3.2908771
31.75	8637.6455	18,509	0.9828753	2.1061613
50.8	6555.356	11,568	0.4662076	0.8227193

Two test sections of 2 and 3m were performed on each pipe to investigate the performance of additives. A mechanical diagram of the flow loop is shown in figure 3-1.

Experiments of effectiveness of drag-reducing agents were carried out in circulating manner during 10 minute to minimize the mechanical degradation of polymer additives. Prior to the test, the concentrated polymer solution was mixed with petroleum fraction in the reservoir to get homogeneous fluid. Typically 0.25-1.25 hour mixing time was used depending on the polymer concentrations (10-50wppm) added and pipe diameters used. While, for degradation experiments, a circulation flow mode was used.

Calibration of laboratory test loop for each pipeline was performed with untreated solvent prior to testing the drag-reduction additives. Figures 4-1 and 4-2 show the calibration pressure drops data for gas oil, using four pipes, while figure 4-3 gives the data for kerosene in one considered pipe, 19.05, 25.4, 31.75 and50.8 mm. As illustrated in figures 4-1, 4-2 and 4-3, gradual increase of pressure drop was observed with increasing the bulk velocity. 31.75 mm pipeline showed higher pressure drop than that for 25.4 mm pipe at given velocities. Percentage drag-reduction was calculated based on pressure drop data as given in equation 3-7.

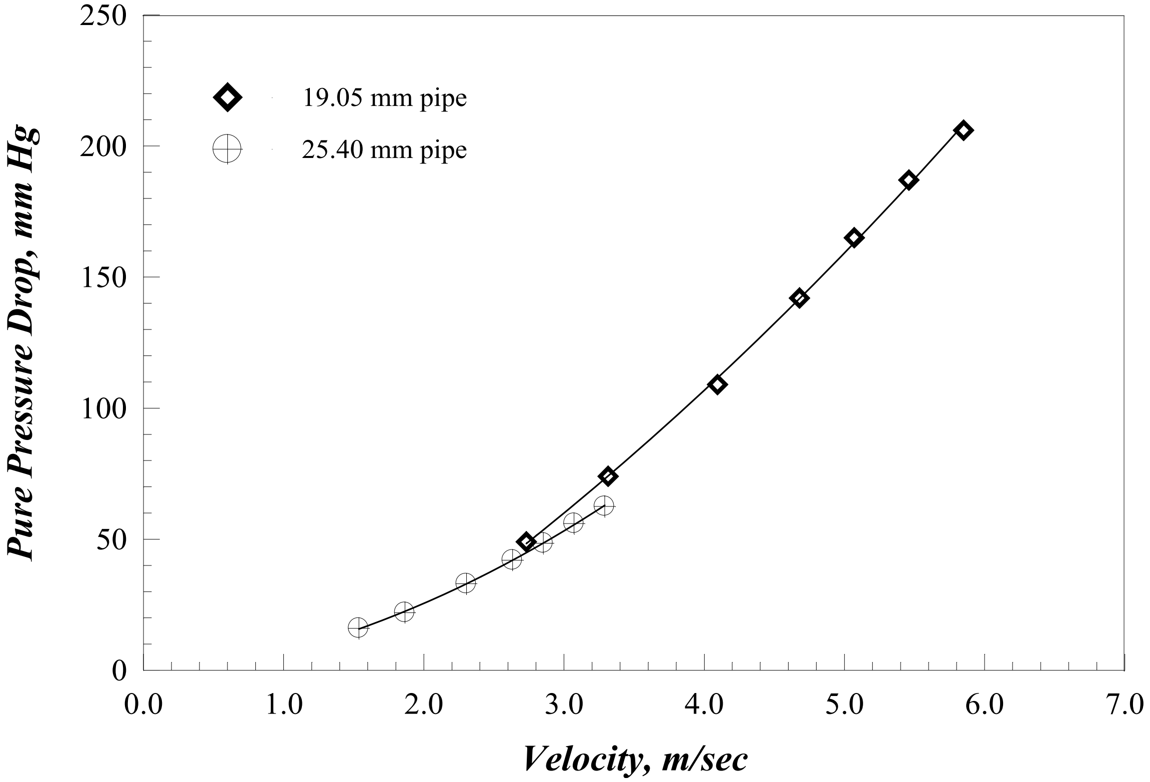


Figure 4-1: Laboratory test loop calibration data for Gas oil.

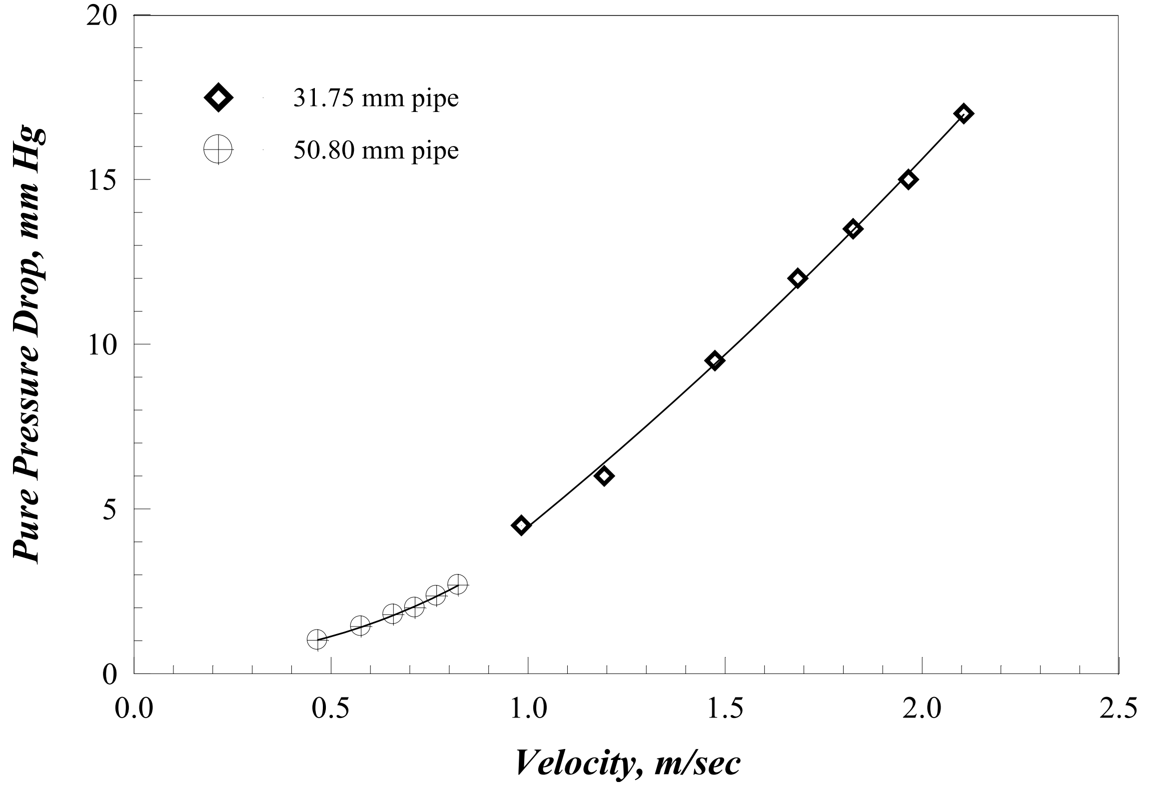


Figure 4-2: Laboratory test loop calibration data for Gas oil.

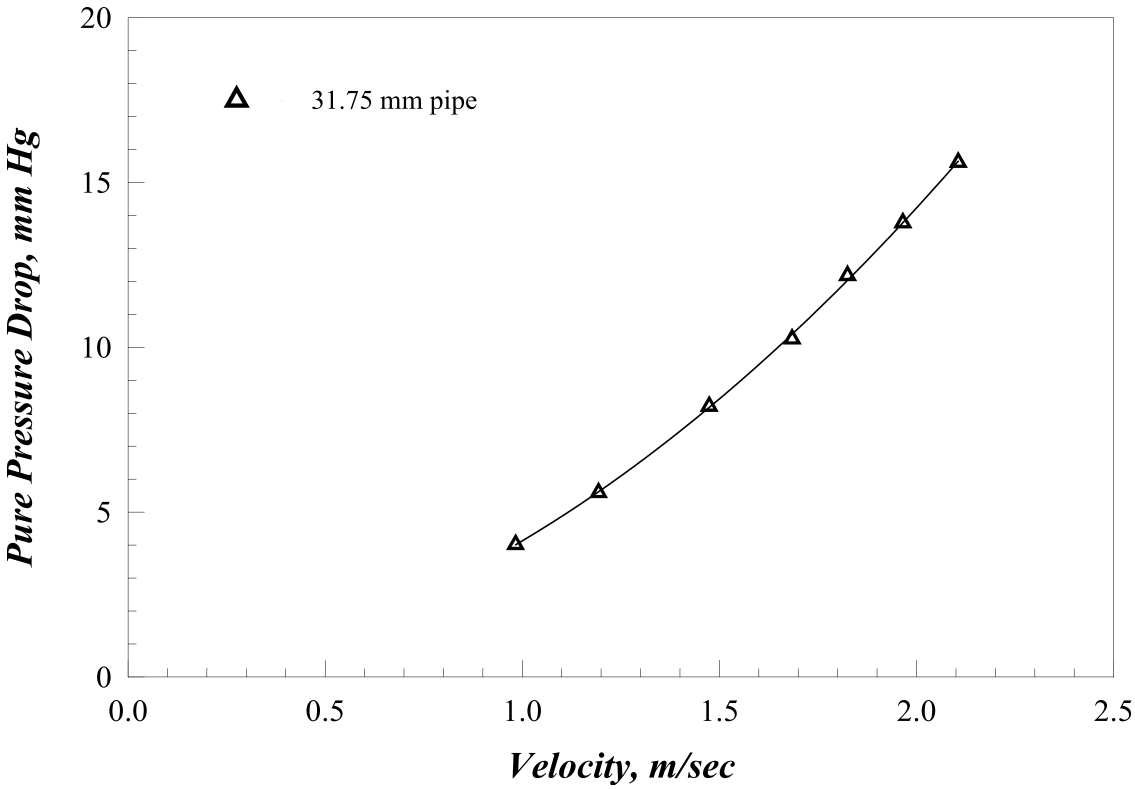


Figure 4-3: Laboratory test loop calibration data for Kerosene

4.2 Effectiveness

4.2.1 Concentration Dependence

Drag-reduction efficiency of polyisobutylene, type oppanol B 250, dissolved in reformate had been studied in gas oil turbulent flow as a function of polymer concentration. This concentration ranged from 10 up to 50wppm which might have been economically feasible for commercial applications(41). Within the concentrations used, Newtonian behavior was observed for all polymer solutions. Higher concentrations could lead to Non-Newtonian fluids, which have different behavior, as pseudoplastic or dilatent.

Figures 4-4 through 4-7 show that percentage drag-reduction increases gradually as polymer concentration increases for all pipe sizes. This phenomenon can be explained by the elastic-sublayer model theory of Virk(30). This sublayer starts to grow with increasing additive concentrations, due to an increase in the number of available polymer molecules. The trend of percentage drag reduction increase with concentration increase is about the same for all flow rates and pipe diameters studied as shown in figures 4-4 through 4-7.

The maximum percentage drag-reduction about 21 %, was achieved in 31.75 mm I.D pipe diameter at 50wppm and Reynolds number equal to 18509.3, while this maximum was about 13% for 50.8 mm I.D pipe at 11568.3 Reynolds number.

The increase in the throughput, %*TI* which is more practical term than drag reduction percentage for a given pipeline, can be estimated using the following equation:-

$$\%FI = \left\{ \frac{1}{\left(1 - \frac{\%DR}{100}\right)^{0.55}} - 1 \right\} \times 100 \tag{3-8}$$

Equation 3-8 assumes that the pressure drop for both treated and untreated fluids is proportional to flow rate rise.

Figure 4-8 summarizes the effect of polymer concentration on percentage throughput increase at different flow rates in a 31.75 mm I.D pipe. A noticeable increase in the pumpability of gas oil was achieved, which is caused by addition of small amounts of oppanol B 250 to the fluid. Polymer concentration effect is initial for increasing flow rate capacity. Therefore, 3.0 % *TI* was achieved by the addition of 10 wppm polymer, while this increase is about 13.8 % when 50wppm is added at Reynolds number equals to 17275, as shown from figure 4-8.

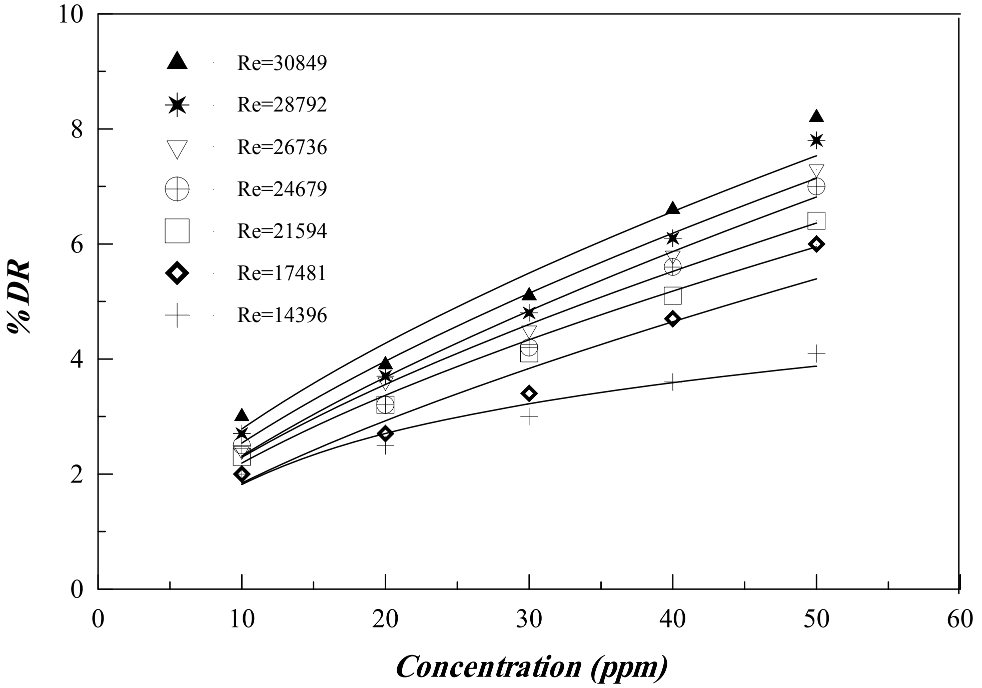


Figure 4-4: Effect of concentration on percent drag reduction for oppanol 250 through 19.05mm I.D pipe.

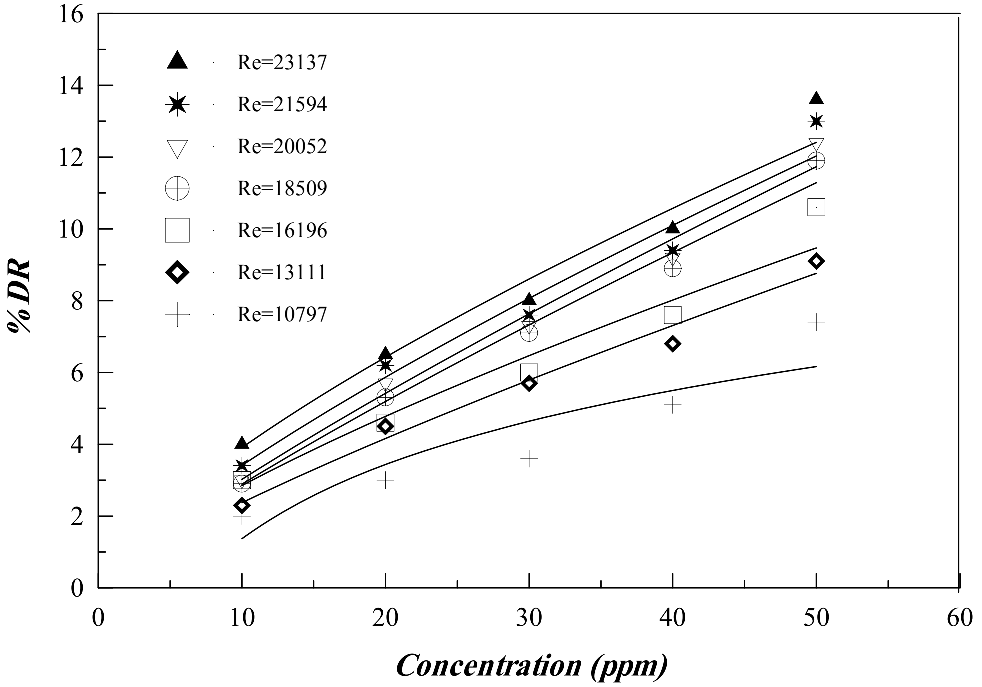


Figure 4-5: Effect of concentration on percent drag reduction for oppanol 250 through 25.4mm I.D pipe.

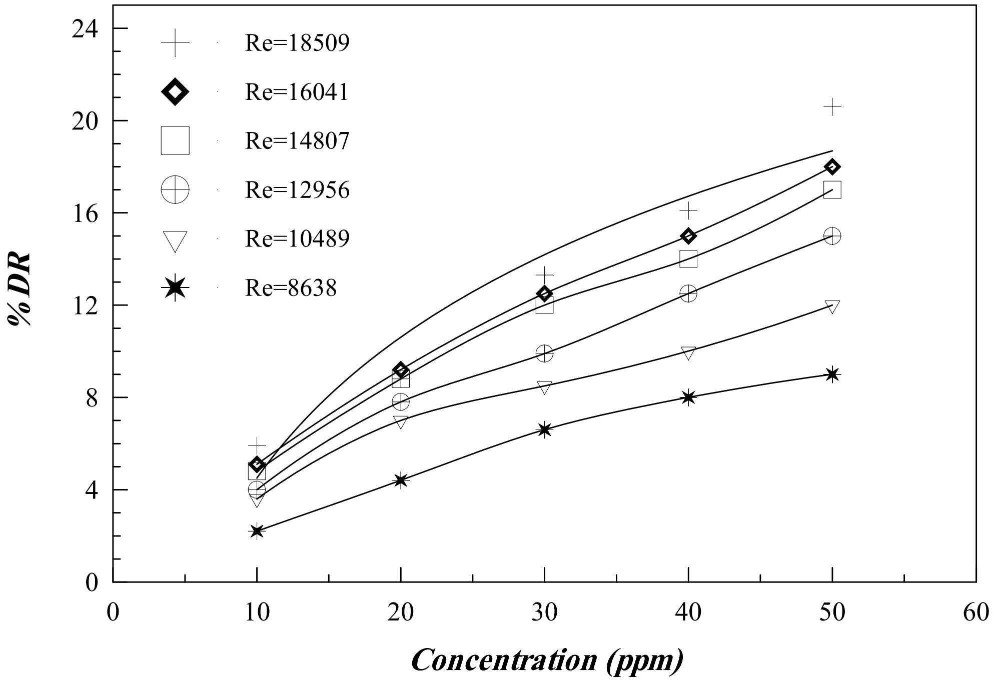


Figure 4-6: Effect of concentration on percent drag reduction for oppanol 250 through 31.75 mm I.D pipe.

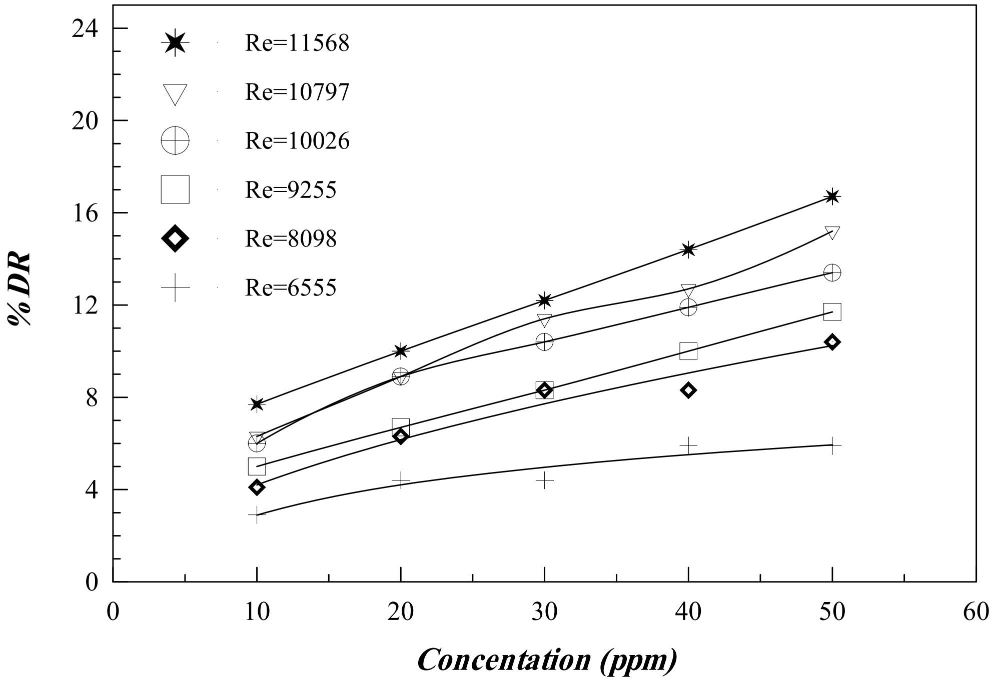


Figure 4-7: Effect of concentration on percent drag reduction for oppanol 250 through 50.80 mm I.D pipe.

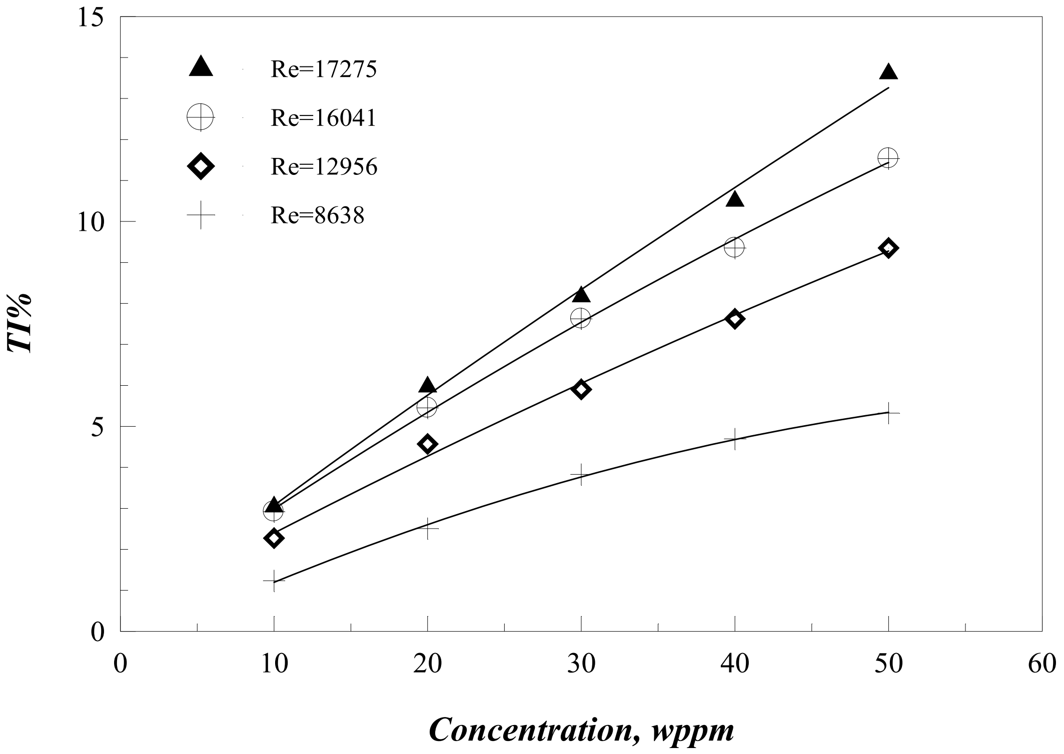


Figure 4-8: Throughput increase (%TI) as a function of polymer concentration in a 31.75 mm I.D pipe.

4.2.2 Effect of Reynolds number

It is well-known, that the drag-reduction phenomenon works in turbulent flow(27,31).Therefore the degree of turbulence has a predominant effect on its effectiveness, as shown in figures 4-4 to 4-7. Different flow rates were chosen to study the effect of turbulency on drag-reduction effectiveness of polyisobutylene, type oppanol B 250.

The use of Reynolds number based on the solvent viscosity provides a direct indication of the degree of drag-reduction, which is defined as a reduction in pressure drop due to the same flow rate, i.e., the same solvent Reynolds number. Figures 4-9 and 4-10 show the variation of drag-reduction with

Reynolds number for gas oil flowing into two different inside pipe diameters for a 10 and 50wppm polymer concentrations respectively. Figure 4-10 shows that the percentage drag-reduction increases with Reynolds number increase (flow rate increase) for fixed pipe diameter. This behavior agrees with Berman and his workers(82,83), who reported, that an increase in Reynolds number leads to an increase in the strain rate and a decrease in the time scale. Then the elongation reaches a constant level for a given solution and pipe diameters when no other limits are present. Moreover, these polymer threads have a high viscoelasticity and they may cause on interaction with turbulent eddies and consequently, a remarkable drag-reduction was observed. It is fair to say, that this effect is not well clear in figure 4-9, because of low polymer concentration.

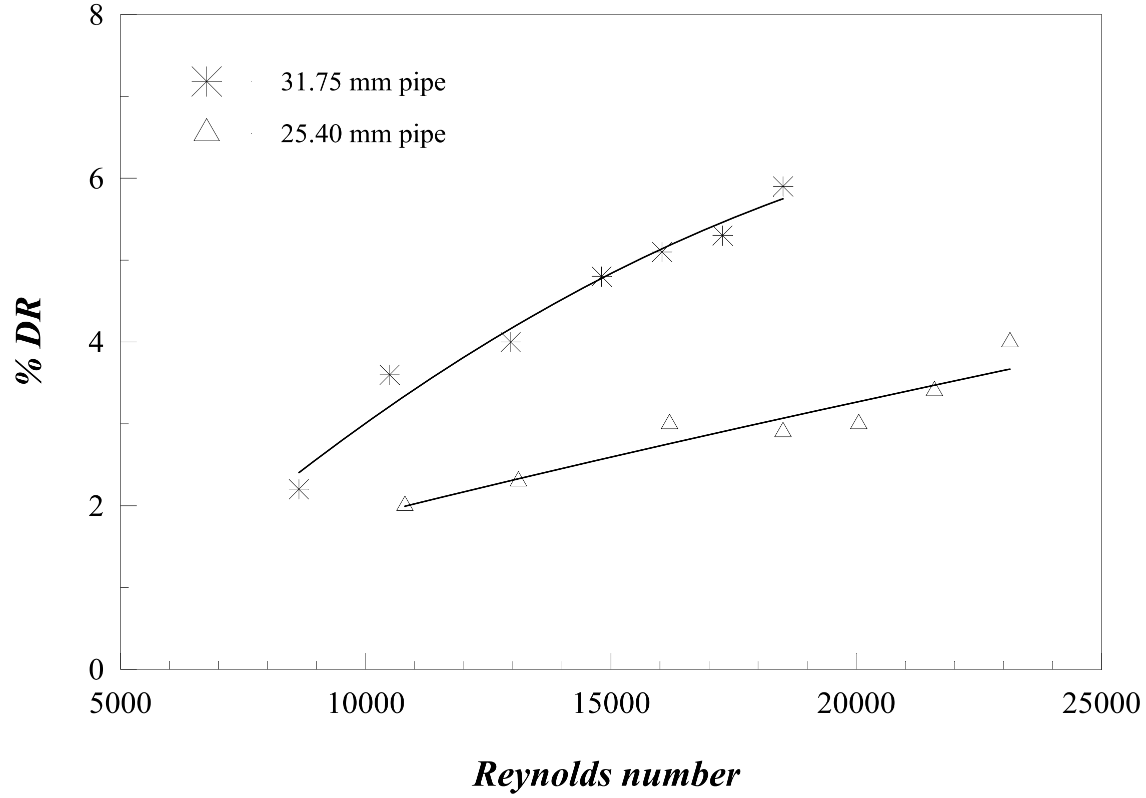


Figure 4-9: Effect of Reynolds number on percentage drag reduction for 10 wppm oppanol B 250.

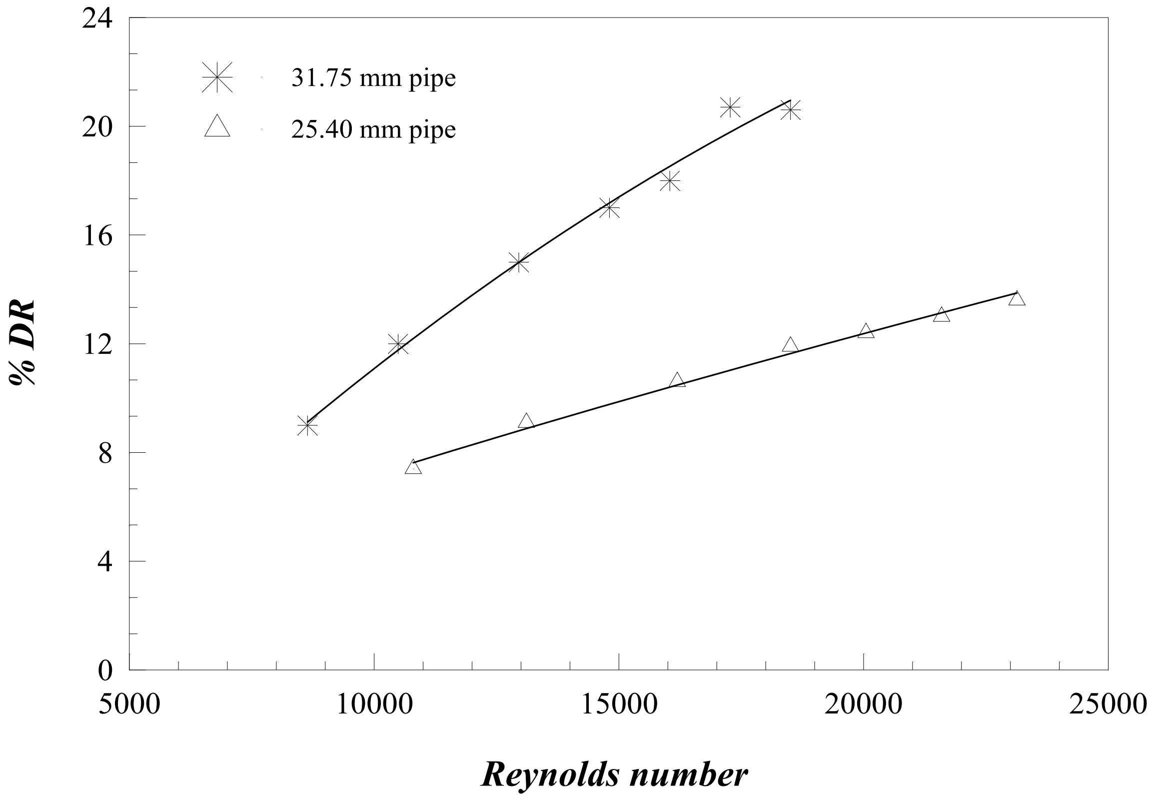


Figure 4-10: Effect of Reynolds number on percentage drag reduction for 50 wppm oppanol B 250.

Further observation of the effect of Reynolds number on percentage drag-reduction is illustrated in figures 4-4 up to 4-7 for different polymer concentrations.

The combined effect of concentration and Reynolds number on percent drag reduction have been illustrated in three dimension plots. For more elaboration, figures 4-11 and 4-12 are plotted for this purpose, which represent the extension of overlapping the two effects on percent drag reduction.

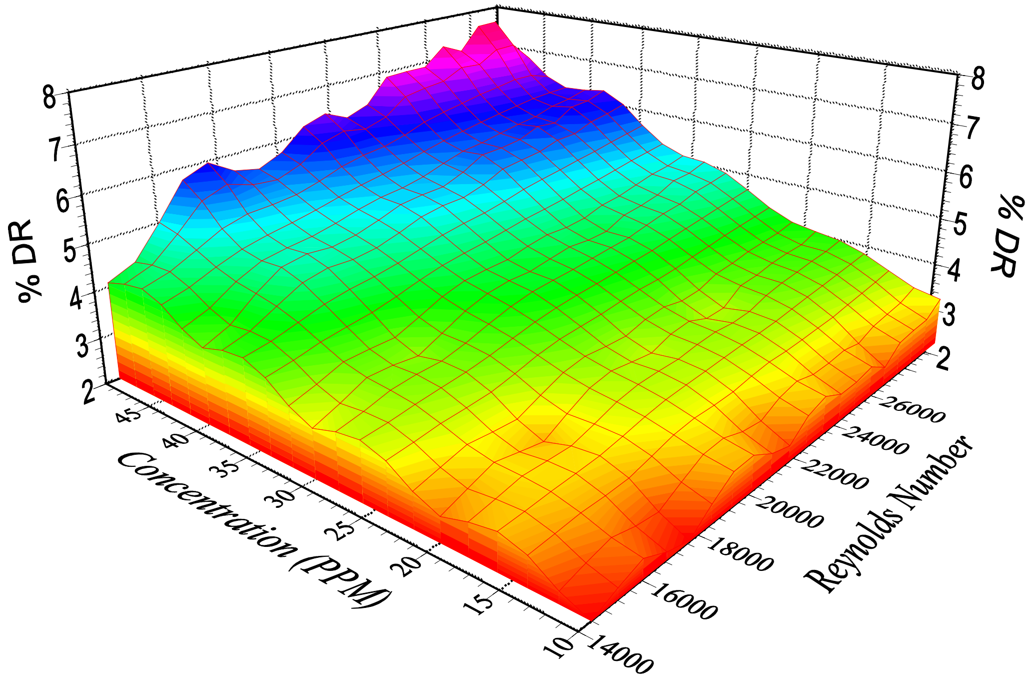


Figure 4-11: Effect of concentration and Reynolds number on percent drag reduction for Oppanol 250 in 19.05 ID pipe diameter

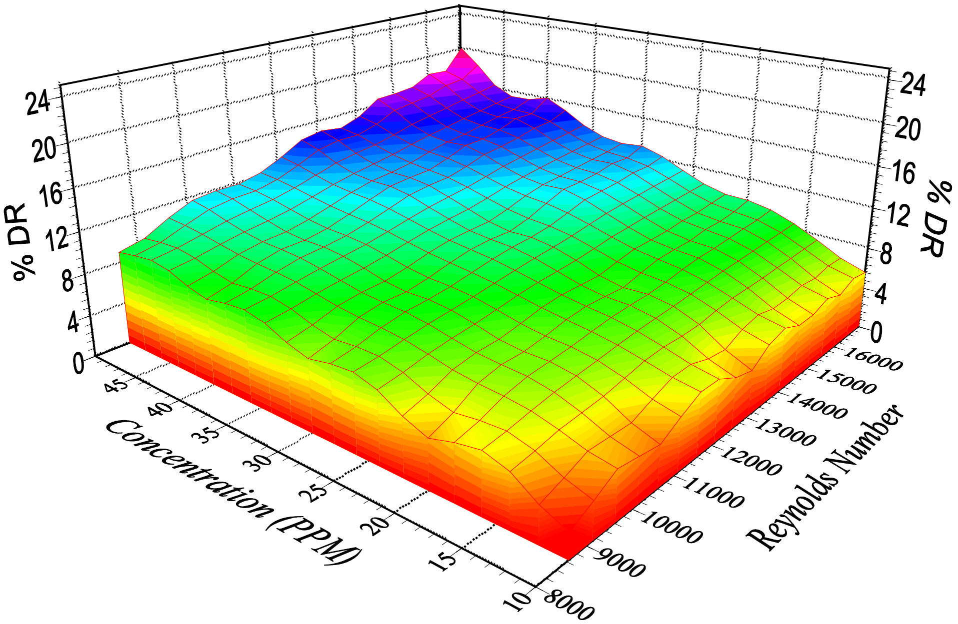


Figure 4-12: Effect of concentration and Reynolds number on percent drag reduction for Oppanol 250 in 31.75 ID pipe diameter

It is clearly observed, that both higher concentrations and Reynolds number enhanced the drag-reduction as expected. As an example; 20.7% drag–reduction was obtained for 16500 Reynolds number and 50wppm as shown in figure 4-12.

4.2.3 Effect of Pipe Diameter

It is well known that the drag-reduction effectiveness of polymeric additives is influenced largely by pipe diameters(43, 92, 111); whereas a satisfactory quantitative explanation of this is still lacking(92). Therefore, it is interesting to study the effect of pipe diameters on achieved drag-reduction. Four nominal diameters, 19.05, 25.4, 31.75 and 50.8mm were chosen to explain such dependence, using polyisobutylene type oppanol B 250, as polymeric additive.

Figures 4-13, 4-14 and 4-15 illustrate the dependence of diameter on percentage drag-reduction for pipes with I.D 19.05, 25.4and 31.75mm at optimum (6.0m^3/hr), moderate (4.8 m^3/hr) and lower (3.4 m^3/hr) flow rates. Figure 4-16 shows the results for the large pipe, with I.D 50.8mm, at different flow rates. Therefore the maximum drag-reduction achieved are, 8.2, 13.6 and 20.7 % for pipe diameters, 19.05, 25.4 and 31.75mm respectively, at flow rate 6.0 m^3/hr and 50wppm concentration. That means the percentage drag-reduction increases with pipe diameter increase within the mentioned diameters. Those, are in agreement with the observations of Elson and Garside(111), Robert et al(43), Mansour Asward(58), and Berman(59) for diameter dependence in this manner.

The results of large diameter pipe, (50.8mm) are shown in figure 4-16 for different flow rates. The maximum percentage drag-reduction obtained in this pipe is 16.7% at 6.0m^3/hr flow rate and 50wppm polymeric concentration. The decrease of maximum percentage drag-reduction in the 50.8mm pipe, as compared with 31.75mm pipe is due to the decrease in velocity of the former one, which gives lower turbulency. Since the flow velocity depends on pipe diameter therefore, the velocities at 6.0m^3/hr are 2.1 and 0.82 m/sec for 31.75 and 50.8mm pipes respectively.

The increase in drag reduction with increasing pipe diameter is attributed to the fact that, a better media will be convenient by increasing the pipe diameter at a given flow rate, for polymer ability to deform and absorb energy of turbulent eddies, which will enhance the drag reduction effectiveness.

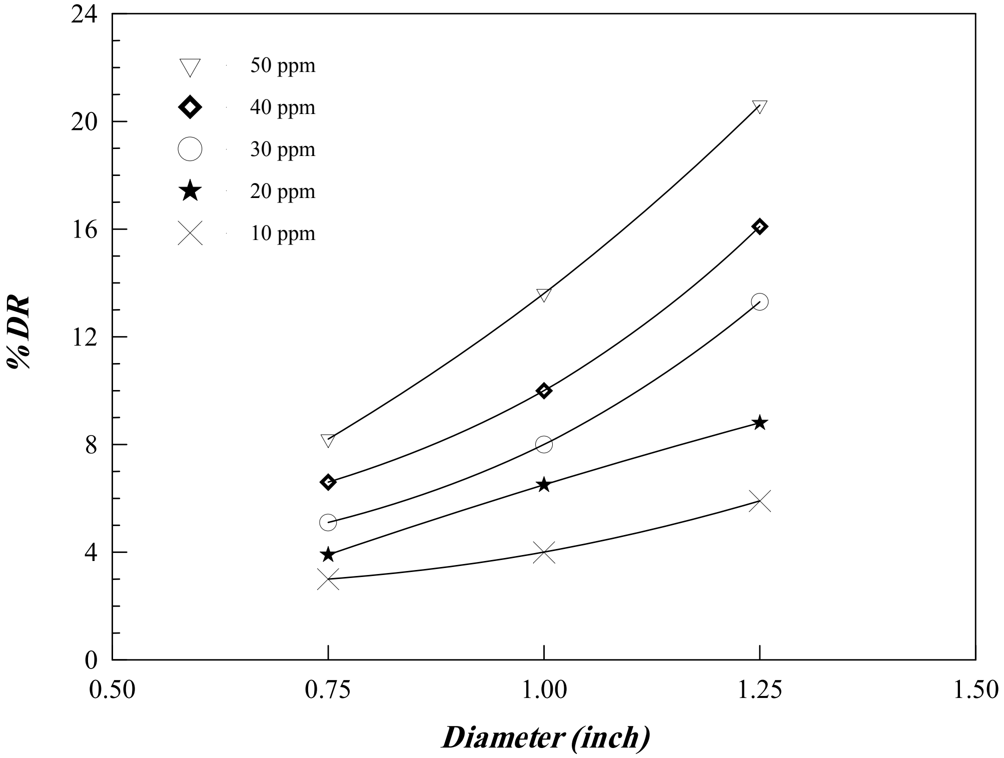


Figure 4-13: Effect of pipe diameter on percent drag reduction for 6 m^3/hr flow rate.

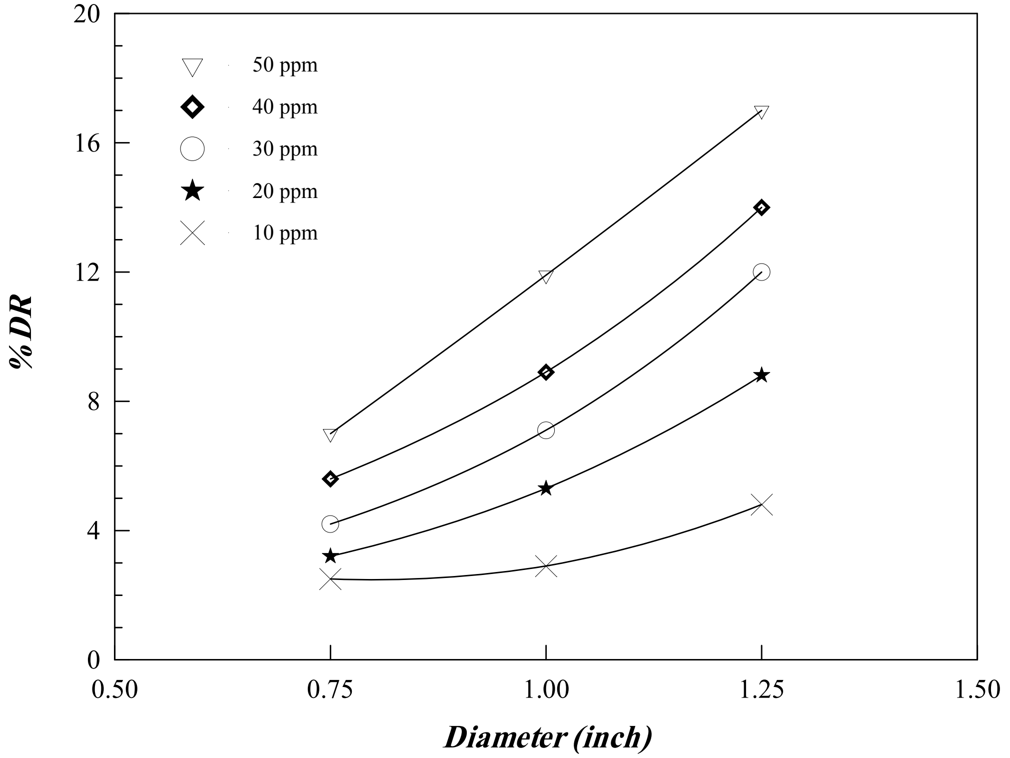


Figure 4-14: Effect of pipe diameter on percent drag reduction for 4.8 m^3/hr flow rate

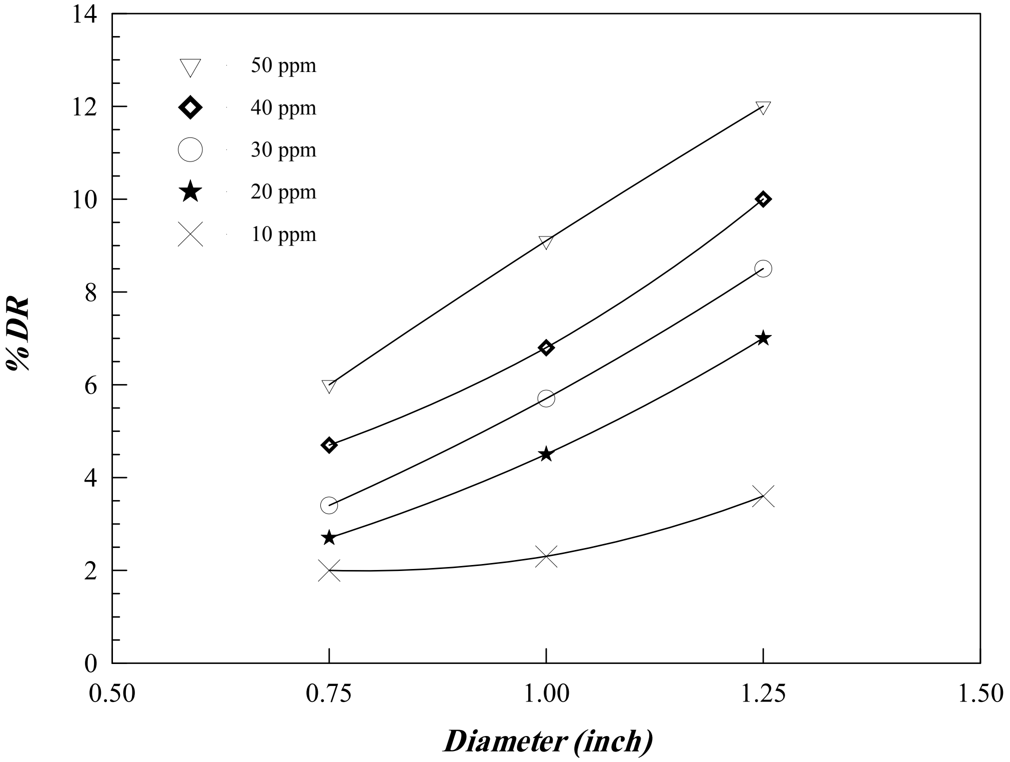


Figure 4-15: Effect of pipe diameter on percent drag reduction for 3.4 m^3/hr flow rate.

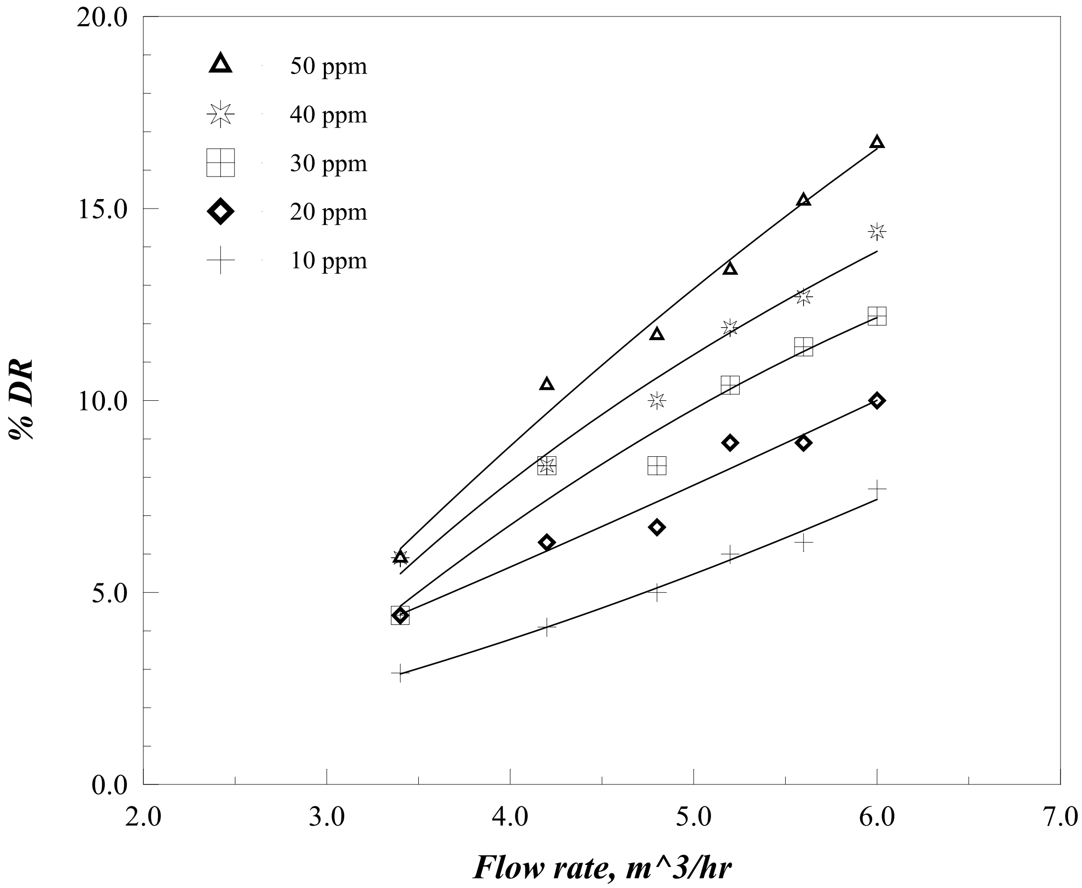


Figure 4-16: Percent drag-reduction (%DR) as a function of flow rate at different polymer concentration for 50.8 mm pipe diameter.

4.2.4 Entrance Length, *le* and Test Section

The boundary layer forms in the inlet of a pipe and grows in thickness until it becomes fully developed. As it was explained in previous chapter, the pressure drop measurements should be obtained in the fully developed region depending upon the entrance length that might be used. In this work, two different entrance lengths have been taken for each pipe in order to manifest the effect of entrance length on percent drag reduction. However, figures 4-17, 4-18 and 4-19 illustrate this effect at different additive concentrations and different flow rates for, 25.4, 31.75 and 50.8 mm I.D pipe diameters respectively. As shown in these figures, the lower *le/D* gives low percent drag reduction, with test section 3m long, on the other hand, the higher *le/D* gives higher values of percent drag reduction with test section 2m long. This refers to the fact that at low *le/D* ratio, the flow will not be fully developed, whereas with high ratio of *le/D,* the flow will reach fully development, in which more homogeneity would occur between the fluid and polymer molecules. Table 4-2 lists the entrance length for each pipe with appropriate test sections and their effects on percent drag reduction at 50wppm polymer additives.

Table 4-2: *le/D* and *Ts* dimensions with % DR at 50wppm

I.D (mm)	***le/D Ratio***	**Test Section (m)**	**% DR at Q=6.0 m^3/hr**	**% DR at Q=3.4 m^3/hr**
25.4	>95	3	10.9	7.1
25.4	>135	2	13.6	9.1
31.75	>75	3	18.7	12.2
31.75	>100	2	20.6	12
50.8	>50	3	12.4	7.1
50.8	>65	2	16.4	5.9

For 50wppm concentration table 4-2 gives 2-3% more for larger entrance length at highest flow rate, 6.0 m^3/hr. while for lower flow rates the entrance length has a lower effect on percentage drag-reduction values. Those at 3.4 m^3/hr, there is lower than 1% difference in the obtained percentage drag-reduction. Moreover, at low concentrations no effect of entrance length was observed. Those can be attributed to the fact that, at low flow rates (low turbulence) the behavior of drag-reducer agents is less effective, mainly at low concentrations, since turbulent flow is necessary for drag-reduction to occur. Therefore, the entrance length has little or no influence on the achieved percentage drag reduction as shown in figures 4-17 to 4-19.

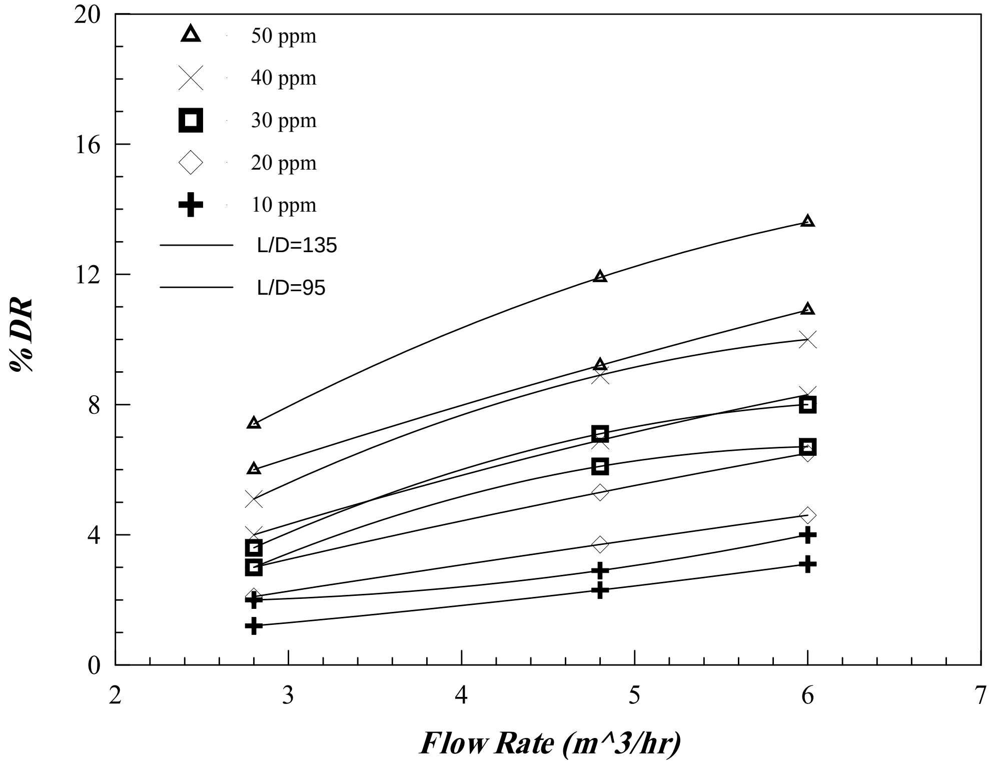


Figure 4-17: Effect of entrance length on percent drag reduction for 25.4 mm I.D pipe

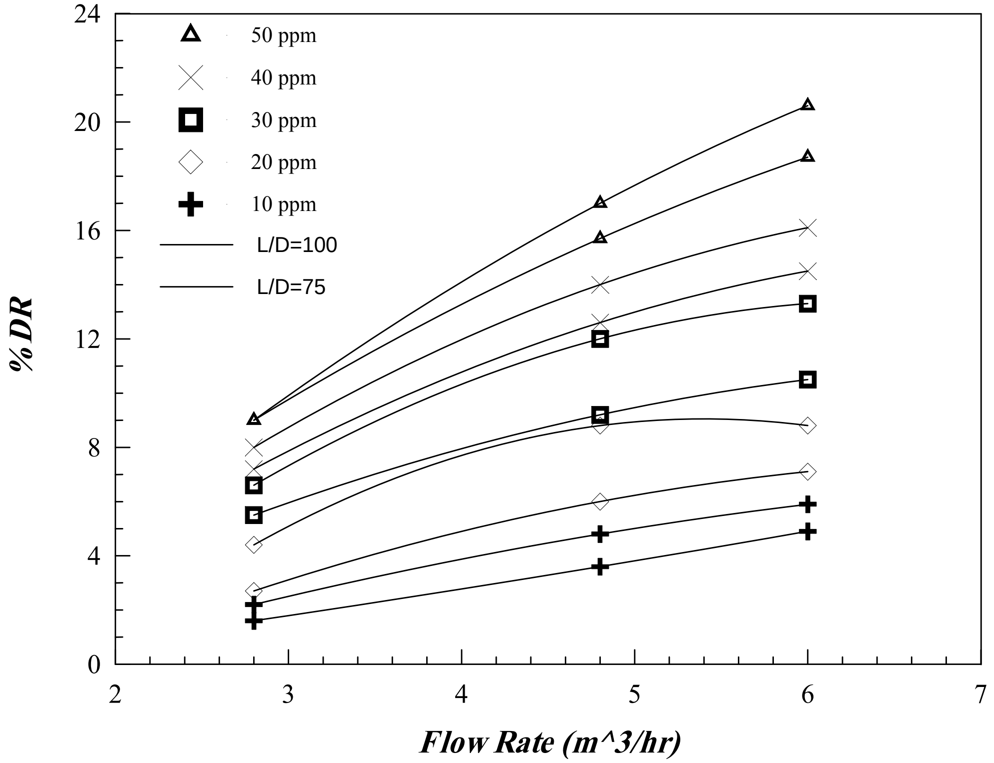


Figure 4-18: Effect of entrance length on percent drag reduction for 31.75 mm I.D pipe

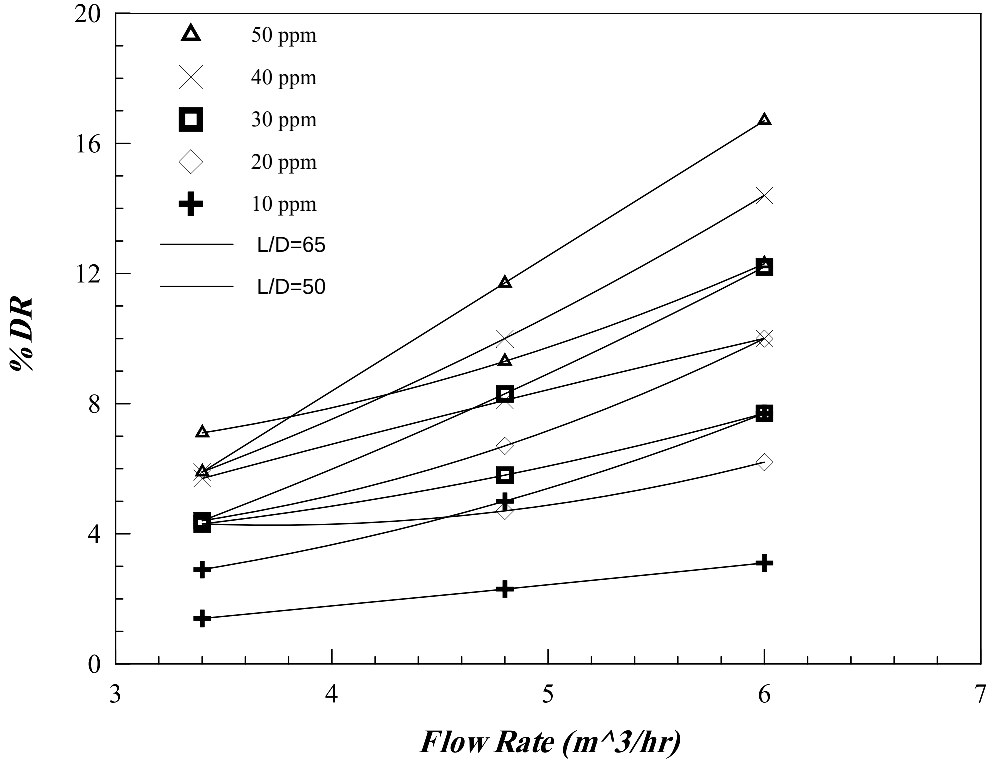


Figure 4-19: Effect of entrance length on percent drag reduction for 50.8 mm I.D pipe

4.2.5 Effect of Solvent Type

It is well known, that the viscosity and density of liquids have predominate effect on their flowing capacity. Therefore, kerosene was chosen in the present investigation to compare its ability for turbulent drag-reduction in presence of polymers with gas oil data at similar conditions. The comparison was taken in a 31.75mm and 100 le/D ratio, as shown in figure 4-20. The results show that at low concentrations (about 10wppm) there was no effect of solvent type on percentage drag-reduction. This refers to the poor interaction between polymer and solvent at low concentrations. Whereas at high concentrations (greater than 30wppm), kerosene gave higher percentage drag-reduction compared with gas oil data. The reason of contrast between two types of solvent, is that, in a low viscosity liquid represented by kerosene, the polymer molecule tends to exclude all others from the volume which it occupies. This lead to more media will be occupied for polymer in good solvent as effective drag reducer. Table 4-3 summarizes the percent drag reduction for kerosene and gas oil at three concentrations and different flow rates for 31.75mm I.D pipe.

The effect of solvent is more dominate for high concentrations and high flow rates, that give usually suitable condition for drag-reduction phenomenon.

Table 4-3: comparison between kerosene and gas oil for %DR data

Solvent type	Conc. (wppm)	Flow rate (m^3/hr)	% DR
Kerosene	10	2.8	2.4
Gas oil	10	2.8	2.2
Kerosene	30	2.8	7.2
Gas oil	30	2.8	6.6
Kerosene	50	2.8	11.6
Gas oil	50	2.8	9.0
Kerosene	10	6.0	5.6
Gas oil	10	6.0	5.9
Kerosene	30	6.0	13.8
Gas oil	30	6.0	13.5
Kerosene	50	6.0	23.9
Gas oil	50	6.0	20.6

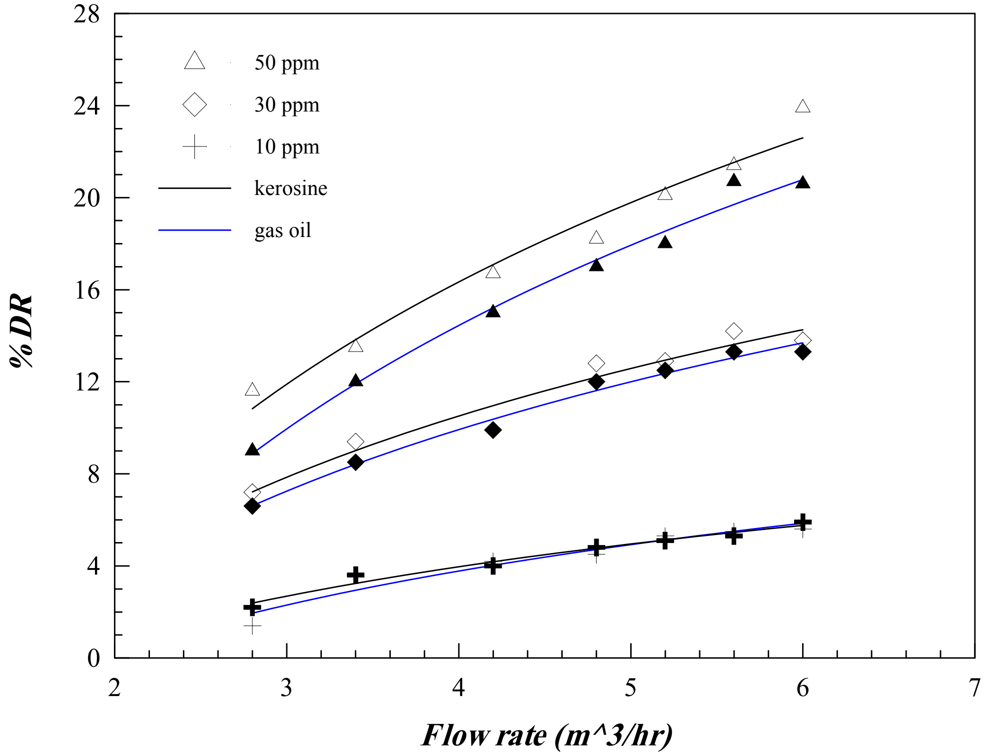


Figure 4-20: Effect of solvent type on % DR at various concentration and flow rate.

4.3 Friction Factor

The drag-reduction properties of solutions could be explained as the fanning friction factor versus solvent Reynolds number. The use of Reynolds number based on the solvent viscosity and pipe diameter provides a direct indication of the degree of drag-reduction. The friction factor was calculated from the experimental data based on pressure drop measurements, as in equation 3-6.

The effect of polymer additives with different concentrations on friction factor as function of Reynolds number are plotted in Figures 4-21 to 4-23 for 19.05, 25.4 and 31.75mm I.D pipes respectively. These figures, show that for untreated solvent friction factor values lies near Blasuis asymptote, while by adding a minute amounts of polymer into the flow, the friction factor values were positioned below Blasius asymptote towards the maximum drag reduction region which is represented by “Virk asymptote”. This effect is rapidly appeared in the nominal pipes sizes of 31.75mm I.D, followed by 25.4mm I.D, as shown in figures 4-23 and 4-22 respectively.

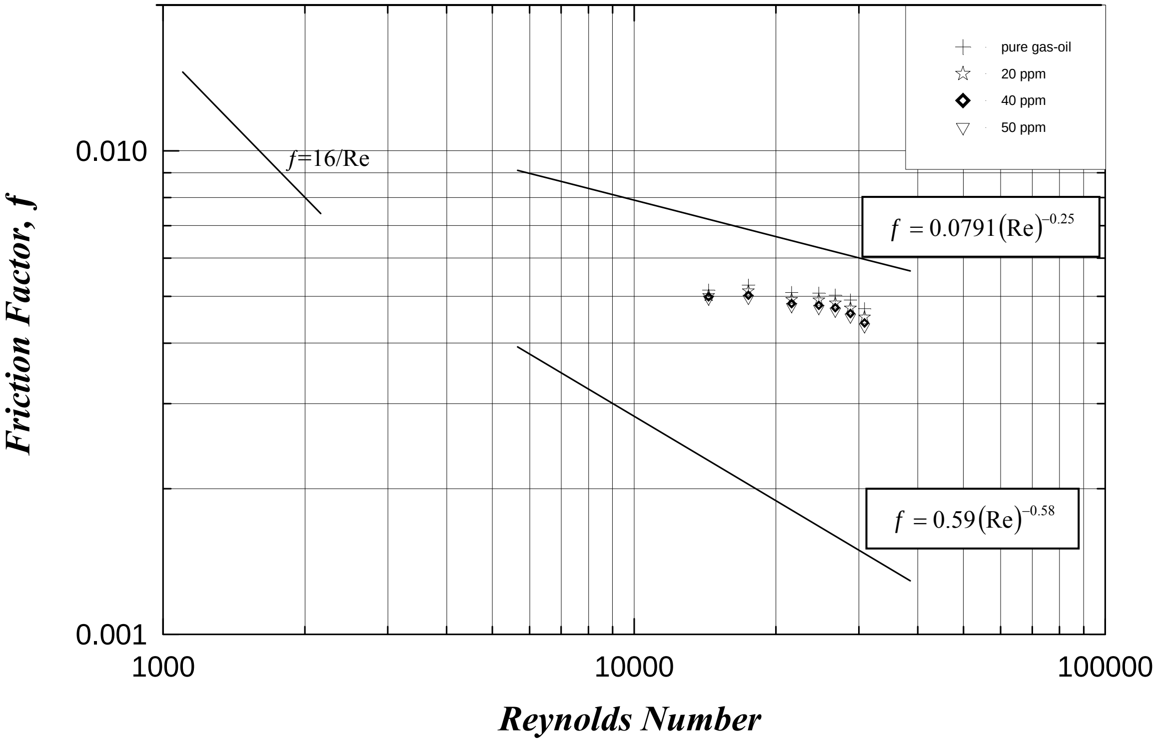


Figure 4-21: Effect of polymer additives with different concentration on friction factor as function of Re for 19.05 mm pipe diameter.

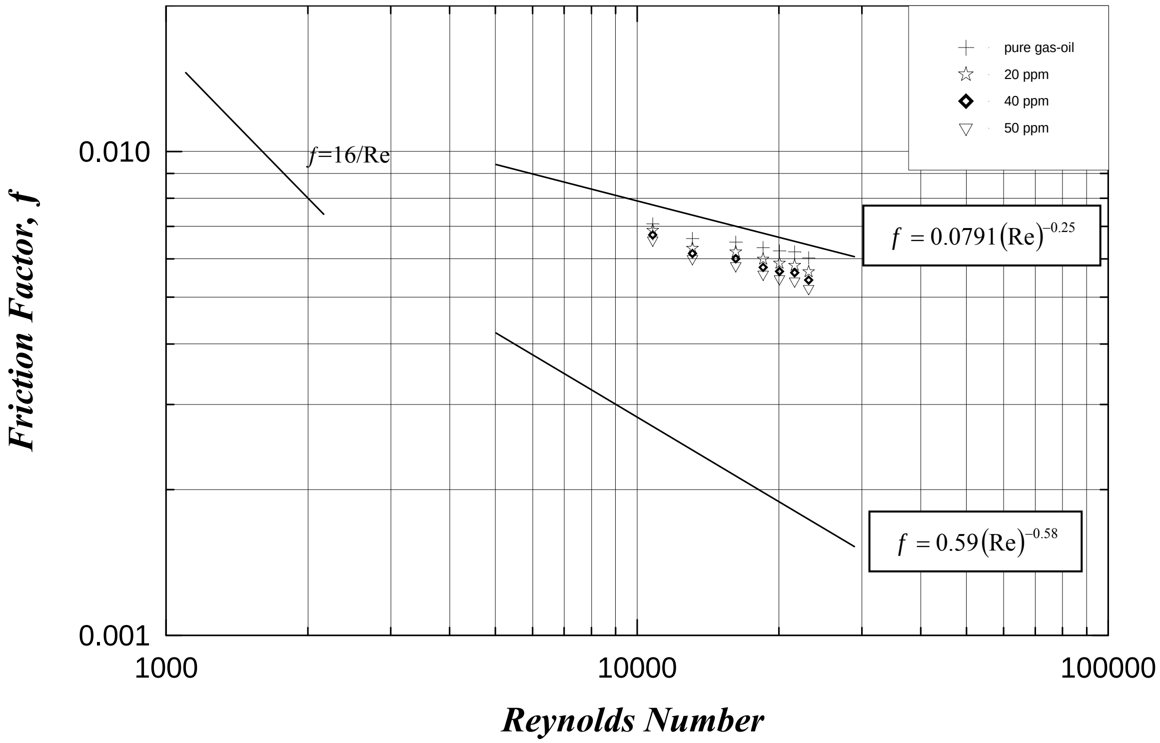


Figure 4-22: Effect of polymer additives with different concentration on friction factor as function of Re for 25.4 mm pipe diameter.

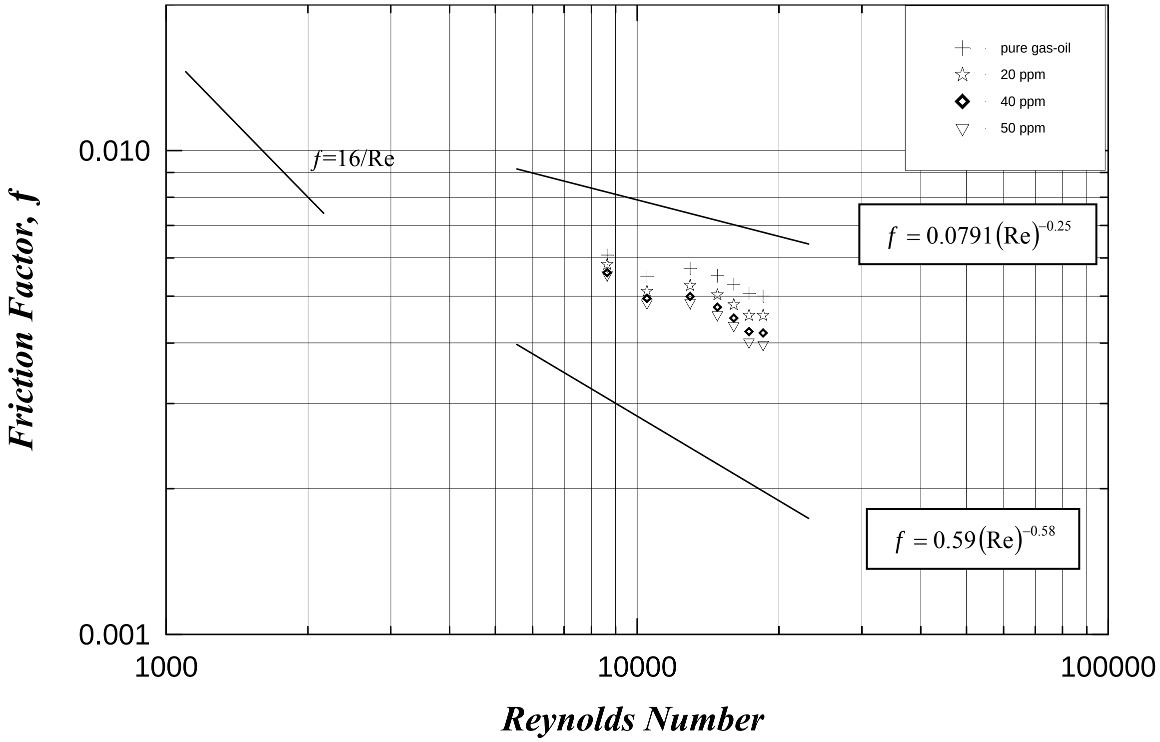


Figure 4-23: Effect of polymer additives with different concentration on friction factor as function of Re for 31.75 mm pipe diameter.

An attempt was made to correlate the fanning friction factor as a function of Reynolds number, for the considered polymer concentrations and pipe diameters. The friction factor was calculated as follows:

$$f = \frac{\Delta h * 133.3}{2} \frac{1}{\rho u^2} \frac{D}{L} \tag{3-6}$$

The friction factor is usually correlated as a function of Reynolds number as shown in the following formula

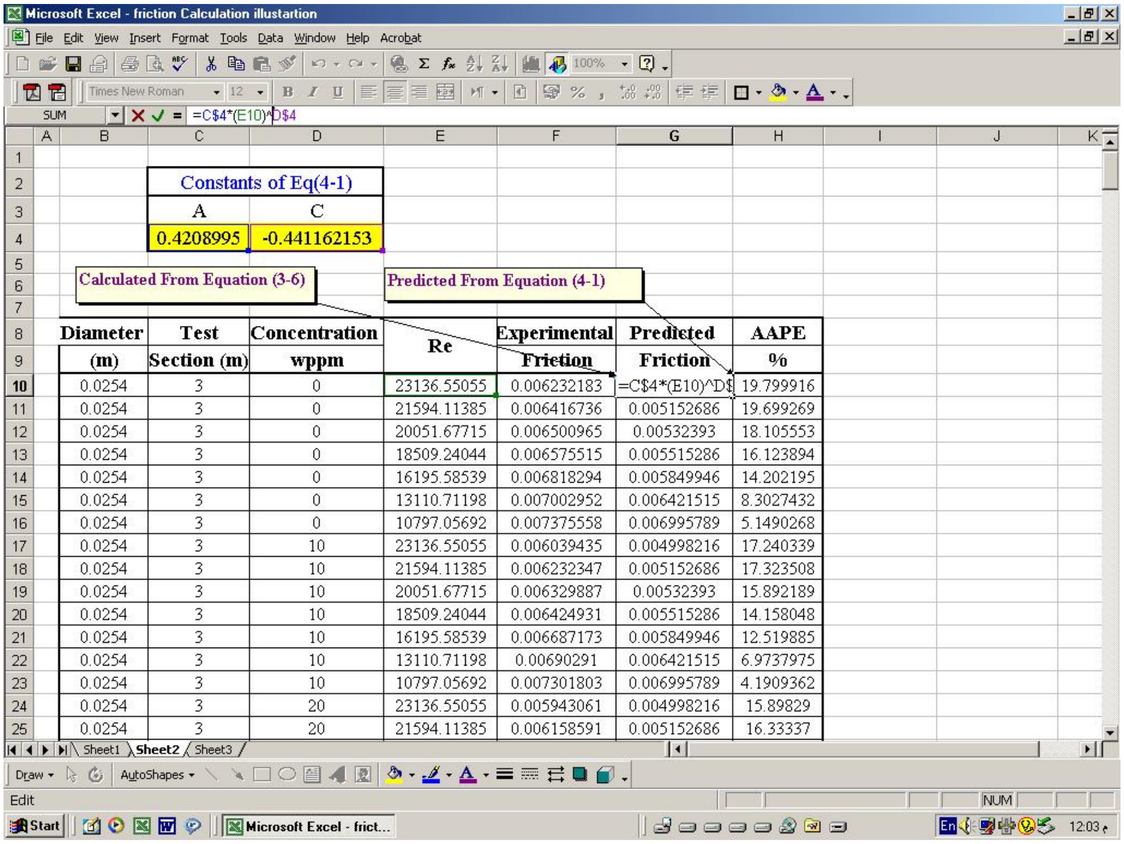
$$f = a\left(\text{Re}\right)^b . \tag{4-1}$$

In accordance with the above formula and by using appropriate software program as illustrated in Appendix C, the constants a, b had been found. Therefore, the formula becomes:

$$f = 0.42\left(\text{Re}\right)^{-0.44} \tag{4-2}$$

The correlation results for friction factor calculation by equation (4-2) are illustrated in table (C-1) for different pipe diameters, concentrations, Reynolds numbers and entrance lengths.

The calculated results give a good agreement with the friction factor obtained experimentally and calculated by equation (3-6) with overall average absolute percent error of about 10.4% for 366 runs.



=C$4*(E10)^D$4

Constants of Eq(4-1)	
A	C
0.4208995	-0.441162153

Calculated From Equation (3-6)

Predicted From Equation (4-1)

Diameter (m)	Test Section (m)	Concentration wppm	Re	Experimental Friction	Predicted Friction	AAPE %
0.0254	3	0	23136.55055	0.006232183	=C$4*(E10)^D$	19.799916
0.0254	3	0	21594.11385	0.006416736	0.005152686	19.699269
0.0254	3	0	20051.67715	0.006500965	0.00532393	18.105553
0.0254	3	0	18509.24044	0.006575515	0.005515286	16.123894
0.0254	3	0	16195.58539	0.006818294	0.005849946	14.202195
0.0254	3	0	13110.71198	0.007002952	0.006421515	8.3027432
0.0254	3	0	10797.05692	0.007375558	0.006995789	5.1490268
0.0254	3	10	23136.55055	0.006039435	0.004998216	17.240339
0.0254	3	10	21594.11385	0.006232347	0.005152686	17.323508
0.0254	3	10	20051.67715	0.006329887	0.00532393	15.892189
0.0254	3	10	18509.24044	0.006424931	0.005515286	14.158048
0.0254	3	10	16195.58539	0.006687173	0.005849946	12.519885
0.0254	3	10	13110.71198	0.00690291	0.006421515	6.9737975
0.0254	3	10	10797.05692	0.007301803	0.006995789	4.1909362
0.0254	3	20	23136.55055	0.005943061	0.004998216	15.89829
0.0254	3	20	21594.11385	0.006158591	0.005152686	16.33337

Illustration 4–1: Friction Factor Prediction

4.4 Correlation of Drag Reduction Results

In order to predict the expected levels of drag reduction in the 19.05 through 50.8mm I.D pipe diameter experiments, the time scale techniques were investigated. Many investigators had used this approach. Berman and George$^{(83)}$ investigated the time scale hypothesis experimentally with regard to the onset of drag reduction. Their results support the contention that the onset of drag reduction is related to a time frame interaction of the turbulence with polymer molecules. Berman and George indicated that the relaxation time of a polydisperse polymer sample should be described by a distribution function rather than a single value. Consequently, by increasing the characteristic time of the turbulence, more of the distribution of relaxation times would be affected, thus increasing the drag reduction. Chorn$^{(84)}$ used this approach to increase the level of drag reduction for a given polymer concentration in a 26.0mm pipe by increasing the solvent viscosity and hence the value of ν/u^{*2} for a given Reynolds number.

Burger$^{(41)}$ had found that the drag reduction data accumulated with CDR drag reducer is Sadlerochit crude which have been correlated well with two parameters describing the flow in pipeline. The Burger correlation had been based on a model of turbulent viscoelastic flow presented by Savins and Seyer$^{(89)}$ for finding the value of drag ratio.

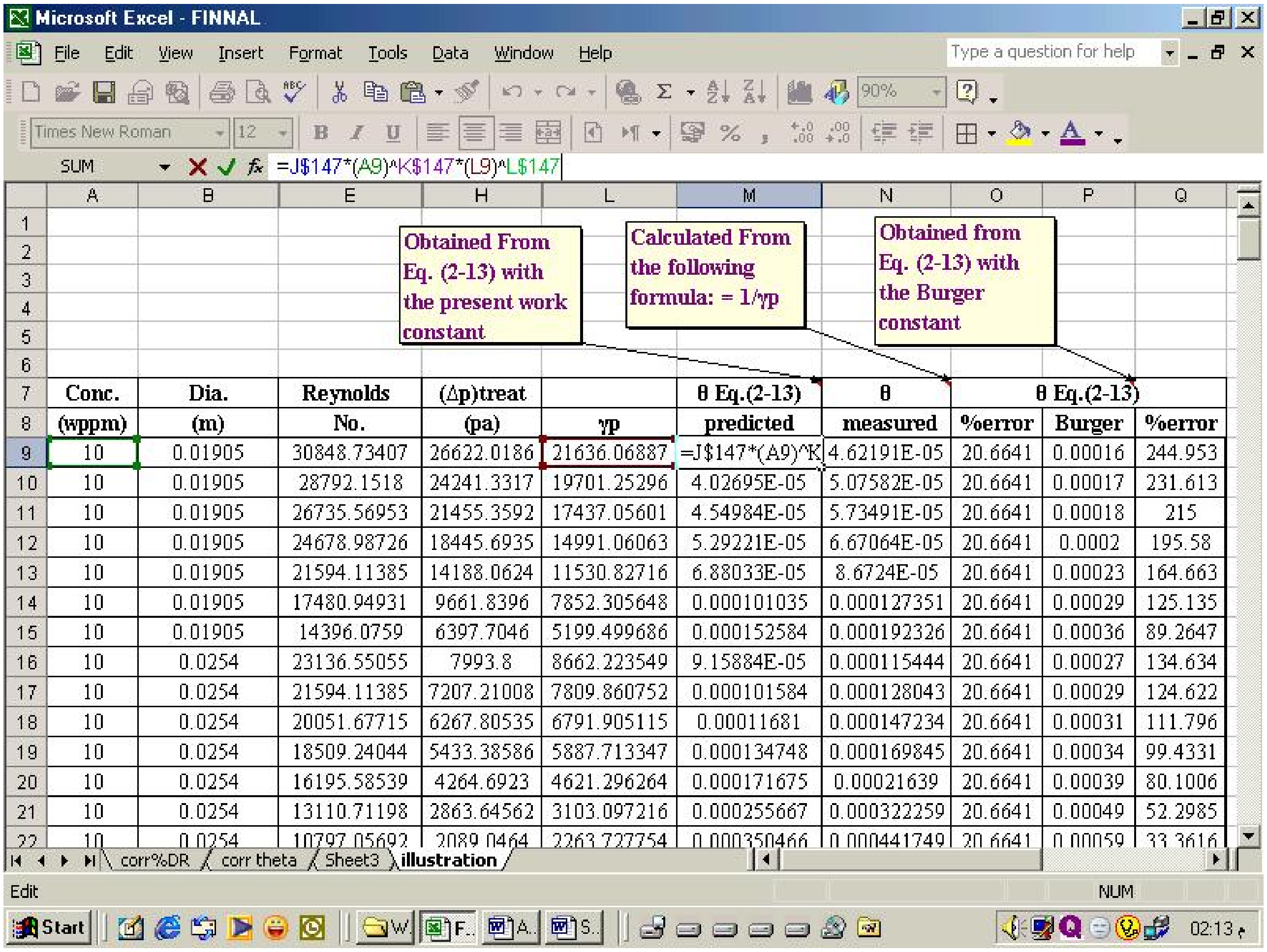
The extension of Berger on the characteristic time was found to relate to the drag reduced shear rate, γ_p, and the additive concentration, φ, in wppm as expressed by Burger in the following equation:-

$$\Theta_p = a\varphi^b \gamma_p{}^c \qquad (2\text{-}13)$$

Where γ_p represents shear rate at polymer additive=($u_p{}^{*2}$ /υ) from equation (2-14).
The constants a, b and c were found by linear regression to be .0515, 0.489 and -0.579 respectively.

Further attempted had been made by Motier$^{(90)}$ to extend the Burger work, through linear regression, in order to find the corresponding exponents for determining the characteristic time. No results have been mentioned in the Motier study to extend the Burger work

In the present study, the drag reduction results have been correlated based on the time scale hypothesis. The experimental data was fitted with equation 2-13 and found to have a good agreement with this time scale approach. The correlation coefficient of about 0.98914 has been obtained by using a suitable software computer program as shown in illustration (4-2) (Microsoft Excel). The values of constants a, b and c were found to be 0.48839, 0.2107 and -1.0 respectively. The results of the mentioned program can be found in Appendix E.



=J$147*(A9)^K$147*(L9)^L$147

Obtained From Eq. (2-13) with the present work constant

Calculated From the following formula: = 1/γp

Obtained from Eq. (2-13) with the Burger constant

	A	B	E	H	L	M	N	O	P	Q
7	Conc.	Dia.	Reynolds	(Δp)treat		θ Eq.(2-13)	θ	θ Eq.(2-13)		
8	(wppm)	(m)	No.	(pa)	γp	predicted	measured	%error	Burger	%error
9	10	0.01905	30848.73407	26622.0186	21636.06887	=J$147*(A9)^K	4.62191E-05	20.6641	0.00016	244.953
10	10	0.01905	28792.1518	24241.3317	19701.25296	4.02695E-05	5.07582E-05	20.6641	0.00017	231.613
11	10	0.01905	26735.56953	21455.3592	17437.05601	4.54984E-05	5.73491E-05	20.6641	0.00018	215
12	10	0.01905	24678.98726	18445.6935	14991.06063	5.29221E-05	6.67064E-05	20.6641	0.0002	195.58
13	10	0.01905	21594.11385	14188.0624	11530.82716	6.88033E-05	8.6724E-05	20.6641	0.00023	164.663
14	10	0.01905	17480.94931	9661.8396	7852.305648	0.000101035	0.000127351	20.6641	0.00029	125.135
15	10	0.01905	14396.0759	6397.7046	5199.499686	0.000152584	0.000192326	20.6641	0.00036	89.2647
16	10	0.0254	23136.55055	7993.8	8662.223549	9.15884E-05	0.000115444	20.6641	0.00027	134.634
17	10	0.0254	21594.11385	7207.21008	7809.860752	0.000101584	0.000128043	20.6641	0.00029	124.622
18	10	0.0254	20051.67715	6267.80535	6791.905115	0.00011681	0.000147234	20.6641	0.00031	111.796
19	10	0.0254	18509.24044	5433.38586	5887.713347	0.000134748	0.000169845	20.6641	0.00034	99.4331
20	10	0.0254	16195.58539	4264.6923	4621.296264	0.000171675	0.00021639	20.6641	0.00039	80.1006
21	10	0.0254	13110.71198	2863.64562	3103.097216	0.000255667	0.000322259	20.6641	0.00049	52.2985
22	10	0.0254	10797.05692	2089.0464	2263.727754	0.000350466	0.000441749	20.6641	0.00059	33.3616

Illustration 4–2: Time scale, Θ_P Correlation

Figure 4-24 summarizes the comparison of the measured values of Θ_p with those calculated by equation (2-13), showing a good agreement.

Based on this acceptability between measured and predicted values of time scale Θ_p, the percent drag reduction has been correlated with flow conditions, polymer concentration and shear rate. The predicted formula of percent drag reduction is expressed as follows:-

$$\%DR = a_1 (\gamma_\circ)^{b_1} (\varphi)^{c_1} (\gamma_p)^{d_1} \tag{4-3}$$

where, $\gamma_\circ$, γ_p from equation 2-14

The constants of equation (4-3) are summarized in table 4-4.

Table 4-4: Constants values of Eq. (4-3)

a_1	b_1	c_1	d_1
1.91699	9.9547	.2134	-9.9886

The correlation coefficient of equation (4-3) was found to be 0.942749 by using the Microsoft Excel program.

Illustration (4-3) demonstrate the starting section of the excel program. Appendix E represents the results of the predicted formula of percent drag reduction.

Figure 4-25 summarizes the comparison of measured and predicted results from equation (4-3) as percent drag reduction for each experiment. These experiments represent concentration of 10 to 50wppm, I.D. pipes of 19.05 to 50.8mm; volumetric flow rate ranged from 2.8 to 6.0 m^3/hr and corresponding Reynolds number 4000 to 32000. As shown in figure 4-25, good agreement between measured and predicted percentage drag-reduction is illustrated.

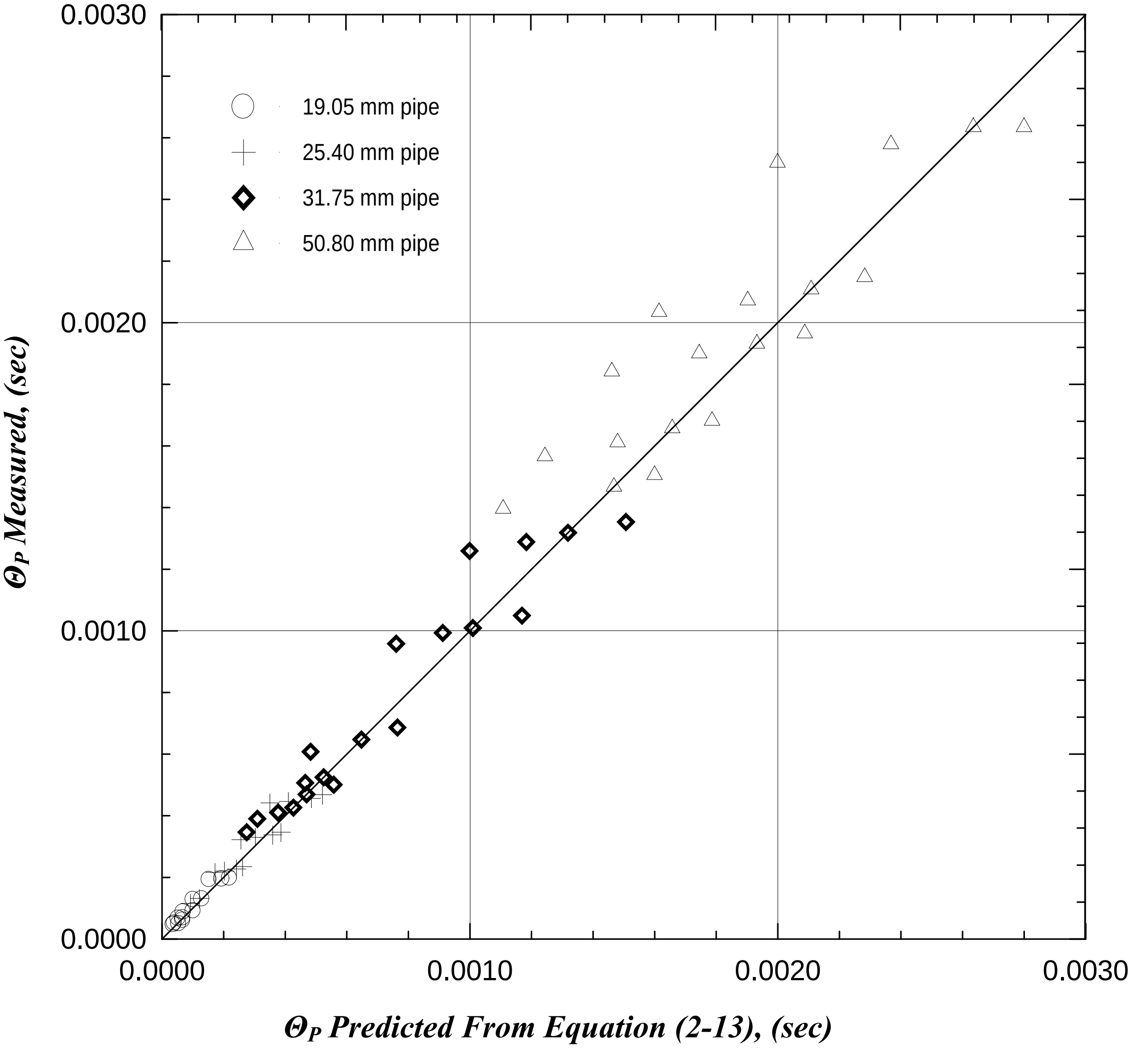


Figure 4-24: Comparison of measured and predicted polymer characteristic time scale.

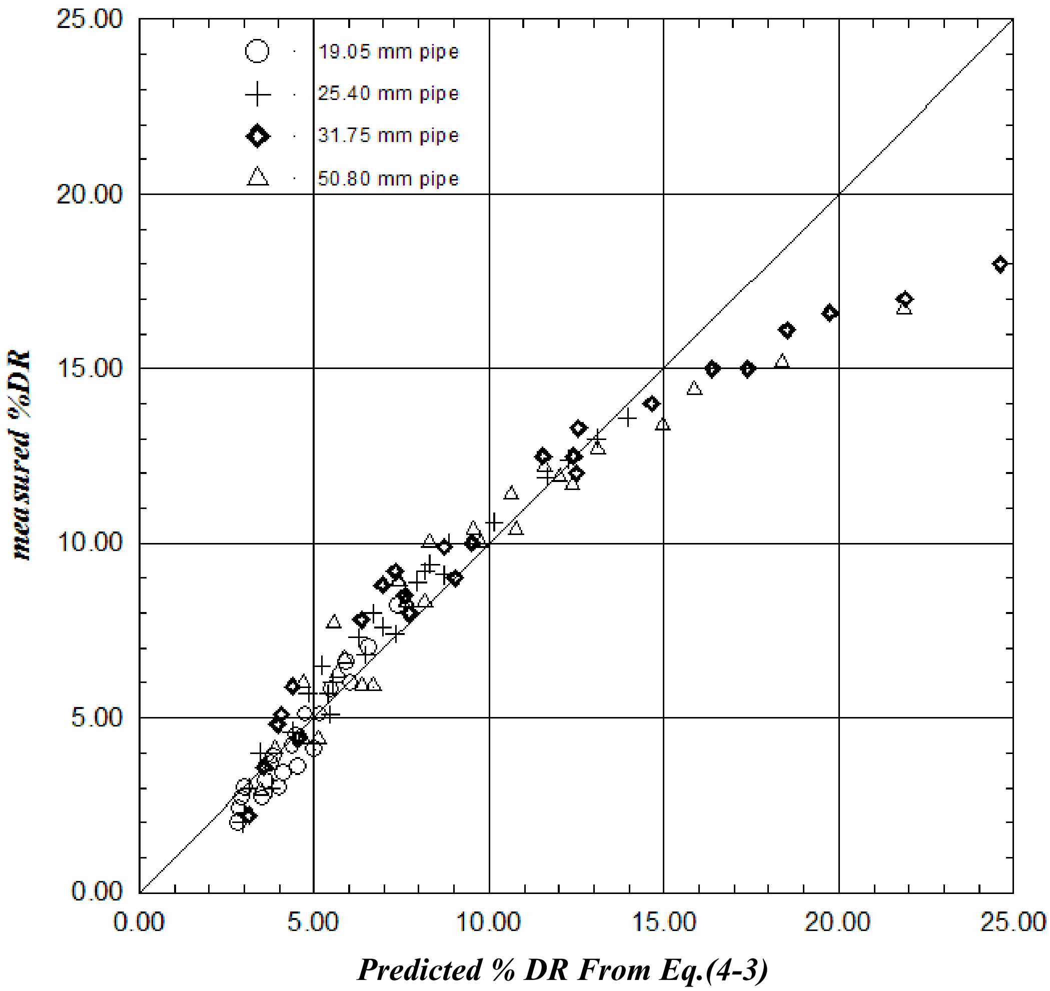
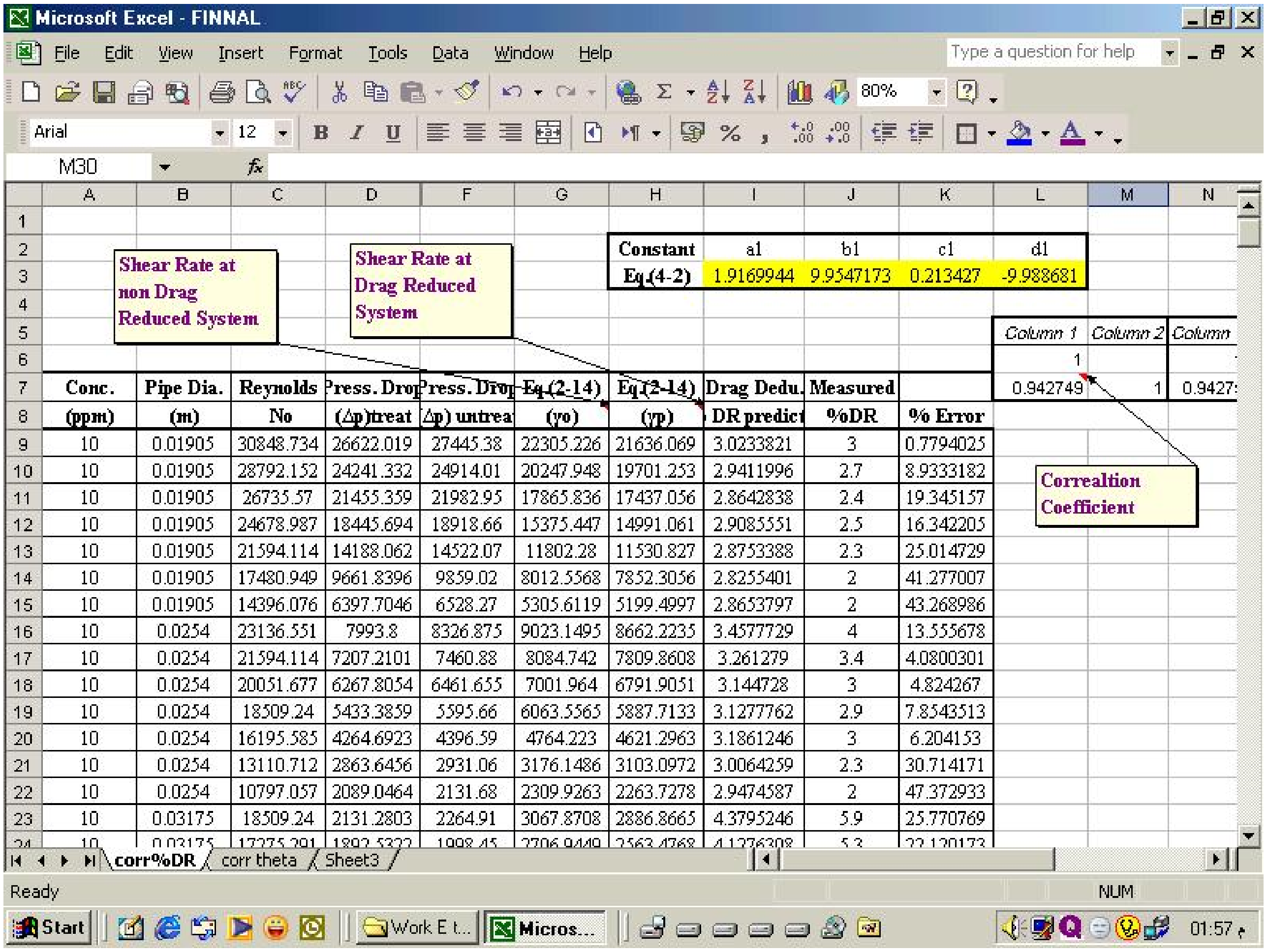


Figure 4-25: Comparison of measured and predicted polymer %DR

It is worth mentioning that the present correlation is to fit the results well for up to 15% drag-reduction, with 11.8% average absolute percent error. But the average absolute percent error with higher percentage drag-reduction is about 13.3%. That means, the present correlation predicted well the percentage drag-reduction for values up to 15%.



Shear Rate at non Drag Reduced System

Shear Rate at Drag Reduced System

Constant	a1	b1	c1	d1
Eq.(4-2)	1.9169944	9.9547173	0.213427	-9.988681

Column 1	Column 2	Column
1		
0.942749	1	0.9427

Correaltion Coefficient

Conc. (ppm)	Pipe Dia. (m)	Reynolds No	Press. Drop (Δp)treat	Press. Drop Δp) untrea	Eq.(2-14) (γo)	Eq.(2-14) (γp)	Drag Dedu. DR predict	Measured %DR	% Error
10	0.01905	30848.734	26622.019	27445.38	22305.226	21636.069	3.0233821	3	0.7794025
10	0.01905	28792.152	24241.332	24914.01	20247.948	19701.253	2.9411996	2.7	8.9333182
10	0.01905	26735.57	21455.359	21982.95	17865.836	17437.056	2.8642838	2.4	19.345157
10	0.01905	24678.987	18445.694	18918.66	15375.447	14991.061	2.9085551	2.5	16.342205
10	0.01905	21594.114	14188.062	14522.07	11802.28	11530.827	2.8753388	2.3	25.014729
10	0.01905	17480.949	9661.8396	9859.02	8012.5568	7852.3056	2.8255401	2	41.277007
10	0.01905	14396.076	6397.7046	6528.27	5305.6119	5199.4997	2.8653797	2	43.268986
10	0.0254	23136.551	7993.8	8326.875	9023.1495	8662.2235	3.4577729	4	13.555678
10	0.0254	21594.114	7207.2101	7460.88	8084.742	7809.8608	3.261279	3.4	4.0800301
10	0.0254	20051.677	6267.8054	6461.655	7001.964	6791.9051	3.144728	3	4.824267
10	0.0254	18509.24	5433.3859	5595.66	6063.5565	5887.7133	3.1277762	2.9	7.8543513
10	0.0254	16195.585	4264.6923	4396.59	4764.223	4621.2963	3.1861246	3	6.204153
10	0.0254	13110.712	2863.6456	2931.06	3176.1486	3103.0972	3.0064259	2.3	30.714171
10	0.0254	10797.057	2089.0464	2131.68	2309.9263	2263.7278	2.9474587	2	47.372933
10	0.03175	18509.24	2131.2803	2264.91	3067.8708	2886.8665	4.3795246	5.9	25.770769
10	0.03175	17275.291	1892.5322	1998.45	2706.9449	2563.4768	4.1276308	5.3	22.120173

Illustration 4–3: % DR Prediction

Part Two

4.5 Degradation

4.5.1 Introduction

In spite of, the additives demonstrate a desirably high drag reduction efficiency (as illustrated adequately in the previous suction), while so undesirable mechanical degradation under turbulent flow occurs. Therefore, molecular degradation is one of the major defects in drag reduction application, since the polymeric additives are exposed to strong turbulent elongational strain and shear stress. The mechanical degradation process was assumed to be that the polymer chains can indeed be fully extended by turbulent flow and experience the chain midpoint scission of macromolecule (101)

The mechanical degradation and the effect of homogenesity of polymer-solvent on the percent drag reduction effectiveness for three oppanol B types of different molecular weights under turbulent flow have been investigated as function of time, by various conditions of polymer concentration, flow rate and pipe diameter. Since the long chain polymer experiences mid-point degradation, the polymer chains having different molecular weights will show different time dependent resistance. In other words, longer molecules are more susceptible to mechanical degradation accompanying more rapid degradation. (5)

The mechanical degradation behavior as a function of time and with ultimate goal of establishing a correlation between polymer degradation and pipeline diameter in turbulent flow was adopted to examine their time-dependent drag reduction efficiency.

4.5.2 Effect of homogenesity on polymer drag reduction

In the present work, the effect of solution homogenesity between three polymer types, of molecular weights $2.5*10^6$, $4*10^6$, $6*10^6$ g/mol and flowing liquid, gas oil has been considered. This effect was detected by chance; through measuring the values of percent drag reduction for oppanol B 250 polymer type after a few minutes from addition of polymeric solution to the gas oil solvent, without taking into account the effect of time, which is indispensable in order the flow becomes homogeneous. Preliminary results have shown irregular and factual values of percent drag reduction, and this render to that the solution is still heterogeneous at the beginning, then as the time passes the flow approaches homogeneous solution and admissible results were obtained, after that a maximum drag reduction (MDR) value was gained at a certain time.

Many tests have been made in this field for three polymer types at various pipe diameters, polymer concentrations and flow rates in order to find the time needed to reach the maximum drag reduction before the polymer begins to degrade. After the maximum drag reduction was obtained, the influence of polymer begins to vanish as time passes and the value of percent drag reduction decreases until a minimum value is reached. This behavior is appeared because of the flow at the beginning is heterogeneous until it reached to homogeneous flow with time passes and so maximum drag reduction is being occured, then the effect of degradation will be discerned depending upon the pipe diameter, concentration and flow rate. For instance, figure 4-26 for oppanpl B 250 at 31.75mm I.D. pipe and 50wppm concentration is a selected sample from the experimental data, in order to elucidate the above phenomena.

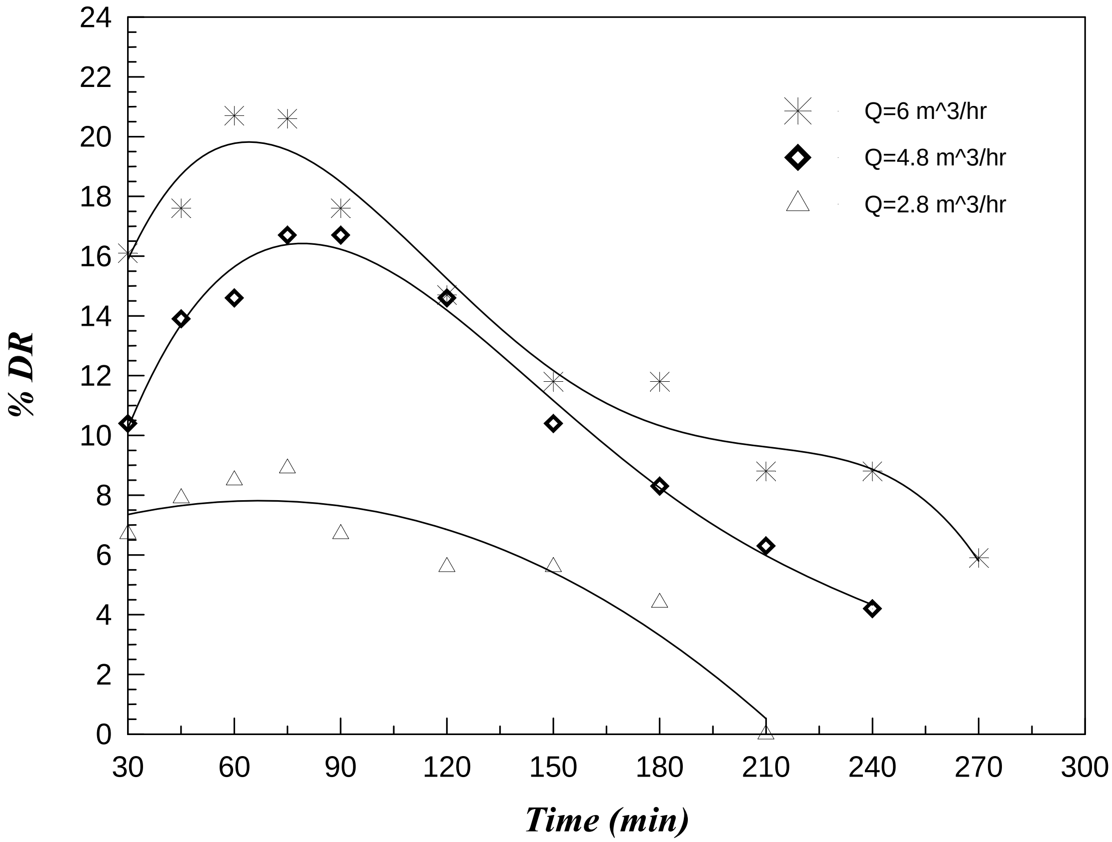


Figure 4-26: Effect of time on effectiveness of oppanol 250 as drag-reducer at 31.75 mm I.D pipe and 50wppm polymer concentration.

As shown in figure (4-26), the percentage drag-reduction increases rapidly during the first 45-75 minutes according to the flow rates. This time is required to take complete homogenous solution of polymeric additive in flowing gas oil. The degree of flow rate enhanced the homogeneity of the system. Therefore, maximum drag-reduction was achieved after about 60 minute circulation at 6.0 m^3/hr flow rate, while it is required about 75 minute for 2.8 m^3/hr and 4.8 m^3/hr flow rates.

In order to demonstrate the behavior of polymer-solvent homogeneity adequately, the effect of polymer concentration with variable pipe diameter at constant flow rate with 6 m^3/hr have been investigated for oppanol B 250, as listed in table 4-5, which summarizes the time needed to reach the maximum drag reduction for each concentration.

Table 4-5: Time required for MDR% at different concentrations and I.D pipes, oppanol B 250, 6.0m^3/hr

I.D pipe (mm)	Conc. (wppm)	MDR%	MDR time, min
50.8	50	16.7	75
50.8	30	12	45
50.8	10	7.7	30
31.75	50	20.6	60
31.75	30	13.9	45
31.75	10	6.9	30
19.05	50	8.3	30
19.05	30	4.9	30
19.05	10	2.9	20

As listed in table 4-5, at high concentration 50wppm, the time needed to reach MDR% is about 75 min for 50.8mm I.D pipe, but for low concentration of 10wppm at the same I.D pipe it is noticed that a 30 minute is enough to reach the MDR at constant flow rate. In other words, the concentrated solution needed an extra time to be homogeneous with solvent than that of diluted one, probably due to the fact, that high concentrations require more time for dissolving the polymer in flowing gas oil.

Furthermore, the small pipe size occupied a little time to obtain MDR than large pipe size did because the velocity is higher in the small pipe than that of large pipe at constant flow rate. As discussed in previous section, high velocities enhance the drag reduction and it will quickly reach the maximum drag reduction.

The effect of flow rate on polymer-solvent homogeneity also has been implemented, and illustrated table (4-6), for oppanol B 200 polymer at 50wppm concentration.

Table 4-6: MDR% time required for oppanol B 200 at different flow rates, 50wppm polymer concentration.

I.D pipe (mm)	Flow rate (m^3/hr)	MDR%	Time needed (min)
50.8	6	10.7	60
50.8	4.8	8.8	75
50.8	3.4	5.9	75
31.75	6	11.8	60
31.75	4.8	8.4	60
31.75	2.8	6.0	75
19.05	6	4.8	20
19.05	4.8	3.7	20
19.05	2.8	3	30

As shown in table 4-6; high flow rate required less time to be completely homogeneous and then to obtain maximum drag reduction at the same I.D pipe and concentration.

The effect of flow rate on polymer-solvent homogeneity for oppanol B 150 type with molecular weight about $2*10^6$ seemed not very noticeable, because of its low molecular weight. Figures 4-27 to 4-30 for oppanol B 200 at 50.8, 31.75, 19.05 mm I.D and for oppanol B 150 at 31.75 mm I.D respectively were plotted to illustrate the flow rate effectiveness.

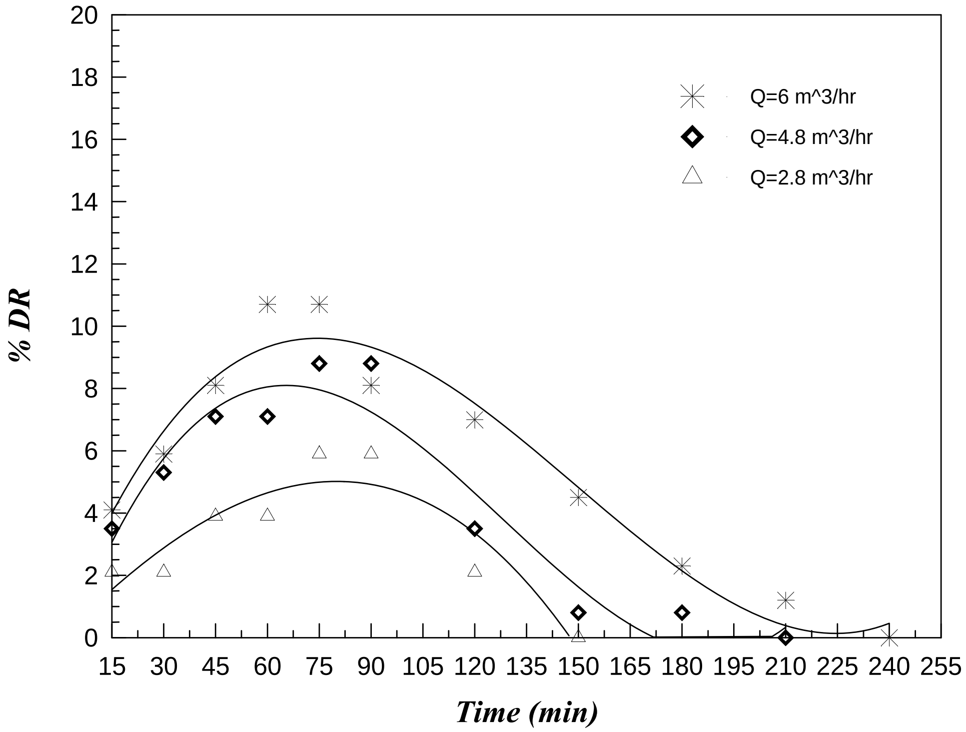


Figure 4-27: Degradation of oppanol 200 in a 50wppm and 50.8 mm I.D pipe.

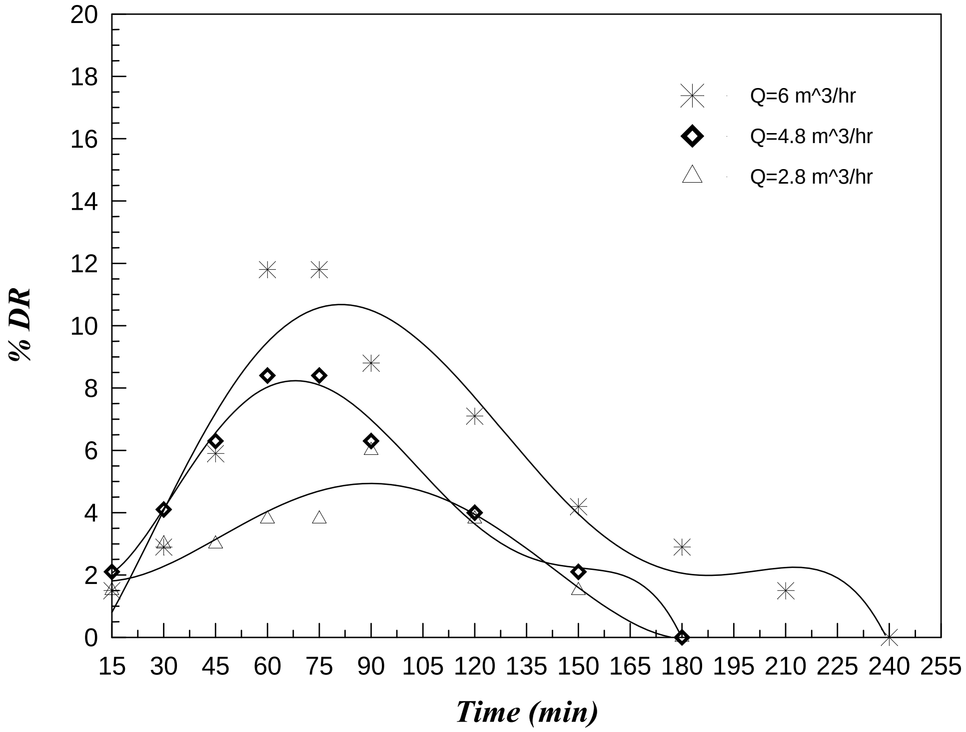


Figure 4-28: Degradation of oppanol 200 at in a 50wppm and 31.75 mm I.D pipe.

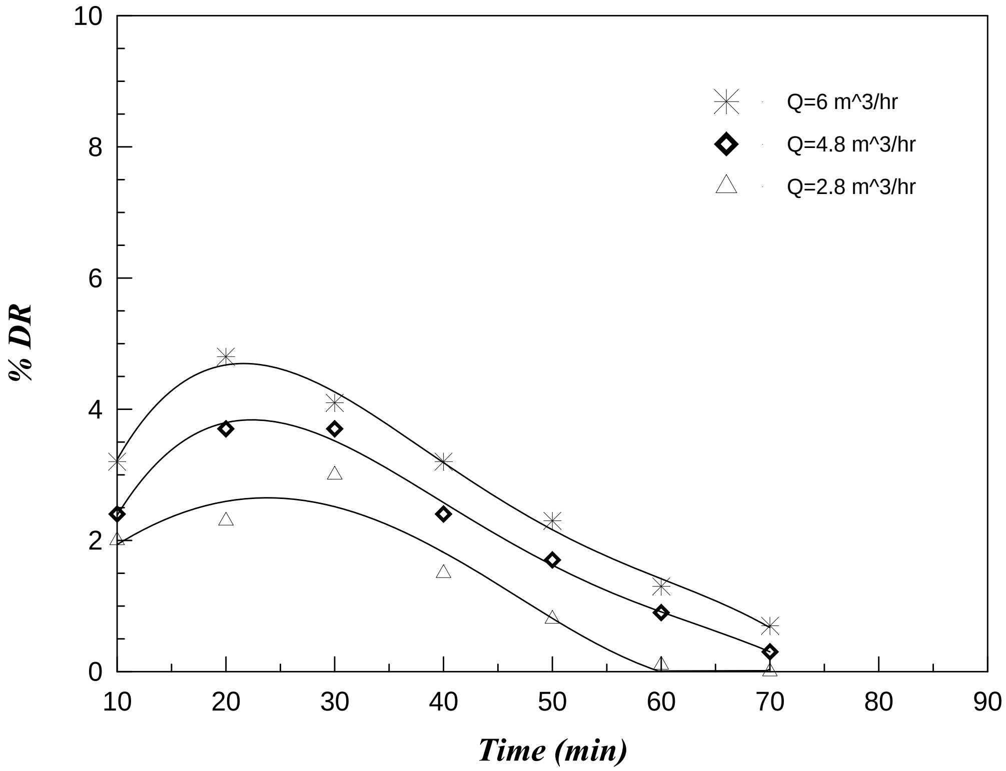


Figure 4-29: Degradation of oppanol 200 in a 50wppm and 19.05 mm I.D pipe.

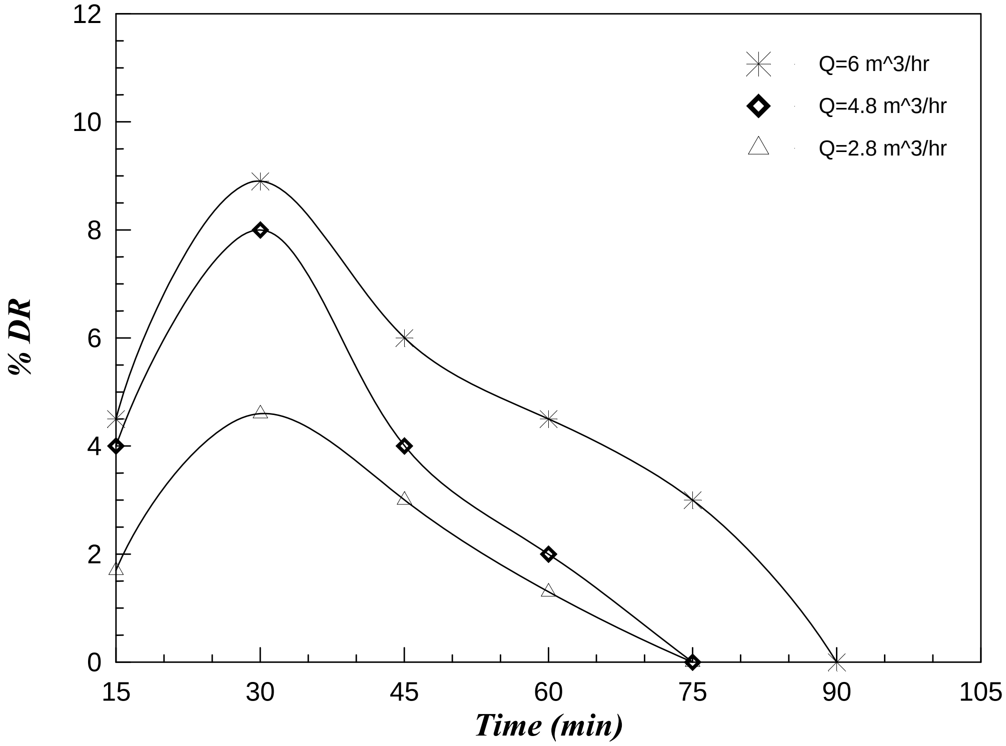


Figure 4-30: Degradation of oppanol 150 in a 50wppm and 31.75 mm I.D pipe.

4.5.3 Effect of Concentration on Polymer Degradation

It was noticed in figures 4-26 through 4-30, that the drag-reduction efficiency decrease gradually with time, mainly due to the mechanical degradation of the polymer molecules. (47,49)

For the sake of easily recognizing the effects of concentration on degradation, the results of oppanol B 250 at different concentrations are plotted in figures 4-31 to 4-33 for 19.05, 31.75 and 50.8mm I.D pipe respectively, at flow rate 6.0m^3/hr, taking the time zero for maximum percentage drag-reduction. These figures indicate clearly, that low concentrations will be degraded quickly compared with high concentrations, i.e. 50wppm, and this agrees with finding of Sellin(112), who found that degradation is more likely to occur at low Reynolds number for low concentration. Therefore, the percentage drag-reduction decreases rapidly, reaching to zero value after 60 minute and 120 minute running for 10wppm and 30wppm concentrations respectively, as shown in figure 4-32 for example. While at 50wppm concentration, there is still undegraded polymer until the 220 minute experimental time elapsed.

Since degradation is generally attributed to mechanical breaking of the polymer chains, and when a low concentration exists in the pipe a larger performance of chains are destroyed and consequently a rapid decrease in the effective drag reduction is noticed. For high concentrations a smaller percentage of the polymer is degraded under the same flow conditions and there is still sufficient effective polymer left to cause high values of drag-reduction at the considered experimental time.

Hence, the percentage drag-reduction value of about 12% was observed for 50wppm polymer concentration after 220 minute which is approximately equal to the initial value (zero time) of percentage drag-reduction for 30wppm. Moreover, at higher concentrations, the molecular extensions are inhibited by the surrounding molecules. Therefore, degradation is limited at higher concentration. In small pipe size, however, the results appear to have a zero percentage drag-reduction after shorter time even though for high concentration, suggesting that the effect of concentration is not dominant in this region, as shown in figure(4-31) for 19.05mm I.D pipe.

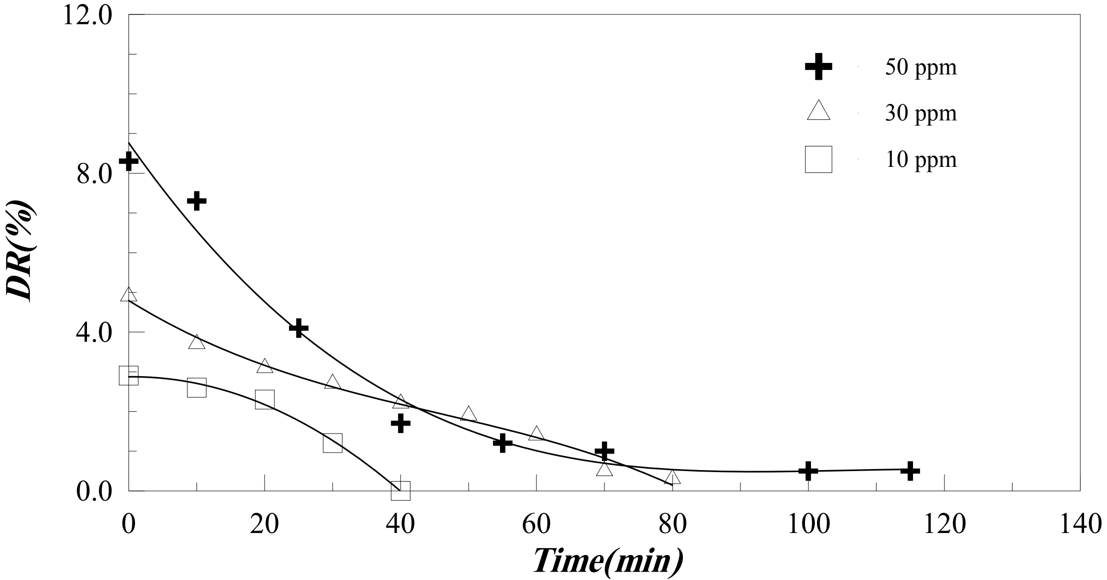


Figure 4-31: Concentration effect on degradation for oppanol 250 at $6m^3$/hr and 19.05 mm I.D

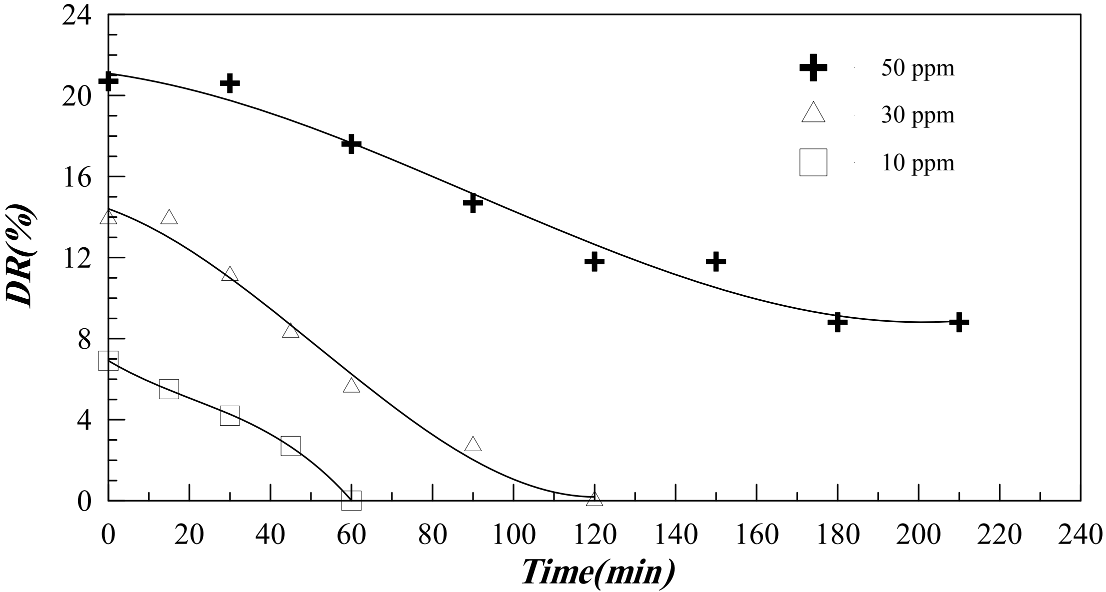


Figure 4-32: Concentration effect on degradation for oppanol 250 at 6m^3/hr and 31.75 mm I.D

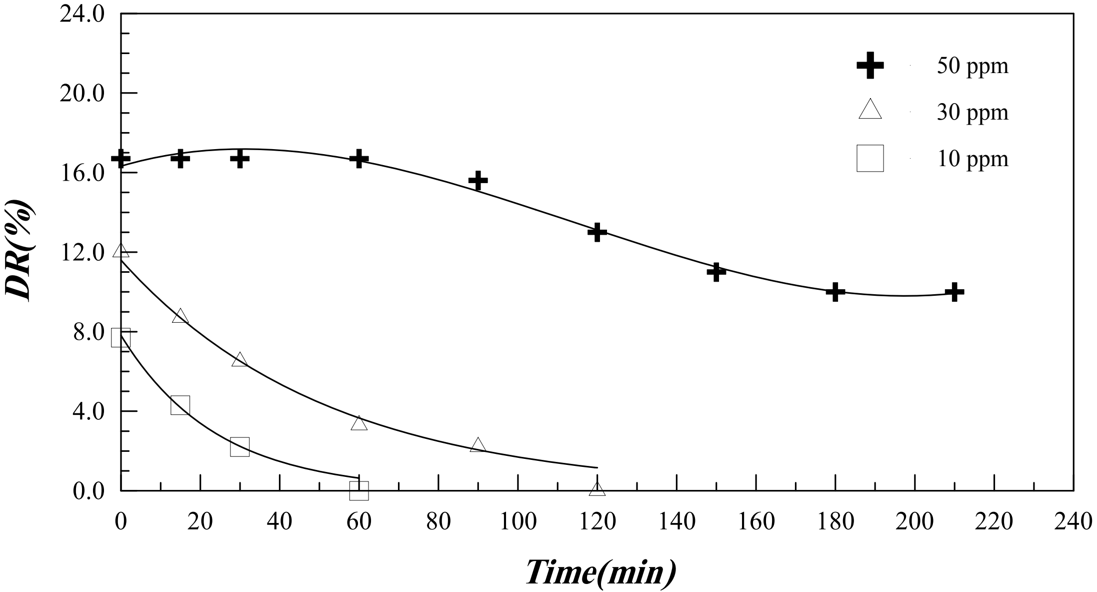


Figure 4-33: Concentration effect on degradation for oppanol 250 at 6 m^3/hr and 50.8 mm I.D

4.5.4 Effect of Polymer Molecular Weight on Degradation

The effect of additive molecular weight on degradation was accomplished by measuring the degradation time for the three polymers, which differ in molecular weights. These polymers are oppanols B 150,200 and 250 with average molecular weight about $2.5*10^6$, $4*10^6$ and $6*10^6$ g/mol respectively. The results are plotted in figure (4-34) at constant flow rate, 6.0m^3/hr and for 31.75mm I.D. pipe. As shown in this figure, the low molecular weight polymers are sharply degraded within the first two hours, resulting in fast decrease of percentage drag-reduction. While the higher molecular weight polymer has higher resistance toward the degradation. Therefore, still about 9% drag-reduction was achieved after 220 minute operation, due to presence of undegradable molecules, which act as a drag reducer agents as shown in figure (4-34).

This means, that the undegradable molecules will not degrade any further as time passes, at high concentration (50wppm) for high molecular weight polymer. Furthermore, the effect of oppanol B 200 had completely vanished within 2.5 hr, whereas oppanol B 250 was affected approximately as the same effect of oppanol B 200 at zero time, during 2.5 hr.

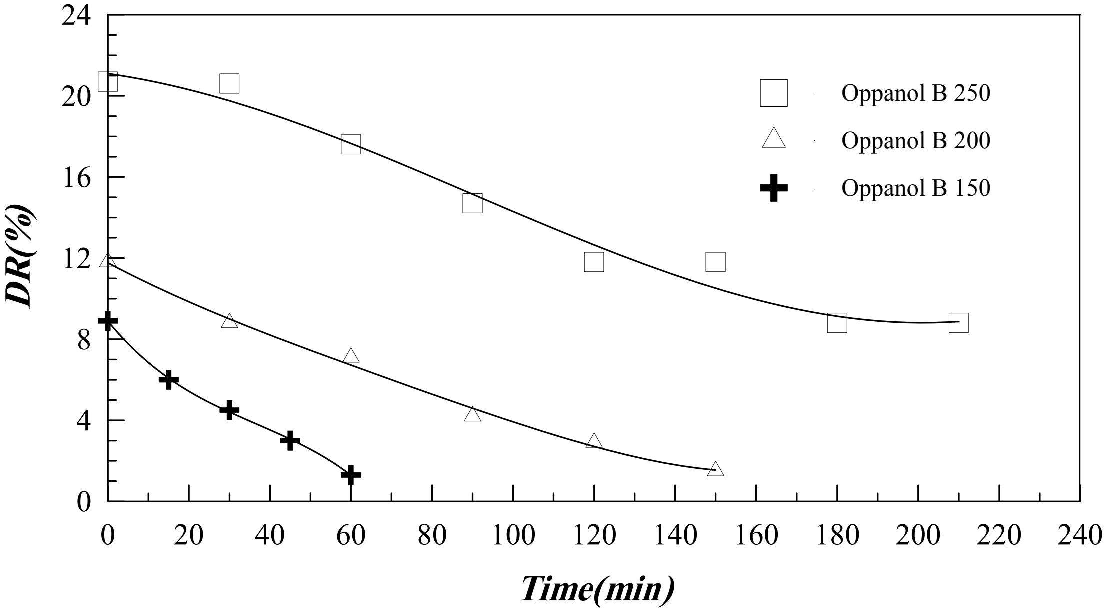


Figure 4-34: Effect of molecular weight on degradation for Q= 6 m3/hr and 31.75 mm I.D.

4.5.5 Effect of Pipe Diameter on Degradation

It is desired to investigate the effect of pipe diameter on degradation of polymeric drag reducers. Generally observed that, the small pipe diameter, 19.05 mm I.D pipe affected more the polymer degradation for all molecular weights studied. Figures (4-35) to (4-37) show such dependence. While for a given polymer concentration and molecular weight, the effectiveness of degradation is lower in the large pipe size than that of small pipe size. This phenomenon can be interpreted by turbulent or molecular interaction as follows; when the pipe diameter increased the persistence time of the large eddies is increased also, which is proportional to D/u^*. This persistence time is related to the length of time the molecules are stretched in the relatively rotation-free, high-strain rate areas of turbulent flow, and the mean distance between two molecules is less than the size of an elongated molecules(113).

The molecular weight has also a predominant effect on the degradation, as discussed in part 4.5.4.

This effect is well noticeable in figure (4-37) for high molecular weight polymer (oppanol B 250). It seems that after about 2 hr, the percent drag reduction goes to zero for small pipe size (19.05mm), while in large pipe sizes 31.75mm and 50.8mm, the percent drag reduction is going to its limiting value within 2.5hr, due to low degradation effect in large pipe sizes.

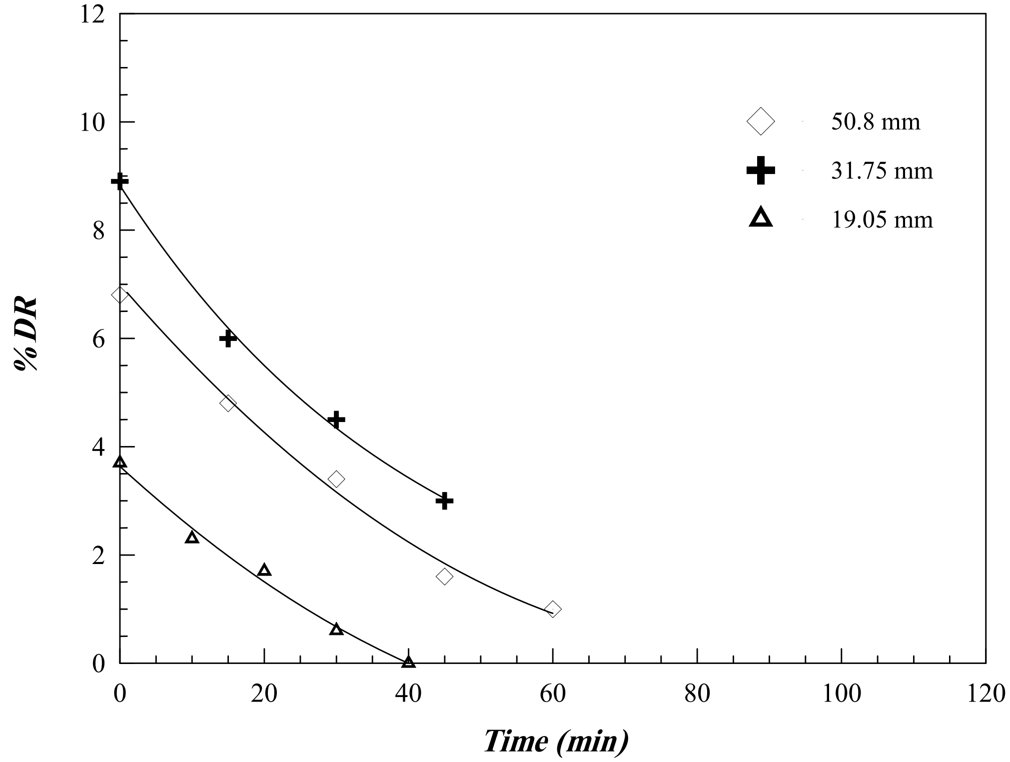


Figure 4-35: Degradation of oppanol 150 at different pipe diameters and 50 wppm and 6.0 m^3/hr volumetric flow rate.

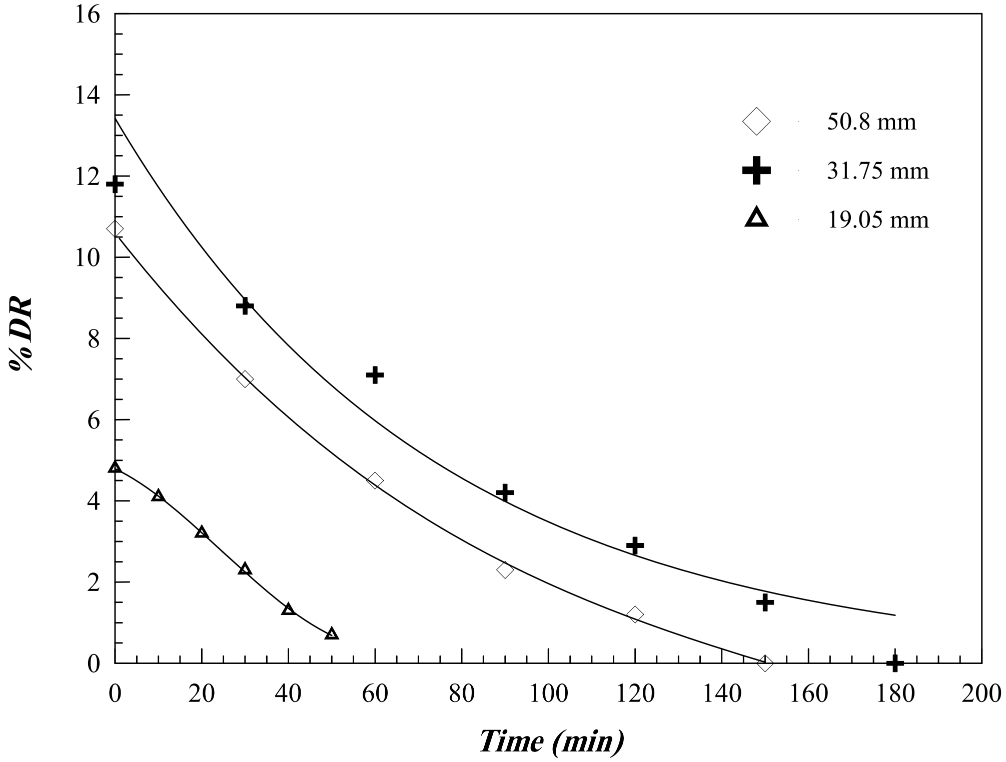


Figure 4-36: Degradation of oppanol 200 at different pipe diameters and 50 wppm and 6.0 m^3/hr Volumetric flow rate.

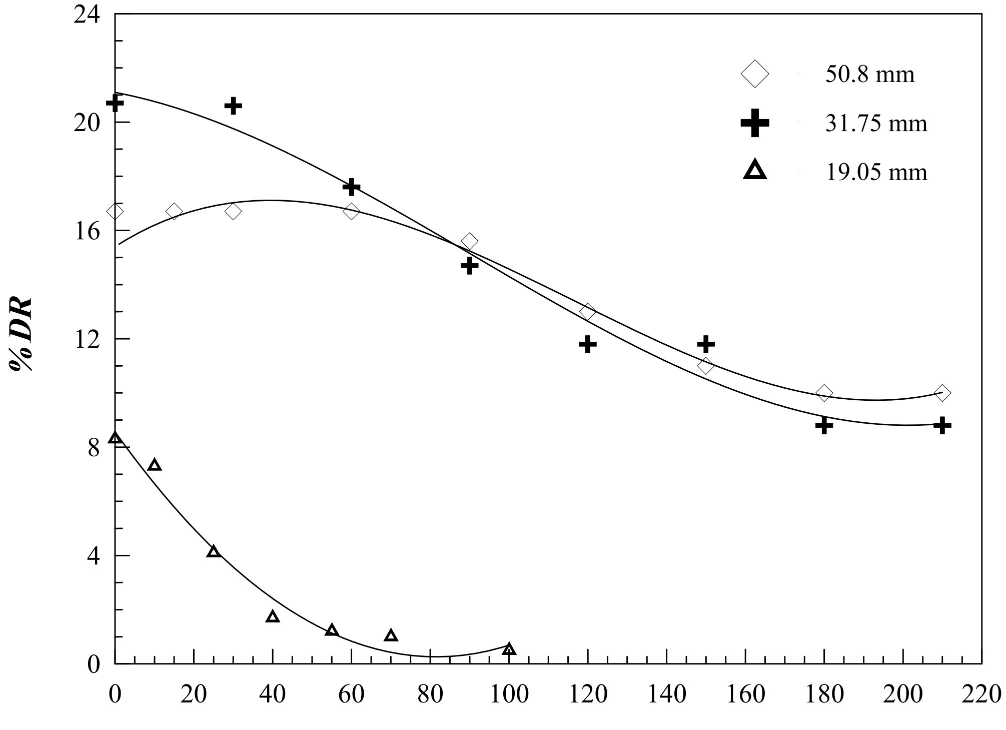


Figure 4-37: Degradation of oppanol 250 at different pipe diameters and 50 wppm and 6.0 m^3/hr volumetric flow rate.

4.6 Prediction of Degradation

In the present study, a prediction has been done for three polymer types to explain time-dependent relative drag reduction efficiency which is related to the mechanical degradation.

Many researchers have investigated that, the adoptability of λ-DNA supports the validity of simple degradation model in fitting the degradation curve of λ apply a Brostow model. (103)

Another investigators have adopted the following single-relaxation decay model for shear resistant drag reducers, as given in equation (2-22). The empirical equation associated with a slow relaxation time of the polymer solution is as follows. (105,106)

$$DR(t)/DR(0) = \exp(-t/\lambda_s) \qquad (2\text{-}22)$$

Where $DR(t)$ and $DR(0)$ are the percent drag reduction efficiency at times t and t=0, respectively. $1/\lambda_s$ quantifies the loss rate of drag-reduction activity or the rate of degradation.

Another form of a fractional experimental, often called the Kohrausch, Williams and Watt (KWW) function, which had been modified from the single exponential decay function shown in equation (2-22) is as in equation (2-23). This equation has been used to describe the second order nonlinear relaxation behavior.

$$DR(t)/DR(0) = \exp\left[-(t/\lambda_F)^{1-nf}\right] \qquad (2\text{-}23)$$

Here λ_F is an observed time scale of the relaxation process and n_f is a fractional exponent i.e. the degree of non-exponentiality in considering the breadth of the distribution of relaxation time. Choi(49) had conjected in his work the single-relaxation decay model (equation.2-22) and the KWW function (equation 2-23) by fitting experimental data, and found that the single-relaxation decay model does not fit the data relatively well. While KWW function gives acceptable results to fit his data.

In the present investigation, the experimental data were fitted to KWW function (equation 2-23), which gave unacceptable results, with relatively high average absolute percent error, as shown in table (4-8). Therefore, a modification was done to equation (2-23) to relate the relative drag efficiency with mechanical degradation time and to improve the fitting of the experimental data by introducing the pipe diameter effect as a new parameter, for the three different in molecular weight polymers at 50wppm concentration and pipe diameters ranging 19.05-50.8mm, with degradation time ranged 0 – 100 min.

The modified equation is as follows:-

$$DR(t)/DR(0) = K\left[\exp(-t/\lambda)\right]^{(1-n/D)} \qquad (4\text{-}4)$$

where K: exponential constant

D: pipe diameter

The values of K, λ and n for three polymer types are listed in table 4-7.

Table 4-7: constants values of Eq.(4-4) for 3 polymer types

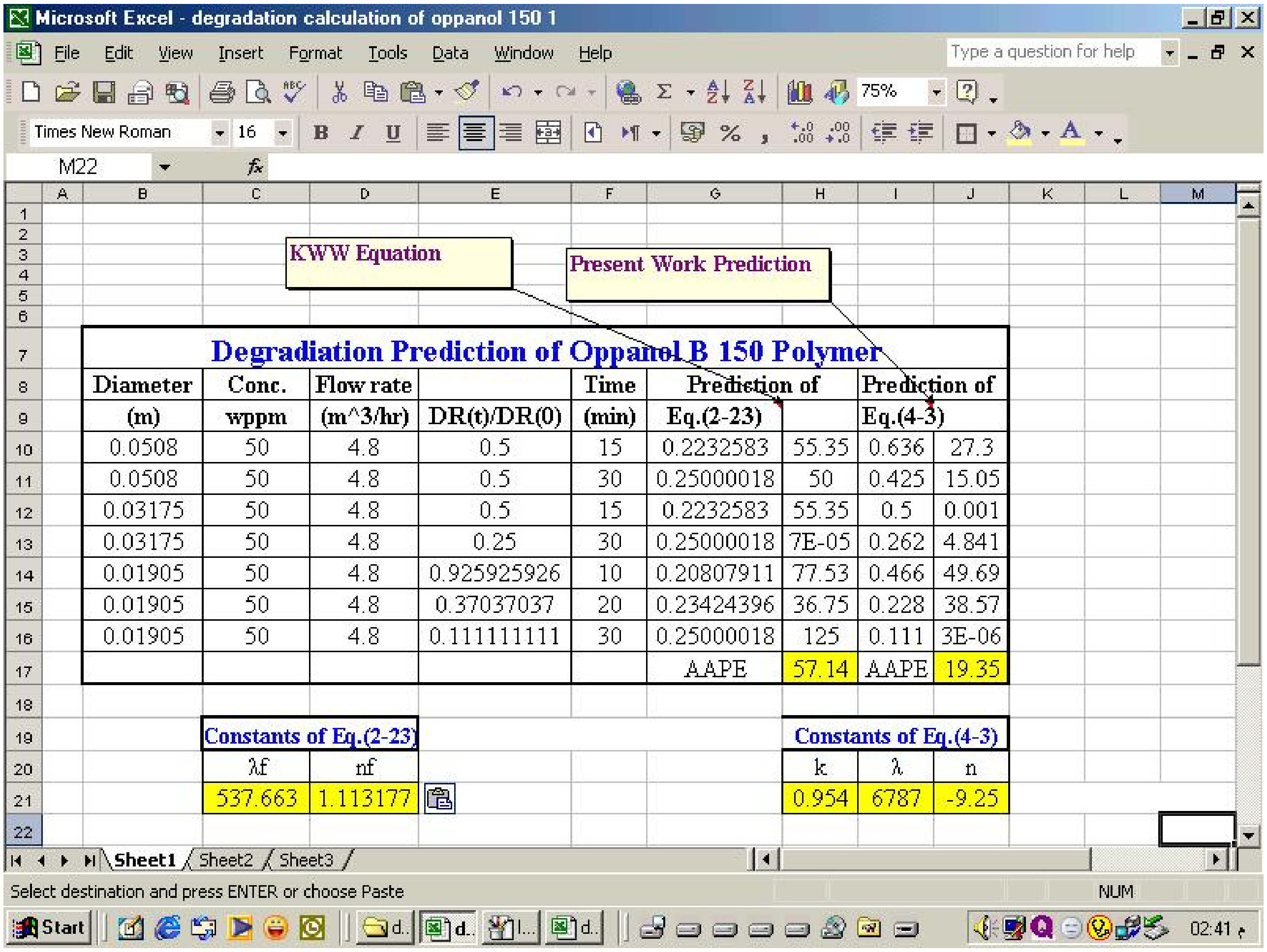
Polymer type	***K***	**λ**	***n***
Oppanol B 250	1.0834	8839.7	-2.3485
Oppanol B 200	1.3088	7005.2	-6.3709
Oppanol B 150	0.9538	6786.9	-9.2460

The modified correlation (equation 4-4) was found to fit the experimental data better than the KWW function as shown in table (4-8), with an average absolute percent error ranged between 7.3-32.0 according the polymeric molecular weight. The more effective drag-reducer, oppanol B 250 correlates the experimental data more satisfactory. The relatively high average absolute percent error values by applying the modified equation are probably due to the wide ranges of time and pipe diameters. It is worthy to mention, that the middle molecular weight polymer, oppanol B 200 gave higher average absolute percent error compared with the low molecular type, oppanol B 150 in both correlations given in equation (2-23) and the modified one (equation 4-4), due to molecular structure of oppanol B 200 polymer.

Table 4-8: AAPE for predicted Eq.(4-4) and Eq.(2-23)

Polymer type	**AAPE for predicted Eq. (4-4)**	**AAPE for Eq. (2-23)**
Oppanol 250	7.3	49.6
Oppanol 200	32.0	64.3
Oppanol 150	19.3	57.1

Illustrations 4-4, 4-5 and 4-6 represent the Microsoft Excel program in order to predict the degradation as a function of pipe diameter for the three polymer types.



KWW Equation

Present Work Prediction

Degradiation Prediction of Oppanol B 150 Polymer								
Diameter (m)	Conc. wppm	Flow rate (m^3/hr)	DR(t)/DR(0)	Time (min)	Prediction of Eq.(2-23)		Prediction of Eq.(4-3)	
0.0508	50	4.8	0.5	15	0.2232583	55.35	0.636	27.3
0.0508	50	4.8	0.5	30	0.25000018	50	0.425	15.05
0.03175	50	4.8	0.5	15	0.2232583	55.35	0.5	0.001
0.03175	50	4.8	0.25	30	0.25000018	7E-05	0.262	4.841
0.01905	50	4.8	0.925925926	10	0.20807911	77.53	0.466	49.69
0.01905	50	4.8	0.37037037	20	0.23424396	36.75	0.228	38.57
0.01905	50	4.8	0.111111111	30	0.25000018	125	0.111	3E-06
					AAPE	57.14	AAPE	19.35

Constants of Eq.(2-23)	
λf	nf
537.663	1.113177

Constants of Eq.(4-3)		
k	λ	n
0.954	6787	-9.25

Sheet1 Sheet2 Sheet3

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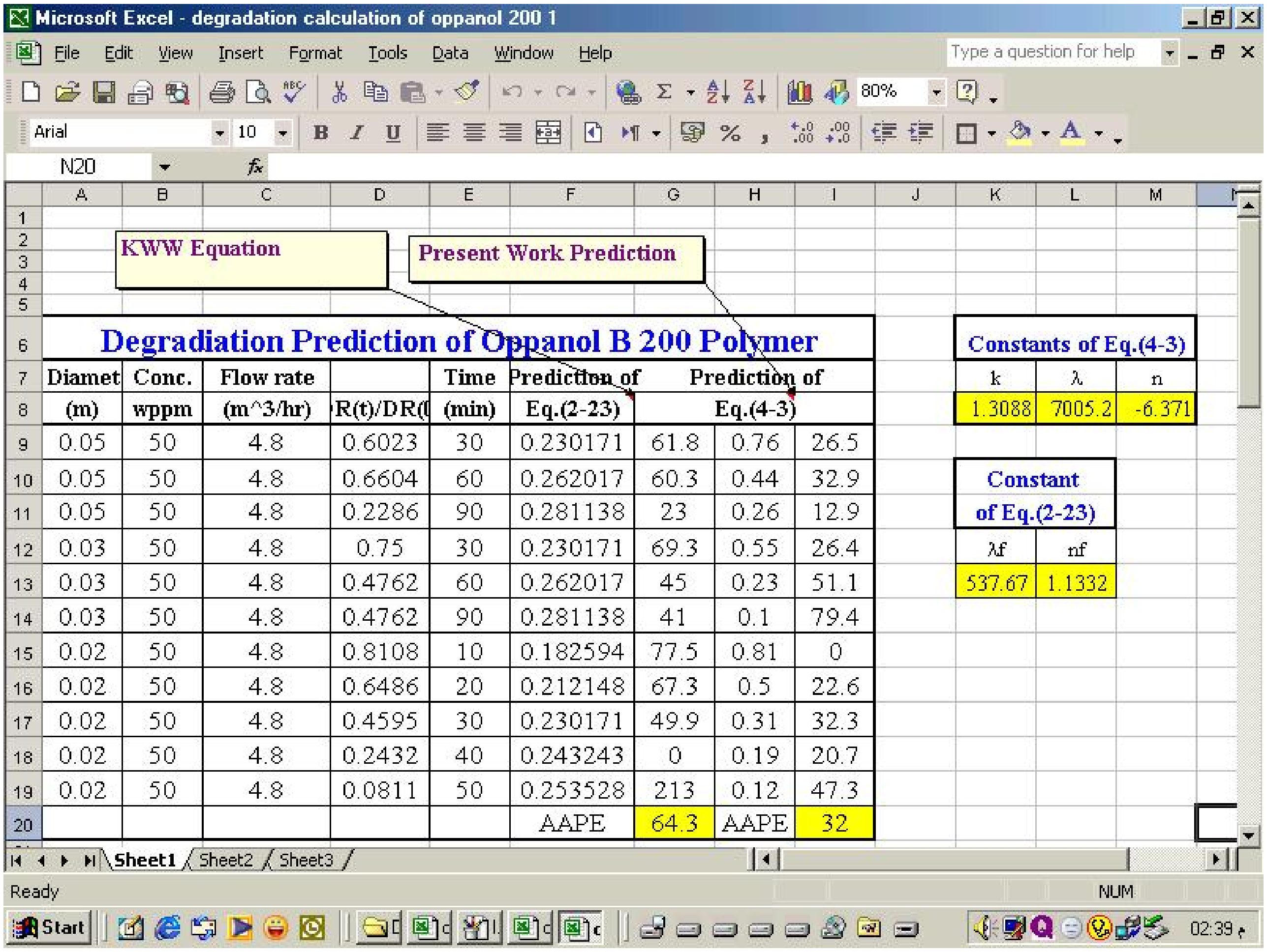
Illustration 4–4: Degradation Correlation of oppanol B 150



KWW Equation

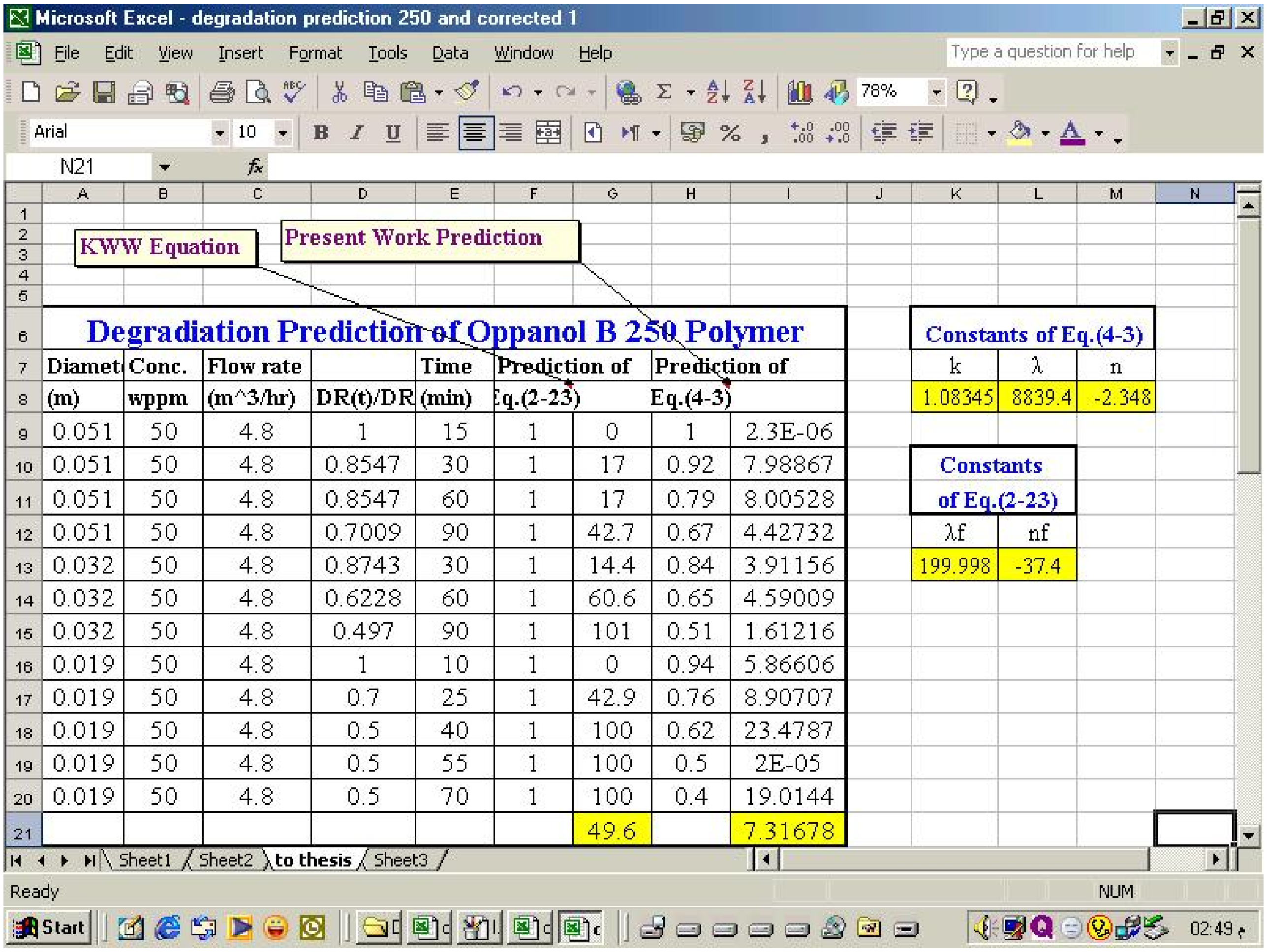
Present Work Prediction

Degradiation Prediction of Oppanol B 200 Polymer								
Diamet (m)	Conc. wppm	Flow rate (m^3/hr)	R(t)/DR(	Time (min)	Prediction of Eq.(2-23)	Prediction of Eq.(4-3)		
0.05	50	4.8	0.6023	30	0.230171	61.8	0.76	26.5
0.05	50	4.8	0.6604	60	0.262017	60.3	0.44	32.9
0.05	50	4.8	0.2286	90	0.281138	23	0.26	12.9
0.03	50	4.8	0.75	30	0.230171	69.3	0.55	26.4
0.03	50	4.8	0.4762	60	0.262017	45	0.23	51.1
0.03	50	4.8	0.4762	90	0.281138	41	0.1	79.4
0.02	50	4.8	0.8108	10	0.182594	77.5	0.81	0
0.02	50	4.8	0.6486	20	0.212148	67.3	0.5	22.6
0.02	50	4.8	0.4595	30	0.230171	49.9	0.31	32.3
0.02	50	4.8	0.2432	40	0.243243	0	0.19	20.7
0.02	50	4.8	0.0811	50	0.253528	213	0.12	47.3
					AAPE	64.3	AAPE	32

Constants of Eq.(4-3)		
k	λ	n
1.3088	7005.2	-6.371

Constant of Eq.(2-23)	
λf	nf
537.67	1.1332

Illustration 4–5: Degradation Correlation of oppanol B 200



KWW Equation

Present Work Prediction

Degradiation Prediction of Oppanol B 250 Polymer

Diamet	Conc.	Flow rate		Time	Prediction of		Prediction of	
(m)	wppm	(m^3/hr)	DR(t)/DR	(min)	Eq.(2-23)		Eq.(4-3)	
0.051	50	4.8	1	15	1	0	1	2.3E-06
0.051	50	4.8	0.8547	30	1	17	0.92	7.98867
0.051	50	4.8	0.8547	60	1	17	0.79	8.00528
0.051	50	4.8	0.7009	90	1	42.7	0.67	4.42732
0.032	50	4.8	0.8743	30	1	14.4	0.84	3.91156
0.032	50	4.8	0.6228	60	1	60.6	0.65	4.59009
0.032	50	4.8	0.497	90	1	101	0.51	1.61216
0.019	50	4.8	1	10	1	0	0.94	5.86606
0.019	50	4.8	0.7	25	1	42.9	0.76	8.90707
0.019	50	4.8	0.5	40	1	100	0.62	23.4787
0.019	50	4.8	0.5	55	1	100	0.5	2E-05
0.019	50	4.8	0.5	70	1	100	0.4	19.0144
						49.6		7.31678

Constants of Eq.(4-3)

k	λ	n
1.08345	8839.4	-2.348

Constants of Eq.(2-23)

λf	nf
199.998	-37.4

Illustration 4–6: Degradation Correlation of oppanol B 250

Figures 4-38 to 4-40 show the experimental and predicted drag-reduction efficiency as a function of various pipe diameters versus time of shear degradation for oppanol 150, 200 and 250 respectively at different pipe diameters. The experimental data of oppanol 250 are better fitted than that of oppanol 200 and oppanol 150. It clearly indicates that the polymer at small pipe size degrades more rapidly over the entire shearing time than that of large pipe size, since the polymer molecules are subjected to experience of the higher breaking force in the small pipe size at the same flow rate.

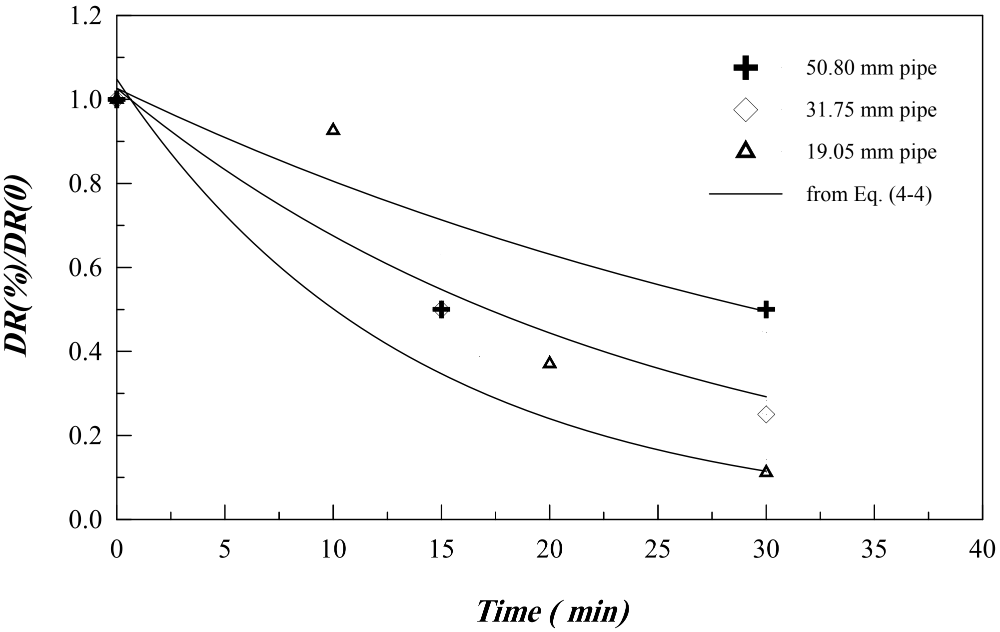


Figure 4-38: DR(t)/DR(0) as a function of time of shear degradation, at various pipe diameter, oppanol 150. Solid lines are obtained from Eq. (4-4), and symbols are experimental data

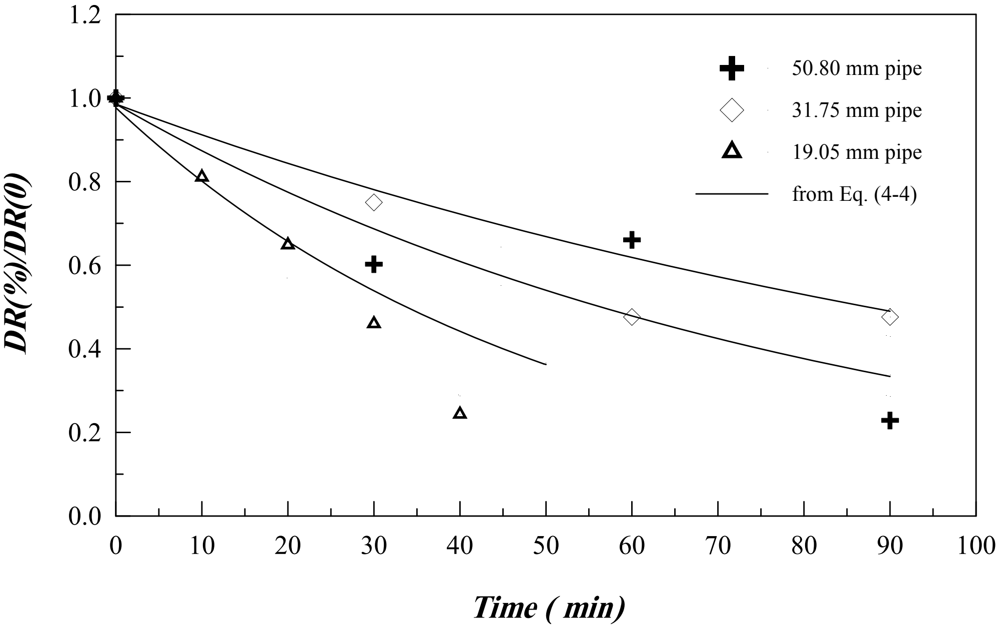


Figure 4-39: DR(t)/DR(0) as a function of time of shear degradation, at various pipe diameter, oppanol 200. Solid lines are obtained from Eq. (4-4), and symbols are experimental data

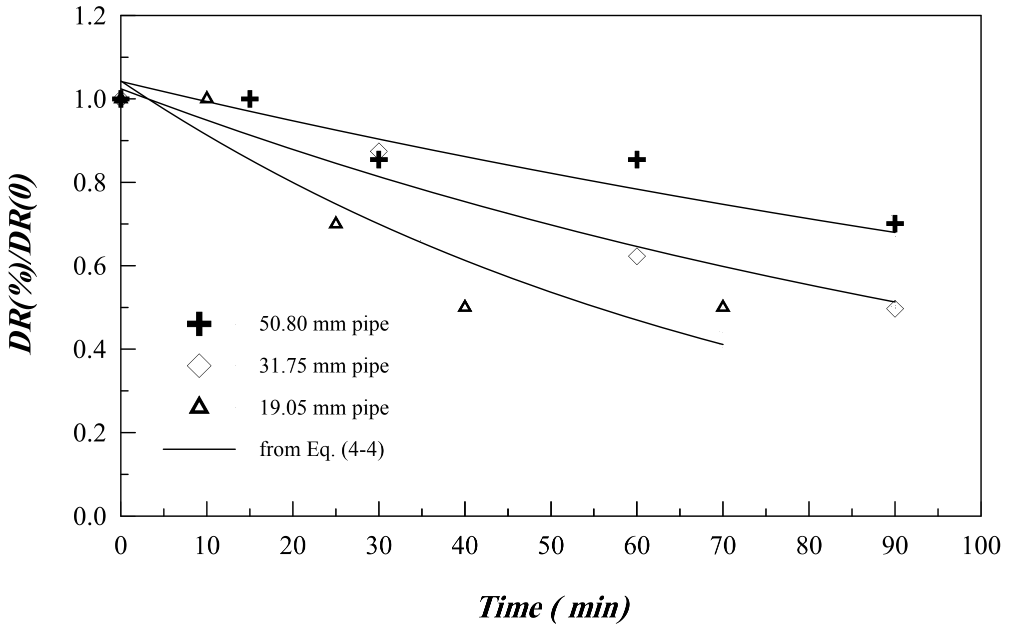


Figure 4-40: DR(t)/DR(0) as a function of time of shear degradation, at various pipe diameter, oppanol 250. Solid lines are obtained from Eq. (4-4), and symbols are experimental data

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. The efficiency of polyisobutylene, type oppanol B 250 as drag-reducing agents is strongly dependent on its concentration and flow velocity. For more concentrated polymer, oppanol B 250 is more efficient drag reducer in lighter liquid (kerosene) than that in heavier liquid (gasoil).

2. Percentage drag-reduction increases with increasing nominal pipe diameter at given velocities. This provides a significant indication for commercial applications in large-scale pipeline for the same polymer-solvent system This suggestion has a good agreement with the observations of Robart et.al.(43),) Manson(58) and Berman(59).
3. Values of calculated fanning friction factor for oppanol B 250 treated gas oil positioned toward Virk line for maximum drag-reduction, especially for high concentrations in 31.75mm I.D pipe. The fanning friction factor correlated as function of Reynolds number, resulted in good agreement with experimental observations

4. The time scale hypothesis was found to correlate the drag-reduction data satisfactory. In this correlation, the drag reduction is a function of the polymer concentration; shear stress at the wall for both treated and untreated cases.

5. The time needed to reach maximum drag-reduction was taken as indication to reach a homogeneous additive-solvent system. Higher molecular weight polyisobutylene additive required more time to be completely homogeneous. Furthermore, the time required is a function of polymeric concentration and pipe diameter and inverse to flow rate.
6. The time dependence of drag-reduction effectiveness was studied for polyisobutylene with three different molecular weights. A gradual decrease of percentage drag-reduction was observed as time progresses, due to mechanical degradation of polymer molecules. The low molecular weight polymers are sharply degraded within the first 2 hr, while the higher molecular weight polymer gradually degraded and it has shown a tendency to approach limiting value. Furthermore, the extent of the degradation was higher in small pipe size compared with large sizes, due to increasing the fluid velocity in small pipeline.
7. A correlation between polymer degradation and pipeline diameter was established, by modifying the fractional decay for 3 polymer types. The modified eq. fits experimental data better than the KWW decay function. It was also found that, the high molecular weight polymer, type B250, shows more enhanced relative drag reduction effectiveness than the other two types.

5.2 Recommendations for Further Work:

1. The effect of pipe roughness and pipe length on drag-reduction effectiveness needs to be investigated.
2. The effect of mechanical configuration such as elbows, valves and inclined pipe on percentage drag-reduction needs to be studied
3. Studying the effect of increasing temperature on efficiency of polymeric additives and their degradation behavior.
4. Studying the effect of other types, of drag-reducer agents, such as surfactants on drag-reduction phenomenon, and making a comparison such additives with polymeric additives.

APPENDIX A

PRESSURE DROP EXPERIMENTAL DATA

Table A-1: Pressure Drop Experimental Data for 19.05 mm pipe diameter at 2 m test section *le*/D=180 using oppanol B 250 polymer in (Pascal).

Volumetric Flow Rate (m^3/h)	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	27460	26660	26393	26060	25660	25194
5.6	24927	24261	23994	23727	23394	22994
5.2	21995	21461	21195	20995	20728	20395
4.8	18929	18462	18329	18129	17862	17596
4.2	14530	14196	14063	13930	13797	13597
3.4	9864.2	9664.3	9597.6	9531	9397.7	9264.4
2.8	6531.7	6398.4	6363.7	6331.8	6331.8	6265.1

Table A-2: Pressure Drop Experimental Data for 19.05 mm pipe diameter at 3 m test section *le* /D=130 using oppanol B 250 polymer in (Pascal).

Volumetric Flow Rate (m^3/h)	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	40923.1	39990.0	39456.8	39256.9	39056.9	38523.7
5.6	36657.5	35857.7	35457.8	35257.9	35057.9	34591.4
5.2	32525.2	31858.7	31525.5	31325.5	31192.2	30792.3
4.8	27459.8	26926.6	26660.0	26526.7	26393.4	26060.2
4.2	21461.3	21128.1	20861.5	20794.8	20661.5	20461.6
3.4	14529.7	14329.8	14196.5	14129.8	14063.2	13996.5
2.8	9997.5	9864.2	9797.6	9797.6	9730.9	9664.3

Table A-3: Pressure Drop Experimental Data for 19.05 mm pipe diameter at 4 m test section *le*/D>75 using oppanol B 250 polymer in (Pascal).

Volumetric Flow Rate (m^3/h)	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	54519.7	53453.3	52920.1	52520.2	52253.6	52120.3
5.6	48121.3	47188.2	46655.0	46388.4	46255.1	46121.8
5.2	42122.8	41456.3	41056.4	40789.8	40656.5	40523.2
4.8	35591.1	35057.9	34724.7	34524.7	34391.4	34324.8
4.2	27859.7	27459.8	27193.2	27126.6	26993.3	26926.6
3.4	18262.1	17995.5	17862.2	17795.6	17728.9	17728.9
2.8	12796.8	12663.5	12530.2	12530.2	12463.6	12463.6

Table A-4: Pressure Drop Experimental Data for 25.40 mm pipe diameter at 2 m test section *le* /D>135 using oppanol B 250 polymer in (Pascal).

Volumetric Flow Rate (m^3/h)	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	8331.3	7998.0	7798.1	7664.8	7495.5	7198.2
5.6	7464.8	7198.2	6998.3	6899.6	6765.0	6498.4
5.2	6465.1	6265.1	6097.1	7198.2	5865.2	5665.3
4.8	5598.6	5433.3	5298.7	5198.7	5098.7	4932.1
4.2	4398.9	4265.6	4199.0	4132.3	4065.7	3932.4
3.4	2932.6	2866.0	2799.3	2766.0	2732.7	2666.0
2.8	2132.8	2090.1	2068.8	2054.2	2023.5	1975.5

Table A-5: Pressure Drop Experimental Data for 25.40 mm pipe diameter at 3 m test section *le* /D>95 using oppanol B 250 polymer in (Pascal).

Volumetric Flow Rate (m^3/h)	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	12930.1	12530.2	12330.3	12063.7	11863.7	11530.5
5.6	11597.1	11263.9	11130.6	10864.0	10664.0	10397.4
5.2	10130.8	9864.2	9730.9	9531.0	9397.7	9131.1
4.80	8731.2	8531.2	8397.9	8198.0	8131.3	7931.4
4.2	6931.6	6798.3	6731.7	6598.4	6465.1	6331.8
3.40	4665.5	4598.9	4532.2	4465.6	4398.9	4332.3
2.8	3332.5	3299.2	3265.9	3232.5	3199.2	3132.6

Table A-6: Pressure Drop Experimental Data for 31.75 mm pipe diameter at 2 m test section *le* /D>100 using oppanol B 250 polymer in (Pascal).

Volumetric Flow Rate (m^3/h)	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	2266.1	2132.8	2066.2	1966.2	1899.5	1799.6
5.6	1999.5	1892.9	1799.6	1732.9	1666.3	1599.6
5.2	1799.6	1708.9	1632.9	1572.9	1533.0	1466.3
4.8	1599.6	1522.3	1458.3	1406.3	1375.7	1333.0
4.2	1266.4	1215.7	1169.0	1141.0	1109.1	1066.4
3.4	799.8	770.5	743.8	733.2	719.8	699.8
2.8	599.9	587.9	573.2	559.9	551.9	546.5

Table A-7: Pressure Drop Experimental Data for 31.75 mm pipe diameter at 3 m test section *le* /D>75 using oppanol B 250 polymer in (Pascal).

Volumetric Flow Rate (m^3/h)	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	3932.4	3732.4	3652.4	3521.8	3361.8	3199.2
5.6	3332.5	3187.2	3108.6	3000.6	2866.0	2734.0
5.2	3065.9	2932.6	2866.0	2766.0	2651.3	2532.7
4.8	2799.3	2698.0	2631.3	2543.4	2448.7	2360.7
4.2	2132.8	2066.2	2015.5	1951.5	1887.5	1827.5
3.4	1599.6	1566.3	1533.0	1486.3	1450.3	1403.6
2.8	1199.7	1181.0	1169.0	1133.1	1113.1	1093.1

Table A-8: Pressure Drop Experimental Data for 50.08 mm pipe diameter at 2 m test section *le* /D>65 using oppanol B 250 polymer in (Pascal).

Volumetric Flow Rate (m^3/h)	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	357.7	329.8	321.9	313.9	306.0	298.0
5.6	313.9	294.1	286.1	278.2	274.2	266.3
5.2	266.3	250.4	242.4	238.4	234.5	230.5
4.8	238.4	226.5	222.5	218.6	214.6	210.6
4.2	190.7	182.8	178.8	174.9	174.9	170.9
3.4	135.1	131.1	129.2	129.2	127.2	127.2

Table A-9: Pressure Drop Experimental Data for 50.80 mm pipe diameter at 3 m test section *le* /D>50 using oppanol B 250 polymer in (Pascal).

Volumetric Flow Rate (m^3/h)	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	516.6	500.7	484.8	476.9	464.9	453.0
5.6	461.0	449.1	433.2	429.2	417.3	405.3
5.2	405.3	397.4	385.5	377.5	369.6	361.6
4.8	341.8	333.8	325.9	321.9	313.9	310.0
4.2	294.1	290.1	282.1	278.2	274.2	270.2
3.4	278.2	274.2	266.3	266.3	262.3	258.3

APPENDIX C

CORRELATION OF FRICTION FACTOR

The following correlated equation has been used for present work:-

$$f = 0.42(\mathrm{Re})^{-0.44}$$

Table C-1: Friction Factor Correlation

Dia (inch)	**Test section**	**Conc (wppm)**	**Re**	**Exp. friction**	**Theo. Friction**	**AAPE%**
1	3	0	23136.55055	0.006232183	0.004998216	19.7999161
1	3	0	21594.11385	0.006416736	0.005152686	19.6992692
1	3	0	20051.67715	0.006500965	0.00532393	18.1055529
1	3	0	18509.24044	0.006575515	0.005515286	16.1238938
1	3	0	16195.58539	0.006818294	0.005849946	14.2021954
1	3	0	13110.71198	0.007002952	0.006421515	8.30274323
1	3	0	10797.05692	0.007375558	0.006995789	5.1490268
1	3	10	23136.55055	0.006039435	0.004998216	17.240339
1	3	10	21594.11385	0.006232347	0.005152686	17.323508
1	3	10	20051.67715	0.006329887	0.00532393	15.8921894
1	3	10	18509.24044	0.006424931	0.005515286	14.1580476
1	3	10	16195.58539	0.006687173	0.005849946	12.5198855
1	3	10	13110.71198	0.00690291	0.006421515	6.97379748
1	3	10	10797.05692	0.007301803	0.006995789	4.19093616
1	3	20	23136.55055	0.005943061	0.004998216	15.8982904
1	3	20	21594.11385	0.006158591	0.005152686	16.3333703
1	3	20	20051.67715	0.006244348	0.00532393	14.7400277
1	3	20	18509.24044	0.006324541	0.005515286	12.7954769
1	3	20	16195.58539	0.006621612	0.005849946	11.6537457
1	3	20	13110.71198	0.006802868	0.006421515	5.60576509
1	3	20	10797.05692	0.007228047	0.006995789	3.21329265
1	3	30	23136.55055	0.005814626	0.004998216	14.0406389
1	3	30	21594.11385	0.00601108	0.005152686	14.2802015
1	3	30	20051.67715	0.00611604	0.00532393	12.9513569
1	3	30	18509.24044	0.006174409	0.005515286	10.6750733
1	3	30	16195.58539	0.006491016	0.005849946	9.87625565
1	3	30	13110.71198	0.006701825	0.006421515	4.1825948
1	3	30	10797.05692	0.007154291	0.006995789	2.21549154
1	3	40	23136.55055	0.005718188	0.004998216	12.5909198

1	3	40	21594.11385	0.005900446	0.005152686	12.6729553
1	3	40	20051.67715	0.006030501	0.00532393	11.7166244
1	3	40	18509.24044	0.006123762	0.005515286	9.93631223
1	3	40	16195.58539	0.00635937	0.005849946	8.01060123
1	3	40	13110.71198	0.006602783	0.006421515	2.74533373
1	3	40	10797.05692	0.007080536	0.006995789	1.19690291
1	3	50	23136.55055	0.005557565	0.004998216	10.0646458
1	3	50	21594.11385	0.005752935	0.005152686	10.4338003
1	3	50	20051.67715	0.005859423	0.00532393	9.13900757
1	3	50	18509.24044	0.005973178	0.005515286	7.66579909
1	3	50	16195.58539	0.006228249	0.005849946	6.07398231
1	3	50	13110.71198	0.006502741	0.006421515	1.24910809
1	3	50	10797.05692	0.006933025	0.006995789	0.90529064
1	2	0	23136.55055	0.006023372	0.004998216	17.0196466
1	2	0	21594.11385	0.006195469	0.005152686	16.831386
1	2	0	20051.67715	0.006222963	0.00532393	14.4470381
1	2	0	18509.24044	0.006324541	0.005515286	12.7954769
1	2	0	16195.58539	0.006490491	0.005849946	9.86897292
1	2	0	13110.71198	0.006602783	0.006421515	2.74533373
1	2	0	10797.05692	0.007080536	0.006995789	1.19690291
1	2	10	23136.55055	0.005782438	0.004998216	13.5621318
1	2	10	21594.11385	0.005974202	0.005152686	13.751067
1	2	10	20051.67715	0.006030501	0.00532393	11.7166244
1	2	10	18509.24044	0.006136311	0.005515286	10.1204916
1	2	10	16195.58539	0.00629381	0.005849946	7.05237833
1	2	10	13110.71198	0.00645272	0.006421515	0.4835973
1	2	10	10797.05692	0.006938925	0.006995789	0.81948682
1	2	20	23136.55055	0.005637877	0.004998216	11.3457762
1	2	20	21594.11385	0.005808252	0.005152686	11.2868117
1	2	20	20051.67715	0.005870115	0.00532393	9.30451029
1	2	20	18509.24044	0.005985726	0.005515286	7.85937184
1	2	20	16195.58539	0.006195469	0.005849946	5.57701925
1	2	20	13110.71198	0.006302657	0.006421515	1.88584086
1	2	20	10797.05692	0.00686812	0.006995789	1.85886297
1	2	30	23136.55055	0.005541503	0.004998216	9.80396365
1	2	30	21594.11385	0.005725277	0.005152686	10.0011134
1	2	30	20051.67715	0.00692866	0.00532393	23.1607657
1	2	30	18509.24044	0.005872788	0.005515286	6.08743669
1	2	30	16195.58539	0.006097128	0.005849946	4.05406795
1	2	30	13110.71198	0.006226425	0.006421515	3.13326222
1	2	30	10797.05692	0.006825636	0.006995789	2.4928393

1	2	40	23136.55055	0.005421035	0.004998216	7.79960729
1	2	40	21594.11385	0.005614644	0.005152686	8.22773628
1	2	40	20051.67715	0.005645575	0.00532393	5.69730331
1	2	40	18509.24044	0.00575985	0.005515286	4.24601388
1	2	40	16195.58539	0.005998787	0.005849946	2.48118382
1	2	40	13110.71198	0.006152594	0.006421515	4.37086137
1	2	40	10797.05692	0.006719428	0.006995789	4.11285257
1	2	50	23136.55055	0.005204194	0.004998216	3.95792426
1	2	50	21594.11385	0.005393377	0.005152686	4.46272033
1	2	50	20051.67715	0.005453112	0.00532393	2.36897284
1	2	50	18509.24044	0.00557162	0.005515286	1.01108191
1	2	50	16195.58539	0.005802499	0.005849946	0.81770367
1	2	50	13110.71198	0.00600253	0.006421515	6.9801329
1	2	50	10797.05692	0.006556576	0.006995789	6.69880895
3/4	4	0	30848.73407	0.004676913	0.004402474	5.86796963
3/4	4	0	28792.1518	0.004738814	0.004538532	4.22641908
3/4	4	0	26735.56953	0.004810818	0.004689365	2.52457385
3/4	4	0	24678.98726	0.004770537	0.004857914	1.83157875
3/4	4	0	21594.11385	0.004877376	0.005152686	5.64462611
3/4	4	0	17480.94931	0.004878668	0.005656128	15.9359161
3/4	4	0	14396.0759	0.005040733	0.006161954	22.2432097
3/4	4	10	30848.73407	0.004585433	0.004402474	3.99002389
3/4	4	10	28792.1518	0.004646926	0.004538532	2.33259121
3/4	4	10	26735.56953	0.004734697	0.004689365	0.95744482
3/4	4	10	24678.98726	0.004698979	0.004857914	3.38231345
3/4	4	10	21594.11385	0.004807366	0.005152686	7.18314008
3/4	4	10	17480.94931	0.004807446	0.005656128	17.6534853
3/4	4	10	14396.0759	0.004988225	0.006161954	23.5299803
3/4	4	20	30848.73407	0.004539693	0.004402474	3.02266896
3/4	4	20	28792.1518	0.004594418	0.004538532	1.21639225
3/4	4	20	26735.56953	0.004689025	0.004689365	0.0072554
3/4	4	20	24678.98726	0.004654401	0.004857914	4.37248186
3/4	4	20	21594.11385	0.004760692	0.005152686	8.23395518
3/4	4	20	17480.94931	0.004771337	0.005656128	18.5438815
3/4	4	20	14396.0759	0.004935718	0.006161954	24.844129
3/4	4	30	30848.73407	0.004505388	0.004402474	2.28426289
3/4	4	30	28792.1518	0.004568217	0.004538532	0.64981232
3/4	4	30	26735.56953	0.004658577	0.004689365	0.66089759
3/4	4	30	24678.98726	0.004627421	0.004857914	4.98100902
3/4	4	30	21594.11385	0.004749024	0.005152686	8.49988627
3/4	4	30	17480.94931	0.00475403	0.005656128	18.9754345

3/4	4	30	14396.0759	0.004935718	0.006161954	24.844129
3/4	4	40	30848.73407	0.004482518	0.004402474	1.78571321
3/4	4	40	28792.1518	0.004555037	0.004538532	0.3623553
3/4	4	40	26735.56953	0.004643353	0.004689365	0.99093332
3/4	4	40	24678.98726	0.004609733	0.004857914	5.38384312
3/4	4	40	21594.11385	0.004726177	0.005152686	9.02438195
3/4	4	40	17480.94931	0.004737187	0.005656128	19.3984718
3/4	4	40	14396.0759	0.004909674	0.006161954	25.5063754
3/4	4	50	30848.73407	0.004471129	0.004402474	1.53553309
3/4	4	50	28792.1518	0.00454191	0.004538532	0.07438522
3/4	4	50	26735.56953	0.004628129	0.004689365	1.32314034
3/4	4	50	24678.98726	0.004600799	0.004857914	5.58847194
3/4	4	50	21594.11385	0.004714019	0.005152686	9.3055785
3/4	4	50	17480.94931	0.004737187	0.005656128	19.3984718
3/4	4	50	14396.0759	0.004909674	0.006161954	25.5063754
3/4	3	0	30848.73407	0.004680725	0.004402474	5.94462438
3/4	3	0	28792.1518	0.0048132	0.004538532	5.70655624
3/4	3	0	26735.56953	0.00495291	0.004689365	5.32100001
3/4	3	0	24678.98726	0.004907519	0.004857914	1.01080755
3/4	3	0	21594.11385	0.005009617	0.005152686	2.85587045
3/4	3	0	17480.94931	0.005175424	0.005656128	9.28821452
3/4	3	0	14396.0759	0.005250764	0.006161954	17.3534813
3/4	3	10	30848.73407	0.004573998	0.004402474	3.74999895
3/4	3	10	28792.1518	0.004708185	0.004538532	3.60335675
3/4	3	10	26735.56953	0.004851416	0.004689365	3.3402678
3/4	3	10	24678.98726	0.004812228	0.004857914	0.94937448
3/4	3	10	21594.11385	0.004931828	0.005152686	4.47820279
3/4	3	10	17480.94931	0.005104202	0.005656128	10.8131664
3/4	3	10	14396.0759	0.005180753	0.006161954	18.9393391
3/4	3	20	30848.73407	0.004513012	0.004402474	2.44932326
3/4	3	20	28792.1518	0.004655677	0.004538532	2.51617656
3/4	3	20	26735.56953	0.004800668	0.004689365	2.31849473
3/4	3	20	24678.98726	0.004764582	0.004857914	1.95886822
3/4	3	20	21594.11385	0.004869597	0.005152686	5.81338749
3/4	3	20	17480.94931	0.005056721	0.005656128	11.8536656
3/4	3	20	14396.0759	0.005145748	0.006161954	19.7484503
3/4	3	30	30848.73407	0.004490142	0.004402474	1.95246073
3/4	3	30	28792.1518	0.004629423	0.004538532	1.96333824
3/4	3	30	26735.56953	0.00477022	0.004689365	1.69499576
3/4	3	30	24678.98726	0.004740759	0.004857914	2.47122434
3/4	3	30	21594.11385	0.004854039	0.005152686	6.15253297

3/4	3	30	17480.94931	0.005032981	0.005656128	12.3812772
3/4	3	30	14396.0759	0.005145748	0.006161954	19.7484503
3/4	3	40	30848.73407	0.004467272	0.004402474	1.45051087
3/4	3	40	28792.1518	0.004603169	0.004538532	1.40419379
3/4	3	40	26735.56953	0.004749921	0.004689365	1.2748889
3/4	3	40	24678.98726	0.004716936	0.004857914	2.98875578
3/4	3	40	21594.11385	0.004822924	0.005152686	6.83738802
3/4	3	40	17480.94931	0.005009241	0.005656128	12.9138899
3/4	3	40	14396.0759	0.005110743	0.006161954	20.5686452
3/4	3	50	30848.73407	0.004406285	0.004402474	0.0865041
3/4	3	50	28792.1518	0.00454191	0.004538532	0.07438522
3/4	3	50	26735.56953	0.004689025	0.004689365	0.0072554
3/4	3	50	24678.98726	0.004657379	0.004857914	4.30574754
3/4	3	50	21594.11385	0.00477625	0.005152686	7.88140158
3/4	3	50	17480.94931	0.0049855	0.005656128	13.4515751
3/4	3	50	14396.0759	0.005075738	0.006161954	21.4001531
3/4	2	0	30848.73407	0.004711218	0.004402474	6.55339704
3/4	2	0	28792.1518	0.004909464	0.004538532	7.55544729
3/4	2	0	26735.56953	0.005023955	0.004689365	6.65989496
3/4	2	0	24678.98726	0.00507428	0.004857914	4.2639735
3/4	2	0	21594.11385	0.005087406	0.005152686	1.28315072
3/4	2	0	17480.94931	0.005270386	0.005656128	7.3190575
3/4	2	0	14396.0759	0.005145748	0.006161954	19.7484503
3/4	2	10	30848.73407	0.004573998	0.004402474	3.74999895
3/4	2	10	28792.1518	0.004776908	0.004538532	4.99018221
3/4	2	10	26735.56953	0.00490338	0.004689365	4.36464648
3/4	2	10	24678.98726	0.004947423	0.004857914	1.80920359
3/4	2	10	21594.11385	0.004970396	0.005152686	3.6675033
3/4	2	10	17480.94931	0.005164978	0.005656128	9.50924235
3/4	2	10	14396.0759	0.005042833	0.006161954	22.1922962
3/4	2	20	30848.73407	0.004527481	0.004402474	2.76107912
3/4	2	20	28792.1518	0.004725687	0.004538532	3.96038135
3/4	2	20	26735.56953	0.004841266	0.004689365	3.13762685
3/4	2	20	24678.98726	0.004911903	0.004857914	1.09914618
3/4	2	20	21594.11385	0.004924609	0.005152686	4.63135405
3/4	2	20	17480.94931	0.005128085	0.005656128	10.2970786
3/4	2	20	14396.0759	0.005014479	0.006161954	22.8832265
3/4	2	30	30848.73407	0.004470946	0.004402474	1.53150373
3/4	2	30	28792.1518	0.00467381	0.004538532	2.89437741
3/4	2	30	26735.56953	0.004795594	0.004689365	2.21512806
3/4	2	30	24678.98726	0.00486116	0.004857914	0.06677818

3/4	2	30	21594.11385	0.004878823	0.005152686	5.61329585
3/4	2	30	17480.94931	0.005091193	0.005656128	11.0963328
3/4	2	30	14396.0759	0.004988225	0.006161954	23.5299803
3/4	2	40	30848.73407	0.004402474	0.004402474	1.0947E-06
3/4	2	40	28792.1518	0.004607545	0.004538532	1.49782703
3/4	2	40	26735.56953	0.004734697	0.004689365	0.95744482
3/4	2	40	24678.98726	0.00479012	0.004857914	1.41528231
3/4	2	40	21594.11385	0.004830702	0.005152686	6.66534713
3/4	2	40	17480.94931	0.005022678	0.005656128	12.6118127
3/4	2	40	14396.0759	0.004988225	0.006161954	23.5299803
3/4	2	50	30848.73407	0.004322429	0.004402474	1.85185297
3/4	2	50	28792.1518	0.004528784	0.004538532	0.21525424
3/4	2	50	26735.56953	0.004658577	0.004689365	0.66089759
3/4	2	50	24678.98726	0.004716936	0.004857914	2.98875578
3/4	2	50	21594.11385	0.004761812	0.005152686	8.20849436
3/4	2	50	17480.94931	0.004949889	0.005656128	14.2677735
3/4	2	50	14396.0759	0.004935718	0.006161954	24.844129
1.25	3	0	18509.24044	0.005784163	0.005515286	4.64850521
1.25	3	0	17275.29108	0.005627104	0.005685736	1.04194706
1.25	3	0	16041.34172	0.00600402	0.005874695	2.15397738
1.25	3	0	14807.39235	0.006433656	0.006085847	5.40607829
1.25	3	0	12956.46831	0.006402394	0.006455129	0.82366989
1.25	3	0	10488.56958	0.007327308	0.007085827	3.29562849
1.25	3	0	8637.645539	0.00810303	0.00771951	4.73305129
1.25	3	10	18509.24044	0.005500739	0.005515286	0.26445299
1.25	3	10	17275.29108	0.005379512	0.005685736	5.69241325
1.25	3	10	16041.34172	0.00576386	0.005874695	1.92294023
1.25	3	10	14807.39235	0.006202044	0.006085847	1.8735252
1.25	3	10	12956.46831	0.00620392	0.006455129	4.04919493
1.25	3	10	10488.56958	0.007173434	0.007085827	1.22127527
1.25	3	10	8637.645539	0.007973382	0.00771951	3.18399522
1.25	3	20	18509.24044	0.005373487	0.005515286	2.63885338
1.25	3	20	17275.29108	0.005244461	0.005685736	8.41410629
1.25	3	20	16041.34172	0.005613759	0.005874695	4.64815254
1.25	3	20	14807.39235	0.006047637	0.006085847	0.63183161
1.25	3	20	12956.46831	0.006050263	0.006455129	6.69171417
1.25	3	20	10488.56958	0.007019561	0.007085827	0.94402036
1.25	3	20	8637.645539	0.007884248	0.00771951	2.0894669
1.25	3	30	18509.24044	0.005176826	0.005515286	6.53798301
1.25	3	30	17275.29108	0.005064394	0.005685736	12.2688301
1.25	3	30	16041.34172	0.00542163	0.005874695	8.3566142

1.25	3	30	14807.39235	0.00584176	0.006085847	4.17832787
1.25	3	30	12956.46831	0.005858191	0.006455129	10.1898032
1.25	3	30	10488.56958	0.006807069	0.007085827	4.09512541
1.25	3	30	8637.645539	0.007657363	0.00771951	0.81158593
1.25	3	40	18509.24044	0.004945459	0.005515286	11.5222161
1.25	3	40	17275.29108	0.00483931	0.005685736	17.4906361
1.25	3	40	16041.34172	0.005193478	0.005874695	13.1167892
1.25	3	40	14807.39235	0.005623015	0.006085847	8.2310317
1.25	3	40	12956.46831	0.005666119	0.006455129	13.9250507
1.25	3	40	10488.56958	0.006645868	0.007085827	6.62003474
1.25	3	40	8637.645539	0.007519612	0.00771951	2.6583499
1.25	3	50	18509.24044	0.00470576	0.005515286	17.202879
1.25	3	50	17275.29108	0.004614226	0.005685736	23.2218867
1.25	3	50	16041.34172	0.004965325	0.005874695	18.3144167
1.25	3	50	14807.39235	0.005423572	0.006085847	12.2110578
1.25	3	50	12956.46831	0.005486852	0.006455129	17.6472227
1.25	3	50	10488.56958	0.006433376	0.007085827	10.1416532
1.25	3	50	8637.645539	0.007373757	0.00771951	4.68895462
1.25	2	0	18509.24044	0.00499987	0.005515286	10.308592
1.25	2	0	17275.29108	0.005064394	0.005685736	12.2688301
1.25	2	0	16041.34172	0.005286148	0.005874695	11.1337541
1.25	2	0	14807.39235	0.005514562	0.006085847	10.3595753
1.25	2	0	12956.46831	0.005702132	0.006455129	13.2055241
1.25	2	0	10488.56958	0.005495481	0.007085827	28.939162
1.25	2	0	8637.645539	0.006077273	0.00771951	27.0225983
1.25	2	10	18509.24044	0.00470576	0.005515286	17.202879
1.25	2	10	17275.29108	0.004794293	0.005685736	18.5938346
1.25	2	10	16041.34172	0.005015967	0.005874695	17.1198814
1.25	2	10	14807.39235	0.005248025	0.006085847	15.9645275
1.25	2	10	12956.46831	0.005474047	0.006455129	17.9224209
1.25	2	10	10488.56958	0.005297643	0.007085827	33.7543174
1.25	2	10	8637.645539	0.005943573	0.00771951	29.8799573
1.25	2	20	18509.24044	0.004558705	0.005515286	20.983617
1.25	2	20	17275.29108	0.004557954	0.005685736	24.7431445
1.25	2	20	16041.34172	0.004800606	0.005874695	22.3740359
1.25	2	20	14807.39235	0.005027443	0.006085847	21.0525506
1.25	2	20	12956.46831	0.005257366	0.006455129	22.7825641
1.25	2	20	10488.56958	0.005110797	0.007085827	38.6442602
1.25	2	20	8637.645539	0.005809873	0.00771951	32.8688266
1.25	2	30	18509.24044	0.004335181	0.005515286	27.2215783
1.25	2	30	17275.29108	0.004389141	0.005685736	29.5409578

1.25	2	30	16041.34172	0.004620485	0.005874695	27.1445492
1.25	2	30	14807.39235	0.004852815	0.006085847	25.4086083
1.25	2	30	12956.46831	0.005137621	0.006455129	25.6443109
1.25	2	30	10488.56958	0.005028365	0.007085827	40.917117
1.25	2	30	8637.645539	0.005676173	0.00771951	35.9984992
1.25	2	40	18509.24044	0.004194008	0.005515286	31.5039316
1.25	2	40	17275.29108	0.004223704	0.005685736	34.6149042
1.25	2	40	16041.34172	0.004503015	0.005874695	30.4613635
1.25	2	40	14807.39235	0.004742523	0.006085847	28.3250876
1.25	2	40	12956.46831	0.004989366	0.006455129	29.3777418
1.25	2	40	10488.56958	0.004945933	0.007085827	43.2657356
1.25	2	40	8637.645539	0.005591091	0.00771951	38.0680416
1.25	2	50	18509.24044	0.003970485	0.005515286	38.9071159
1.25	2	50	17275.29108	0.004017752	0.005685736	41.515332
1.25	2	50	16041.34172	0.004346389	0.005874695	35.1626739
1.25	2	50	14807.39235	0.004577087	0.006085847	32.9633438
1.25	2	50	12956.46831	0.004846812	0.006455129	33.1829695
1.25	2	50	10488.56958	0.004836023	0.007085827	46.521775
1.25	2	50	8637.645539	0.005530318	0.00771951	39.5852728
2	3	0	11568.27528	0.007976117	0.006786065	14.9201823
2	3	0	10797.05692	0.008170198	0.006995789	14.3743055
2	3	0	10025.83857	0.008331901	0.007228286	13.2456576
2	3	0	9254.620221	0.008244544	0.00748809	9.17519883
2	3	0	8097.792693	0.009265818	0.007942458	14.2821744
2	3	0	6555.35599	0.013374909	0.008718475	34.8146962
2	3	10	11568.27528	0.007730698	0.006786065	12.2192357
2	3	10	10797.05692	0.0079589	0.006995789	12.1010569
2	3	10	10025.83857	0.008168531	0.007228286	11.5105708
2	3	10	9254.620221	0.00805281	0.00748809	7.01270356
2	3	10	8097.792693	0.009140604	0.007942458	13.1079577
2	3	10	6555.35599	0.013183839	0.008718475	33.8699816
2	3	20	11568.27528	0.007485279	0.006786065	9.34117785
2	3	20	10797.05692	0.007677169	0.006995789	8.87540765
2	3	20	10025.83857	0.007923475	0.007228286	8.77378429
2	3	20	9254.620221	0.007861076	0.00748809	4.74472072
2	3	20	8097.792693	0.008890177	0.007942458	10.6602945
2	3	20	6555.35599	0.012801699	0.008718475	31.8959512
2	3	30	11568.27528	0.007362569	0.006786065	7.83019748
2	3	30	10797.05692	0.007606736	0.006995789	8.03166143
2	3	30	10025.83857	0.007760104	0.007228286	6.85323238
2	3	30	9254.620221	0.00776521	0.00748809	3.56872962

2	3	30	8097.792693	0.008764963	0.007942458	9.38401298
2	3	30	6555.35599	0.012801699	0.008718475	31.8959512
2	3	40	11568.27528	0.007178505	0.006786065	5.46686921
2	3	40	10797.05692	0.007395438	0.006995789	5.40399461
2	3	40	10025.83857	0.007596734	0.007228286	4.85007609
2	3	40	9254.620221	0.007573476	0.00748809	1.12743164
2	3	40	8097.792693	0.008639749	0.007942458	8.07073781
2	3	40	6555.35599	0.012610629	0.008718475	30.8640717
2	3	50	11568.27528	0.006994441	0.006786065	2.97915524
2	3	50	10797.05692	0.007184139	0.006995789	2.62175916
2	3	50	10025.83857	0.007433363	0.007228286	2.75886897
2	3	50	9254.620221	0.007477609	0.00748809	0.14016539
2	3	50	8097.792693	0.008514536	0.007942458	6.71883689
2	3	50	6555.35599	0.012419559	0.008718475	29.800442
2	2	0	11568.27528	0.00828289	0.006786065	18.0712867
2	2	0	10797.05692	0.00834628	0.006995789	16.1807547
2	2	0	10025.83857	0.008209373	0.007228286	11.9508167
2	2	0	9254.620221	0.008628011	0.00748809	13.2118567
2	2	0	8097.792693	0.009015391	0.007942458	11.9011237
2	2	0	6555.35599	0.009744577	0.008718475	10.5299751
2	2	10	11568.27528	0.007638665	0.006786065	11.1616361
2	2	10	10797.05692	0.007818034	0.006995789	10.5172922
2	2	10	10025.83857	0.007719262	0.007228286	6.36039234
2	2	10	9254.620221	0.00819661	0.00748809	8.64405964
2	2	10	8097.792693	0.008639749	0.007942458	8.07073781
2	2	10	6555.35599	0.009457972	0.008718475	7.81876226
2	2	20	11568.27528	0.007454601	0.006786065	8.96809628
2	2	20	10797.05692	0.007606736	0.006995789	8.03166143
2	2	20	10025.83857	0.007474206	0.007228286	3.29024127
2	2	20	9254.620221	0.00805281	0.00748809	7.01270356
2	2	20	8097.792693	0.008451929	0.007942458	6.02786532
2	2	20	6555.35599	0.009314669	0.008718475	6.40058938
2	2	30	11568.27528	0.007270537	0.006786065	6.66349112
2	2	30	10797.05692	0.007395438	0.006995789	5.40399461
2	2	30	10025.83857	0.007351678	0.007228286	1.67841195
2	2	30	9254.620221	0.00790901	0.00748809	5.32202545
2	2	30	8097.792693	0.008264108	0.007942458	3.89213498
2	2	30	6555.35599	0.009314669	0.008718475	6.40058938
2	2	40	11568.27528	0.007086473	0.006786065	4.23916622
2	2	40	10797.05692	0.007289789	0.006995789	4.03303801
2	2	40	10025.83857	0.00722915	0.007228286	0.01194436

2	2	40	9254.620221	0.00776521	0.00748809	3.56872962
2	2	40	8097.792693	0.008264108	0.007942458	3.89213498
2	2	40	6555.35599	0.009171366	0.008718475	4.93809859
2	2	50	11568.27528	0.006902409	0.006786065	1.68554398
2	2	50	10797.05692	0.00707849	0.006995789	1.16835258
2	2	50	10025.83857	0.007106622	0.007228286	1.71198763
2	2	50	9254.620221	0.007621409	0.00748809	1.74927169
2	2	50	8097.792693	0.00807779	0.007942458	1.67536131
2	2	50	6555.35599	0.009171366	0.008718475	4.93809859
					AAPE	10.4165356

APPENDIX B

FRICTION FACTOR CALCULATIONS

B.1 Sample Calculation of Friction Factor

1. Area $A = \frac{\pi}{4} D^2$
2. Volumetric flow rate Q (m^3/s) = Q $_{\text{measured}}$ /3600
3. u (m/s) = Q / A
4. $\Delta P = \left(\Delta P\right)_{measured} * \frac{1.01325 * 10^5 (pa)}{760 (mmHg)} = \left(\Delta H\right)_{measured} * 133.3$
5. selection of test section in m
6. $f = \frac{\Delta P}{2} * \frac{1}{\rho\, u^2} * \frac{D}{L}$

$$f = \left(\Delta H\right)_{measured} * \frac{133.3}{2} * \frac{1}{\rho\, u^2} * \frac{D}{L}$$

as example

d=3/4” = 0.01905 m , area $A = \frac{\pi}{4}(0.01905)^2 = 2.8488 * 10^{-4}\, m^2$

test section L=2 m

Q=6m^3/hr=1.66*10^{-3} m^3/sec u=5.8502141 m/sec

$\rho_{\text{gas oil}}$ =811 kg/m^3

$\left(\Delta H\right)_{measured}\ for\ pure\ gas\ oil$

$$f = 206 * \frac{133.3}{2} * \frac{1}{811 * \left(5.85\right)^2} * \frac{0.01905}{2}$$

$$f = 0.00471159$$

B.2 Friction Factor Results

Table B-1: Friction Factor for 19.05 mm pipe diameter at 2 m test section *le*/D=180 using oppanol B 250 polymer.

Reynolds Number	Pure Gas oil	Concentration, wppm				
		10	20	30	40	50
30848.7	0.004711	0.004574	0.00453	0.004471	0.004402	0.004322
28792.2	0.004909	0.004777	0.00473	0.004674	0.004608	0.004529
26735.6	0.005024	0.004903	0.00484	0.004796	0.004735	0.004659
24679	0.005074	0.004947	0.00491	0.004861	0.00479	0.004717
21594.1	0.005087	0.00497	0.00492	0.004879	0.004831	0.004762
17480.9	0.00527	0.005165	0.00513	0.005091	0.005023	0.00495
14396.1	0.005146	0.005043	0.00501	0.004988	0.004988	0.004936

Table B-2: Friction Factor for 19.05 mm pipe diameter at 3 m test section *le*/D=130 using oppanol B 250 polymer.

Reynolds Number	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
30848.7	0.004681	0.004574	0.00451	0.00449	0.004467	0.004406
28792.2	0.004813	0.004708	0.00466	0.004629	0.004603	0.004542
26735.6	0.004953	0.004851	0.0048	0.00477	0.00475	0.004689
24679	0.004908	0.004812	0.00476	0.004741	0.004717	0.004657
21594.1	0.00501	0.004932	0.00487	0.004854	0.004823	0.004776
17480.9	0.005175	0.005104	0.00506	0.005033	0.005009	0.004986
14396.1	0.005251	0.005181	0.00515	0.005146	0.005111	0.005076

Table B-3: Friction Factor for 19.05 mm pipe diameter at 4 m test section *le*/D>75 using oppanol B 250 polymer.

Reynolds Number	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
30848.7	0.004677	0.004585	0.00454	0.004505	0.004483	0.004471
28792.2	0.004739	0.004647	0.00459	0.004568	0.004555	0.004542
26735.6	0.004811	0.004735	0.00469	0.004659	0.004643	0.004628
24679	0.004771	0.004699	0.00465	0.004627	0.00461	0.004601
21594.1	0.004877	0.004807	0.00476	0.004749	0.004726	0.004714
17480.9	0.004879	0.004807	0.00477	0.004754	0.004737	0.004737
14396.1	0.005041	0.004988	0.00494	0.004936	0.00491	0.00491

Table B-4: Friction Factor for 25.40 mm pipe diameter at 2 m test section *le*/D>135 using oppanol B 250 polymer.

Reynolds Number	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
23136.6	0.006023	0.005782	0.00564	0.005542	0.005421	0.005204
21594.1	0.006195	0.005974	0.00581	0.005725	0.005615	0.005393
20051.7	0.006223	0.006031	0.00587	0.006929	0.005646	0.005453
18509.2	0.006325	0.006136	0.00599	0.005873	0.00576	0.005572
16195.6	0.00649	0.006294	0.0062	0.006097	0.005999	0.005802
13110.7	0.006603	0.006453	0.0063	0.006226	0.006153	0.006003
10797.1	0.007081	0.006939	0.00687	0.006826	0.006719	0.006557

Table B-5: Friction Factor for 25.40 mm pipe diameter at 3 m test section *le*/D>95 using oppanol B 250 polymer.

Reynolds Number	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
23136.6	0.006232	0.006039	0.00594	0.005815	0.005718	0.005558
21594.1	0.006417	0.006232	0.00616	0.006011	0.0059	0.005753
20051.7	0.006501	0.00633	0.00624	0.006116	0.006031	0.005859
18509.2	0.006576	0.006425	0.00632	0.006174	0.006124	0.005973
16195.6	0.006818	0.006687	0.00662	0.006491	0.006359	0.006228
13110.7	0.007003	0.006903	0.0068	0.006702	0.006603	0.006503
10797.1	0.007376	0.007302	0.00723	0.007154	0.007081	0.006933

Table B-6: Friction Factor for 31.75 mm pipe diameter at 2 m test section *le*/D>100 using oppanol B 250 polymer.

Reynolds Number	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
18509.2	0.005	0.004706	0.00456	0.004335	0.004194	0.00397
17275.3	0.005064	0.004794	0.00456	0.004389	0.004224	0.004018
16041.3	0.005286	0.005016	0.0048	0.00462	0.004503	0.004346
14807.4	0.005515	0.005248	0.00503	0.004853	0.004743	0.004577
12956.5	0.005702	0.005474	0.00526	0.005138	0.004989	0.004847
10488.6	0.005495	0.005298	0.00511	0.005028	0.004946	0.004836
8637.65	0.006077	0.005944	0.00581	0.005676	0.005591	0.00553

Table B-7: Friction Factor for 31.75 mm pipe diameter at 3 m test section *le*/D>75 using oppanol B 250 polymer.

Reynolds Number	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
18509.2	0.005784	0.005501	0.00537	0.005177	0.004945	0.004706
17275.3	0.005627	0.00538	0.00524	0.005064	0.004839	0.004614
16041.3	0.006004	0.005764	0.00561	0.005422	0.005193	0.004965
14807.4	0.006434	0.006202	0.00605	0.005842	0.005623	0.005424
12956.5	0.006402	0.006204	0.00605	0.005858	0.005666	0.005487
10488.6	0.007327	0.007173	0.00702	0.006807	0.006646	0.006433
8637.65	0.008103	0.007973	0.00788	0.007657	0.00752	0.007374

Table B-8: Friction Factor for 50.08 mm pipe diameter at 2 m test section *le*/D>65 using oppanol B 250 polymer.

Reynolds Number	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
11568.3	0.008283	0.007639	0.00745	0.007271	0.007086	0.006902
10797.1	0.008346	0.007818	0.00761	0.007395	0.00729	0.007078
10025.8	0.008209	0.007719	0.00747	0.007352	0.007229	0.007107
9254.62	0.008628	0.008197	0.00805	0.007909	0.007765	0.007621
8097.79	0.009015	0.00864	0.00845	0.008264	0.008264	0.008078
6555.36	0.009745	0.009458	0.00931	0.009315	0.009171	0.009171

Table B-9: Friction Factor for 50.80 mm pipe diameter at 3 m test section *le*/D>50 using oppanol B 250 polymer.

Reynolds Number	Pure Gas oil	Concentration				
		10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
11568.3	0.007976	0.007731	0.00749	0.007363	0.007179	0.006994
10797.1	0.00817	0.007959	0.00768	0.007607	0.007395	0.007184
10025.8	0.008332	0.008169	0.00792	0.00776	0.007597	0.007433
9254.62	0.008245	0.008053	0.00786	0.007765	0.007573	0.007478
8097.79	0.009266	0.009141	0.00889	0.008765	0.00864	0.008515
6555.36	0.013375	0.013184	0.0128	0.012802	0.012611	0.01242

APPENDIX D

PERCENT DRAG-REDUCTION CALCULATIONS

Where the % DR is calculated from equation (3-7), as follows:-

$$\%DR = \frac{(\Delta p)_{untreated} - (\Delta p)_{treated}}{(\Delta p)_{untreated}} \times 100$$

$(\Delta p)_{\text{untreated}}$, $(\Delta \text{p})_{\text{treated}}$ are obtained from Appendix A for each point

Table D-1:% DR Data for 19.05 mm pipe diameter at 2 m test section *le*/D=180 using oppanol B 250 polymer.

Volumetric Flow Rate (m^3/h)	Concentration				
	10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	3.0	3.9	5.1	6.6	8.2
5.6	2.7	3.7	4.8	6.1	7.8
5.2	2.4	3.6	4.5	5.8	7.3
4.8	2.5	3.2	4.2	5.6	7.0
4.2	2.3	3.2	4.1	5.1	6.4
3.4	2.0	2.7	3.4	4.7	6.0
2.8	2.0	2.5	3.0	3.6	4.1

Table D-2: %DR Data for 19.05 mm pipe diameter at 3 m test section *le*/D=130 using oppanol B 250 polymer.

Volumetric Flow Rate (m^3/h)	Concentration				
	10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	2.3	3.6	4.1	4.6	5.9
5.6	2.1	3.3	3.8	4.4	5.6
5.2	2.0	3.1	3.7	4.1	5.3
4.8	1.9	2.9	3.4	3.9	5.1
4.2	1.6	2.8	3.1	3.7	4.7
3.4	1.4	2.3	2.8	3.2	3.7
2.8	1.3	2.0	2.0	2.7	3.3

Table D-3: %DR Data for 19.05 mm pipe diameter at 4 m test section *le*/D>75 using oppanol B 250 polymer.

Volumetric Flow Rate (m^3/h)	Concentration, wppm				
	10	20	30	40	50
6.0	2.0	2.9	3.7	4.2	4.4
5.6	1.9	2.8	3.6	3.9	4.2
5.2	1.6	2.5	3.2	3.5	3.8
4.8	1.5	2.5	3	3.4	3.6
4.2	1.4	2.4	2.6	3.1	3.3
3.4	1.5	2.2	2.5	2.9	2.9
2.8	1.1	2.0	2.0	2.6	2.6

Table D-4: %DR Data for 25.40 mm pipe diameter at 2 m test section *le* /D>135 using oppanol B 250 polymer.

Volumetric Flow Rate (m^3/h)	Concentration				
	10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	4.0	6.5	8	10.0	13.6
5.6	3.4	6.2	7.6	9.4	13
5.2	3.0	5.7	7.3	9.2	12.4
4.8	2.9	5.3	7.1	8.9	11.9
4.2	3.0	4.6	6.0	7.6	10.6
3.4	2.3	4.5	5.7	6.8	9.1
2.8	2.0	3.0	3.6	5.1	7.4

Table D-5: %DR Data for 25.40 mm pipe diameter at 3 m test section *le* /D>95 using oppanol B 250 polymer.

Volumetric Flow Rate (m^3/h)	Concentration				
	10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	3.1	4.6	6.7	8.3	10.9
5.6	2.8	4	6.3	8	10.3
5.2	2.6	4.1	5.9	7.2	9.9
4.8	2.3	3.7	6.1	6.9	9.2
4.2	1.9	2.9	4.8	6.7	8.6
3.4	1.5	2.9	4.3	5.7	7.1
2.8	1.2	2.1	3.0	4.0	6.0

Table D-6: %DR Data for 31.75 mm pipe diameter at 2 m test section *le* /D>100 using oppanol B 250 polymer.

Volumetric Flow Rate (m^3/h)	Concentration				
	10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	5.9	8.8	13.3	16.1	20.6
5.6	5.3	10	13.3	16.6	20.7
5.2	5.1	9.2	12.5	15	18
4.8	4.8	8.8	12	14	17
4.2	4	7.8	9.9	12.5	15
3.4	3.6	7	8.5	10	12
2.8	2.2	4.4	6.6	8	9

Table D-7: %DR Data for 31.75 mm pipe diameter at 3 m test section *le* /D>75 using oppanol B 250 polymer.

Volumetric Flow Rate (m^3/h)	Concentration				
	10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6	4.9	7.1	10.5	14.5	18.7
5.6	4.4	6.8	10.1	14	18
5.2	4	6.5	9.7	13.5	17.3
4.8	3.6	6	9.2	12.6	15.7
4.2	3.1	5.5	8.5	11.5	14.3
3.4	2.1	4.2	7.1	9.3	12.2
2.8	1.6	2.7	5.5	7.2	9

Table D-8: %DR Data for 50.08 mm pipe diameter at 2 m test section *le* /D>65 using oppanol B 250 polymer.

Volumetric Flow Rate (m^3/h)	Concentration				
	10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	7.7	10	12.2	14.4	16.7
5.6	6.3	8.9	11.4	12.7	15.2
5.2	6	8.9	10.4	11.9	13.4
4.8	5	6.7	8.3	10	11.7
4.2	4.1	6.3	8.3	8.3	10.4
3.4	2.9	4.4	4.4	5.9	5.9

Table D-9: %DR Data for 50.80 mm pipe diameter at 3 m test section *le* /D>50 using oppanol B 250 polymer.

Volumetric Flow Rate (m^3/h)	Concentration				
	10 wppm	20 wppm	30 wppm	40 wppm	50 wppm
6.0	3.1	6.2	7.7	10	12.3
5.6	2.6	6	6.9	9.5	12
5.2	2	4.9	6.9	8.8	10.8
4.8	2.3	4.7	5.8	8.1	9.3
4.2	1.4	4.1	5.4	6.8	8.1
3.4	1.4	4.3	4.3	5.7	7.1
2.8	3.1	6.2	7.7	10	12.3

APPENDIX E

Θ AND %DR CORRELATIONS

E.1 Sample of Calculations of Θ measured

From Chapter Two we have

$$\Theta_P = a\varphi^b Y_p^C \qquad (2.12)$$

where:

a	B	c
0.48839	0.2107	-1.0

$$\gamma_p = \frac{U_p^{*2}}{\upsilon} \qquad (2.13)$$

and

$$U^* = \sqrt{\frac{\tau_w}{\rho}} \qquad (2.14)$$

and

$$\tau_w = \frac{D}{4}\frac{\Delta P}{L} \qquad (2.2)$$

by sub. Eq 2-2 and 2-15 into eq.2-14

$$\gamma_p = \frac{D}{4}\frac{\Delta P / L_{Treated}}{\mu} \qquad \text{(D.1)}$$

where ΔP in pa

for untreated case

$$\gamma_p = \frac{D}{4}\frac{\Delta P / L_{Untreated}}{\mu} \qquad \text{(D.2)}$$

at conc. = 10 ppm, Dia = 0.01905 m, ΔP = from appendix A for specific conditions ΔP =26622.02 pa.

$$\gamma_p = \frac{0.01905}{4} * \frac{26622.02/2}{0.00293} = 21636.07$$

sub. The values of Y_p into Eq.2-13 at φ=10 wppm

$$\Theta_P = 0.48839(10)^{0.2107}(21636.07)^{-1}$$

$$\Theta_P = 3.6668*10^{-5} = \Theta \text{ predicted from Eq.2-13}$$

for Θ measured

since we dependent on time scale hypothesis

$$\Theta_{measured} = \frac{\upsilon}{U_p^{*2}} = \frac{1}{\gamma_p} \qquad \text{(D.3)}$$

$$\Theta_{measured} = \frac{1}{21636.07} = 4.6219 * 10^{-5}$$

$$\% error = ABS\left(\frac{\Theta_m - \Theta_p}{\Theta_m}\right) * 100 = 20.664\%$$

E.2 Sample Calculation of % DR

$$\% DR = a_1 (\gamma_\circ)^{b_1} (\varphi)^{c_1} (\gamma_P)^{d_1} \qquad \text{(4.3)}$$

The constants of Eq.(4.3) have been summarized in the following table :

a_1	b_1	c_1	d_1
1.91699	9.9547	.2134	-9.9886

Where Y_P, Y_O from Eq. (appendix –1) and Eq(B-2)

At conc. = 10 wppm, Dia=0.01905 m, $\Delta P_{Treated}$ and $\Delta P_{Untreated}$ from Appendix A for above conditions we have :

$\Delta P_{Treated}$ =26622.02 pa

$\Delta P_{Untreated}$ =27445.38 pa

$$\gamma_o = \frac{D}{4}\frac{(\Delta P)_m / L}{\upsilon} = \frac{0.01905}{4} * \frac{27445.38/2}{0.00293}$$

$$\gamma_o = 22305.22$$

and $\gamma_P = 21636.07$

$$\%DR = 1.91699(22305.22)^{9.9547}(10)^{0.2134}(21636.07)^{-9.98}$$

$$\%DR = 3.0233$$

and %DR$_{\text{measured}}$ $= ABS\left(\frac{\Delta P_{Unt} - \Delta P_t}{\Delta P_{Unt}}\right) * 100 = \left(\frac{27445.38 - 26622.02}{27445.38}\right) * 100 = 2.999$

$$\%error = ABS\left(\frac{\%DR_m - \%DR_P}{\%DR_m}\right)*100 = 0.777\%$$

Table E-1: Theta (Θ) Correlation

Conc. (wppm)	**Dia (m)**	**U (m/sec)**	**Reynolds No**	**(Δp)treat (Pa)**	**γp Eq(E-2)**	**Θ Predicted Eq.(2-13)**	**Θ measured**	**% error**	**Θ BERUG Eq.(2-13)**	**% error**
10	0.01905	5.850448	30848.73	26622	21636.07	3.67E-05	4.6E-05	20.66	0.000159	245
10	0.01905	5.460418	28792.15	24241.3	19701.25	4.03E-05	5.1E-05	20.66	0.000168	231.6
10	0.01905	5.070388	26735.57	21455.4	17437.06	4.55E-05	5.7E-05	20.66	0.000181	215
10	0.01905	4.680358	24678.99	18445.7	14991.06	5.29E-05	6.7E-05	20.66	0.000197	195.6
10	0.01905	4.095314	21594.11	14188.1	11530.83	6.88E-05	8.7E-05	20.66	0.00023	164.7
10	0.01905	3.315254	17480.95	9661.84	7852.306	0.000101	0.00013	20.66	0.000287	125.1
10	0.01905	2.730209	14396.08	6397.7	5199.5	0.000153	0.00019	20.66	0.000364	89.26
10	0.0254	3.290877	23136.55	7993.8	8662.224	9.16E-05	0.00012	20.66	0.000271	134.6
10	0.0254	3.071485	21594.11	7207.21	7809.861	0.000102	0.00013	20.66	0.000288	124.6
10	0.0254	2.852093	20051.68	6267.81	6791.905	0.000117	0.00015	20.66	0.000312	111.8
10	0.0254	2.632702	18509.24	5433.39	5887.713	0.000135	0.00017	20.66	0.000339	99.43
10	0.0254	2.303614	16195.59	4264.69	4621.296	0.000172	0.00022	20.66	0.00039	80.1
10	0.0254	1.86483	13110.71	2863.65	3103.097	0.000256	0.00032	20.66	0.000491	52.3
10	0.0254	1.535743	10797.06	2089.05	2263.728	0.00035	0.00044	20.66	0.000589	33.36
10	0.03175	2.106161	18509.24	2131.28	2886.866	0.000275	0.00035	20.66	0.000512	47.74
10	0.03175	1.965751	17275.29	1892.53	2563.477	0.000309	0.00039	20.66	0.000548	40.53

10	0.03175	1.82534	16041.34	1706.88	2312.002	0.000343	0.00043	20.66	0.000582	34.55
10	0.03175	1.684929	14807.39	1522.02	2061.609	0.000385	0.00049	20.66	0.000622	28.21
10	0.03175	1.474313	12956.47	1215.06	1645.822	0.000482	0.00061	20.66	0.000709	16.61
10	0.03175	1.193491	10488.57	770.602	1043.798	0.00076	0.00096	20.66	0.000922	3.731
10	0.03175	0.982875	8637.646	586.345	794.2176	0.000999	0.00126	20.66	0.00108	14.19
10	0.0508	0.822719	11568.28	330.449	716.1602	0.001108	0.0014	20.66	0.001147	17.85
10	0.0508	0.767871	10797.06	294.46	638.1645	0.001243	0.00157	20.66	0.001226	21.74
10	0.0508	0.713023	10025.84	250.532	542.961	0.001461	0.00184	20.66	0.001347	26.89
10	0.0508	0.658175	9254.62	226.743	491.4064	0.001614	0.00203	20.66	0.001427	29.9
10	0.0508	0.575903	8097.793	183.113	396.8495	0.001999	0.00252	20.66	0.001615	35.93
10	0.0508	0.466208	6555.356	131.328	284.6192	0.002787	0.00351	20.66	0.001957	44.29
20	0.01905	5.850448	30848.73	26375	21435.32	4.28E-05	4.7E-05	8.189	0.00016	243.6
20	0.01905	5.460418	28792.15	23992.2	19498.77	4.71E-05	5.1E-05	8.189	0.000169	230.2
20	0.01905	5.070388	26735.57	21191.6	17222.67	5.33E-05	5.8E-05	8.189	0.000182	213.4
20	0.01905	4.680358	24678.99	18313.3	14883.43	6.17E-05	6.7E-05	8.189	0.000198	194.7
20	0.01905	4.095314	21594.11	14057.4	11424.61	8.04E-05	8.8E-05	8.189	0.000231	163.6
20	0.01905	3.315254	17480.95	9592.83	7796.218	0.000118	0.00013	8.189	0.000288	124.5
20	0.01905	2.730209	14396.08	6365.06	5172.972	0.000177	0.00019	8.189	0.000365	88.86
20	0.0254	3.290877	23136.55	7785.63	8436.645	0.000109	0.00012	8.189	0.000275	132
20	0.0254	3.071485	21594.11	6998.31	7583.488	0.000121	0.00013	8.189	0.000293	121.9
20	0.0254	2.852093	20051.68	6093.34	6602.852	0.000139	0.00015	8.189	0.000317	109.3
20	0.0254	2.632702	18509.24	5299.09	5742.188	0.00016	0.00017	8.189	0.000344	97.34

20	0.0254	2.303614	16195.59	4194.35	4545.069	0.000202	0.00022	8.189	0.000393	78.84
20	0.0254	1.86483	13110.71	2799.16	3033.222	0.000303	0.00033	8.189	0.000497	50.85
20	0.0254	1.535743	10797.06	2067.73	2240.628	0.00041	0.00045	8.189	0.000593	32.79
20	0.03175	2.106161	18509.24	2065.6	2797.898	0.000328	0.00036	8.189	0.000521	45.8
20	0.03175	1.965751	17275.29	1798.61	2436.25	0.000377	0.00041	8.189	0.000565	37.55
20	0.03175	1.82534	16041.34	1633.13	2212.115	0.000415	0.00045	8.189	0.000597	32.07
20	0.03175	1.684929	14807.39	1458.07	1974.987	0.000465	0.00051	8.189	0.000638	25.92
20	0.03175	1.474313	12956.47	1166.96	1580.675	0.000581	0.00063	8.189	0.000725	14.65
20	0.03175	1.193491	10488.57	743.423	1006.983	0.000912	0.00099	8.189	0.000942	5.175
20	0.03175	0.982875	8637.646	573.155	776.3518	0.001183	0.00129	8.188	0.001095	15.01
20	0.0508	0.822719	11568.28	322.214	698.3144	0.001315	0.00143	8.188	0.001164	18.72
20	0.0508	0.767871	10797.06	286.289	620.4566	0.00148	0.00161	8.188	0.001246	22.66
20	0.0508	0.713023	10025.84	242.802	526.2101	0.001745	0.0019	8.188	0.001371	27.85
20	0.0508	0.658175	9254.62	222.686	482.6128	0.001902	0.00207	8.188	0.001442	30.43
20	0.0508	0.575903	8097.793	178.913	387.7455	0.002368	0.00258	8.188	0.001636	36.55
20	0.0508	0.466208	6555.356	129.299	280.2224	0.003276	0.00357	8.188	0.001975	44.66
30	0.01905	5.850448	30848.73	26045.7	21167.66	4.72E-05	4.7E-05	2E-04	0.000161	241.8
30	0.01905	5.460418	28792.15	23718.1	19276.05	5.19E-05	5.2E-05	2E-04	0.00017	228.6
30	0.01905	5.070388	26735.57	20993.7	17061.87	5.86E-05	5.9E-05	2E-04	0.000183	212.1
30	0.01905	4.680358	24678.99	18124.1	14729.68	6.79E-05	6.8E-05	2E-04	0.000199	193.4
30	0.01905	4.095314	21594.11	13926.7	11318.39	8.84E-05	8.8E-05	2E-04	0.000232	162.6
30	0.01905	3.315254	17480.95	9523.81	7740.13	0.000129	0.00013	2E-04	0.000289	123.8

30	0.01905	2.730209	14396.08	6332.42	5146.444	0.000194	0.00019	2E-04	0.000366	88.45
30	0.0254	3.290877	23136.55	7660.73	8301.298	0.00012	0.00012	2E-04	0.000278	130.5
30	0.0254	3.071485	21594.11	6893.85	7470.302	0.000134	0.00013	2E-04	0.000295	120.5
30	0.0254	2.852093	20051.68	5989.95	6490.821	0.000154	0.00015	2E-04	0.00032	107.8
30	0.0254	2.632702	18509.24	5198.37	5633.044	0.000178	0.00018	2E-04	0.000348	95.75
30	0.0254	2.303614	16195.59	4132.79	4478.37	0.000223	0.00022	2E-04	0.000397	77.73
30	0.0254	1.86483	13110.71	2763.99	2995.108	0.000334	0.00033	1E-04	0.000501	50.04
30	0.0254	1.535743	10797.06	2054.94	2226.769	0.000449	0.00045	1E-04	0.000595	32.44
30	0.03175	2.106161	18509.24	1963.68	2659.844	0.000376	0.00038	1E-04	0.000537	42.73
30	0.03175	1.965751	17275.29	1732.66	2346.921	0.000426	0.00043	1E-04	0.000577	35.4
30	0.03175	1.82534	16041.34	1573.78	2131.719	0.000469	0.00047	1E-04	0.00061	30.03
30	0.03175	1.684929	14807.39	1406.91	1905.689	0.000525	0.00052	1E-04	0.000651	24.04
30	0.03175	1.474313	12956.47	1140.38	1544.673	0.000647	0.00065	1E-04	0.000735	13.54
30	0.03175	1.193491	10488.57	731.433	990.7418	0.001009	0.00101	1E-04	0.000951	5.822
30	0.03175	0.982875	8637.646	559.966	758.4859	0.001318	0.00132	1E-04	0.00111	15.84
30	0.0508	0.822719	11568.28	314.338	681.2445	0.001468	0.00147	1E-04	0.001181	19.56
30	0.0508	0.767871	10797.06	278.433	603.4298	0.001657	0.00166	1E-04	0.001267	23.56
30	0.0508	0.713023	10025.84	238.805	517.5458	0.001932	0.00193	1E-04	0.001384	28.35
30	0.0508	0.658175	9254.62	218.867	474.3365	0.002108	0.00211	9E-05	0.001456	30.93
30	0.0508	0.575903	8097.793	175.094	379.4692	0.002635	0.00264	9E-05	0.001657	37.12
30	0.0508	0.466208	6555.356	129.299	280.2224	0.003569	0.00357	8E-05	0.001975	44.66
40	0.01905	5.850448	30848.73	25634	20833.08	5.1E-05	4.8E-05	6.249	0.000163	239.5

40	0.01905	5.460418	28792.15	23394.3	19012.82	5.59E-05	5.3E-05	6.249	0.000172	226.7
40	0.01905	5.070388	26735.57	20707.9	16829.62	6.31E-05	5.9E-05	6.249	0.000184	210.3
40	0.01905	4.680358	24678.99	17859.2	14514.42	7.32E-05	6.9E-05	6.249	0.000201	191.6
40	0.01905	4.095314	21594.11	13781.4	11200.36	9.49E-05	8.9E-05	6.249	0.000233	161.4
40	0.01905	3.315254	17480.95	9395.65	7635.967	0.000139	0.00013	6.249	0.000291	122.5
40	0.01905	2.730209	14396.08	6293.25	5114.61	0.000208	0.0002	6.249	0.000367	87.96
40	0.0254	3.290877	23136.55	7494.19	8120.835	0.000131	0.00012	6.249	0.000281	128.3
40	0.0254	3.071485	21594.11	6759.56	7324.776	0.000145	0.00014	6.249	0.000298	118.6
40	0.0254	2.852093	20051.68	5867.18	6357.783	0.000167	0.00016	6.249	0.000324	106
40	0.0254	2.632702	18509.24	5097.65	5523.9	0.000192	0.00018	6.249	0.000351	94.15
40	0.0254	2.303614	16195.59	4062.45	4402.142	0.000241	0.00023	6.249	0.000401	76.45
40	0.0254	1.86483	13110.71	2731.75	2960.171	0.000359	0.00034	6.249	0.000504	49.3
40	0.0254	1.535743	10797.06	2022.96	2192.12	0.000485	0.00046	6.249	0.0006	31.57
40	0.03175	2.106161	18509.24	1900.26	2573.944	0.000413	0.00039	6.249	0.000547	40.77
40	0.03175	1.965751	17275.29	1666.71	2257.592	0.000471	0.00044	6.249	0.00059	33.21
40	0.03175	1.82534	16041.34	1528.81	2070.813	0.000513	0.00048	6.249	0.00062	28.45
40	0.03175	1.684929	14807.39	1374.93	1862.378	0.000571	0.00054	6.249	0.00066	22.84
40	0.03175	1.474313	12956.47	1107.47	1500.099	0.000708	0.00067	6.249	0.000748	12.15
40	0.03175	1.193491	10488.57	719.442	974.5001	0.00109	0.00103	6.249	0.00096	6.475
40	0.03175	0.982875	8637.646	551.572	747.1168	0.001422	0.00134	6.249	0.001119	16.37
40	0.0508	0.822719	11568.28	306.462	664.1746	0.0016	0.00151	6.249	0.001198	20.42
40	0.0508	0.767871	10797.06	274.348	594.5759	0.001787	0.00168	6.249	0.001278	24.04

40	0.0508	0.713023	10025.84	234.807	508.8815	0.002088	0.00197	6.249	0.001398	28.86
40	0.0508	0.658175	9254.62	214.81	465.5429	0.002282	0.00215	6.249	0.001472	31.47
40	0.0508	0.575903	8097.793	175.094	379.4692	0.0028	0.00264	6.249	0.001657	37.12
40	0.0508	0.466208	6555.356	127.271	275.8256	0.003852	0.00363	6.249	0.001993	45.03
50	0.01905	5.850448	30848.73	25194.9	20476.2	5.44E-05	4.9E-05	11.36	0.000165	237
50	0.01905	5.460418	28792.15	22970.7	18668.61	5.97E-05	5.4E-05	11.36	0.000174	224.2
50	0.01905	5.070388	26735.57	20378.2	16561.63	6.72E-05	6E-05	11.36	0.000186	208.2
50	0.01905	4.680358	24678.99	17594.4	14299.17	7.79E-05	7E-05	11.36	0.000203	189.8
50	0.01905	4.095314	21594.11	13592.7	11046.93	0.000101	9.1E-05	11.36	0.000235	159.9
50	0.01905	3.315254	17480.95	9267.48	7531.803	0.000148	0.00013	11.36	0.000294	121.2
50	0.01905	2.730209	14396.08	6260.61	5088.082	0.000219	0.0002	11.36	0.000369	87.55
50	0.0254	3.290877	23136.55	7194.42	7796.001	0.000143	0.00013	11.36	0.000288	124.5
50	0.0254	3.071485	21594.11	6490.97	7033.726	0.000158	0.00014	11.36	0.000306	114.9
50	0.0254	2.852093	20051.68	5660.41	6133.72	0.000182	0.00016	11.36	0.000331	102.9
50	0.0254	2.632702	18509.24	4929.78	5341.993	0.000208	0.00019	11.36	0.000358	91.43
50	0.0254	2.303614	16195.59	3930.55	4259.215	0.000261	0.00023	11.36	0.000409	74.02
50	0.0254	1.86483	13110.71	2664.33	2887.119	0.000386	0.00035	11.36	0.000512	47.74
50	0.0254	1.535743	10797.06	1973.94	2138.992	0.000521	0.00047	11.36	0.000609	30.22
50	0.03175	2.106161	18509.24	1798.34	2435.889	0.000457	0.00041	11.36	0.000565	37.54
50	0.03175	1.965751	17275.29	1584.77	2146.607	0.000519	0.00047	11.36	0.000608	30.41
50	0.03175	1.82534	16041.34	1474.86	1997.725	0.000557	0.0005	11.36	0.000633	26.52
50	0.03175	1.684929	14807.39	1326.97	1797.411	0.00062	0.00056	11.36	0.000673	21.02

50	0.03175	1.474313	12956.47	1075.83	1457.239	0.000764	0.00069	11.36	0.00076	10.79
50	0.03175	1.193491	10488.57	703.454	952.8446	0.001169	0.00105	11.36	0.000972	7.356
50	0.03175	0.982875	8637.646	545.577	738.9959	0.001507	0.00135	11.36	0.001126	16.76
50	0.0508	0.822719	11568.28	298.227	646.3288	0.001723	0.00155	11.36	0.001217	21.32
50	0.0508	0.767871	10797.06	266.491	577.5491	0.001928	0.00173	11.36	0.001299	24.96
50	0.0508	0.713023	10025.84	230.809	500.2173	0.002226	0.002	11.36	0.001412	29.37
50	0.0508	0.658175	9254.62	210.752	456.7493	0.002438	0.00219	11.36	0.001488	32.02
50	0.0508	0.575903	8097.793	171.084	370.7791	0.003004	0.0027	11.36	0.001679	37.73
50	0.0508	0.466208	6555.356	127.271	275.8256	0.004037	0.00363	11.36	0.001993	45.03
							AAPE	9.293	AAPE	81.97

Table E-2: Percent Drag Reduction (%DR) Correlation

Conc. (wppm)	Dia (m)	U (m/sec)	Reynolds No	(Δp)treat (Pa)	(Δp)untreat (Pa)	γo	γp	% DR predicted	%DR Exp.	% Error
10	0.01905	5.850448	30848.73	26622	27445	22305.2	21636.07	3.023382075	3	0.7794025
10	0.01905	5.460418	28792.15	24241.3	24914	20247.9	19701.25	2.941199591	2.7	8.9333182
10	0.01905	5.070388	26735.57	21455.4	21983	17865.8	17437.06	2.864283759	2.4	19.345157
10	0.01905	4.680358	24678.99	18445.7	18919	15375.4	14991.06	2.908555136	2.5	16.342205
10	0.01905	4.095314	21594.11	14188.1	14522	11802.3	11530.83	2.875338775	2.3	25.014729
10	0.01905	3.315254	17480.95	9661.84	9859	8012.56	7852.306	2.825540132	2	41.277007
10	0.01905	2.730209	14396.08	6397.7	6528.3	5305.61	5199.5	2.86537972	2	43.268986
10	0.0254	3.290877	23136.55	7993.8	8326.9	9023.15	8662.224	3.457772873	4	13.555678
10	0.0254	3.071485	21594.11	7207.21	7460.9	8084.74	7809.861	3.261278977	3.4	4.0800301
10	0.0254	2.852093	20051.68	6267.81	6461.7	7001.96	6791.905	3.144728011	3	4.824267
10	0.0254	2.632702	18509.24	5433.39	5595.7	6063.56	5887.713	3.127776189	2.9	7.8543513
10	0.0254	2.303614	16195.59	4264.69	4396.6	4764.22	4621.296	3.18612459	3	6.204153
10	0.0254	1.86483	13110.71	2863.65	2931.1	3176.15	3103.097	3.006425927	2.3	30.714171
10	0.0254	1.535743	10797.06	2089.05	2131.7	2309.93	2263.728	2.947458666	2	47.372933
10	0.03175	2.106161	18509.24	2131.28	2264.9	3067.87	2886.866	4.379524644	5.9	25.770769
10	0.03175	1.965751	17275.29	1892.53	1998.5	2706.94	2563.477	4.12763083	5.3	22.120173
10	0.03175	1.82534	16041.34	1706.88	1798.6	2436.25	2312.002	4.056046967	5.1	20.469667
10	0.03175	1.684929	14807.39	1522.02	1598.8	2165.56	2061.609	3.945921646	4.8	17.793299
10	0.03175	1.474313	12956.47	1215.06	1265.7	1714.4	1645.822	3.658412046	4	8.5396988
10	0.03175	1.193491	10488.57	770.602	799.38	1082.78	1043.798	3.56478428	3.6	0.9782144

10	0.03175	0.982875	8637.646	586.345	599.54	812.083	794.2176	3.116946139	2.2	41.67937
10	0.0508	0.822719	11568.28	330.449	358.02	775.905	716.1602	5.565299249	7.7	27.723386
10	0.0508	0.767871	10797.06	294.46	314.26	681.072	638.1645	4.809572674	6.3	23.657577
10	0.0508	0.713023	10025.84	250.532	266.52	577.618	542.961	4.684570234	6	21.923829
10	0.0508	0.658175	9254.62	226.743	238.68	517.27	491.4064	4.230502106	5	15.389958
10	0.0508	0.575903	8097.793	183.113	190.94	413.816	396.8495	3.879534921	4.1	5.3771971
10	0.0508	0.466208	6555.356	131.328	135.25	293.12	284.6192	3.466738168	2.9	19.542695
20	0.01905	5.850448	30848.73	26375	27445	22305.2	21435.32	3.847499781	3.9	1.3461595
20	0.01905	5.460418	28792.15	23992.2	24914	20247.9	19498.77	3.78083019	3.7	2.1845997
20	0.01905	5.070388	26735.57	21191.6	21983	17865.8	17222.67	3.757776885	3.6	4.3826913
20	0.01905	4.680358	24678.99	18313.3	18919	15375.4	14883.43	3.623951627	3.2	13.248488
20	0.01905	4.095314	21594.11	14057.4	14522	11802.3	11424.61	3.656651056	3.2	14.270346
20	0.01905	3.315254	17480.95	9592.83	9859	8012.56	7796.218	3.519220857	2.7	30.341513
20	0.01905	2.730209	14396.08	6365.06	6528.3	5305.61	5172.972	3.496387551	2.5	39.855502
20	0.0254	3.290877	23136.55	7785.63	8326.9	9023.15	8436.645	5.218082003	6.5	19.721815
20	0.0254	3.071485	21594.11	6998.31	7460.9	8084.74	7583.488	5.072641448	6.2	18.183202
20	0.0254	2.852093	20051.68	6093.34	6461.7	7001.96	6602.852	4.833844326	5.7	15.195714
20	0.0254	2.632702	18509.24	5299.09	5595.7	6063.56	5742.188	4.656429973	5.3	12.142831
20	0.0254	2.303614	16195.59	4194.35	4396.6	4764.22	4545.069	4.361767537	4.6	5.1789666
20	0.0254	1.86483	13110.71	2799.16	2931.1	3176.15	3033.222	4.376212457	4.5	2.7508343
20	0.0254	1.535743	10797.06	2067.73	2131.7	2309.93	2240.628	3.786070059	3	26.202335
20	0.03175	2.106161	18509.24	2065.6	2264.9	3067.87	2797.898	6.941748464	8.8	21.116495

20	0.03175	1.965751	17275.29	1798.61	1998.5	2706.94	2436.25	7.957437481	10	20.425625
20	0.03175	1.82534	16041.34	1633.13	1798.6	2436.25	2212.115	7.31033768	9.2	20.539808
20	0.03175	1.684929	14807.39	1458.07	1598.8	2165.56	1974.987	7.02435536	8.8	20.17778
20	0.03175	1.474313	12956.47	1166.96	1265.7	1714.4	1580.675	6.349581853	7.8	18.595104
20	0.03175	1.193491	10488.57	743.423	799.38	1082.78	1006.983	5.916236477	7	15.482336
20	0.03175	0.982875	8637.646	573.155	599.54	812.083	776.3518	4.536020484	4.4	3.0913746
20	0.0508	0.822719	11568.28	322.214	358.02	775.905	698.3144	8.30241269	10	16.975873
20	0.0508	0.767871	10797.06	286.289	314.26	681.072	620.4566	7.386321814	8.9	17.00762
20	0.0508	0.713023	10025.84	242.802	266.52	577.618	526.2101	7.427769222	8.9	16.541919
20	0.0508	0.658175	9254.62	222.686	238.68	517.27	482.6128	5.874497115	6.7	12.320939
20	0.0508	0.575903	8097.793	178.913	190.94	413.816	387.7455	5.671574886	6.3	9.9750018
20	0.0508	0.466208	6555.356	129.299	135.25	293.12	280.2224	4.695759154	4.4	6.7217989
30	0.01905	5.850448	30848.73	26045.7	27445	22305.2	21167.66	4.756321628	5.1	6.7387916
30	0.01905	5.460418	28792.15	23718.1	24914	20247.9	19276.05	4.623881689	4.8	3.6691315
30	0.01905	5.070388	26735.57	20993.7	21983	17865.8	17061.87	4.499913153	4.5	0.0019299
30	0.01905	4.680358	24678.99	18124.1	18919	15375.4	14729.68	4.383413647	4.2	4.3669916
30	0.01905	4.095314	21594.11	13926.7	14522	11802.3	11318.39	4.377112711	4.1	6.7588466
30	0.01905	3.315254	17480.95	9523.81	9859	8012.56	7740.13	4.124305206	3.4	21.303094
30	0.01905	2.730209	14396.08	6332.42	6528.3	5305.61	5146.444	4.013337968	3	33.777932
30	0.0254	3.290877	23136.55	7660.73	8326.9	9023.15	8301.298	6.687316234	8	16.408547
30	0.0254	3.071485	21594.11	6893.85	7460.9	8084.74	7470.302	6.427639968	7.6	15.42579
30	0.0254	2.852093	20051.68	5989.95	6461.7	7001.96	6490.821	6.253321411	7.3	14.338063

30	0.0254	2.632702	18509.24	5198.37	5595.7	6063.56	5633.044	6.150126072	7.1	13.378506
30	0.0254	2.303614	16195.59	4132.79	4396.6	4764.22	4478.37	5.512869107	6	8.1188482
30	0.0254	1.86483	13110.71	2763.99	2931.1	3176.15	2995.108	5.41421695	5.7	5.0137377
30	0.0254	1.535743	10797.06	2054.94	2131.7	2309.93	2226.769	4.392257333	3.6	22.007148
30	0.03175	2.106161	18509.24	1963.68	2264.9	3067.87	2659.844	12.54758555	13.3	5.6572515
30	0.03175	1.965751	17275.29	1732.66	1998.5	2706.94	2346.921	12.60103882	13.3	5.2553472
30	0.03175	1.82534	16041.34	1573.78	1798.6	2436.25	2131.719	11.53761483	12.5	7.6990814
30	0.03175	1.684929	14807.39	1406.91	1598.8	2165.56	1905.689	10.94296932	12	8.808589
30	0.03175	1.474313	12956.47	1140.38	1265.7	1714.4	1544.673	8.715168641	9.9	11.967994
30	0.03175	1.193491	10488.57	731.433	799.38	1082.78	990.7418	7.588689167	8.5	10.721304
30	0.03175	0.982875	8637.646	559.966	599.54	812.083	758.4859	6.240988019	6.6	5.4395755
30	0.0508	0.822719	11568.28	314.338	358.02	775.905	681.2445	11.59164905	12.2	4.9864832
30	0.0508	0.767871	10797.06	278.433	314.26	681.072	603.4298	10.63458674	11.4	6.7141514
30	0.0508	0.713023	10025.84	238.805	266.52	577.618	517.5458	9.560114391	10.4	8.0758232
30	0.0508	0.658175	9254.62	218.867	238.68	517.27	474.3365	7.613623061	8.3	8.2696017
30	0.0508	0.575903	8097.793	175.094	190.94	413.816	379.4692	7.671544152	8.3	7.5717572
30	0.0508	0.466208	6555.356	129.299	135.25	293.12	280.2224	5.120217882	4.4	16.368588
40	0.01905	5.850448	30848.73	25634	27445	22305.2	20833.08	5.929957151	6.6	10.152164
40	0.01905	5.460418	28792.15	23394.3	24914	20247.9	19012.82	5.640504934	6.1	7.532706
40	0.01905	5.070388	26735.57	20707.9	21983	17865.8	16829.62	5.486896181	5.8	5.3983417
40	0.01905	4.680358	24678.99	17859.2	18919	15375.4	14514.42	5.399338231	5.6	3.5832459
40	0.01905	4.095314	21594.11	13781.4	14522	11802.3	11200.36	5.168035017	5.1	1.33402

40	0.01905	3.315254	17480.95	9395.65	9859	8012.56	7635.967	5.021017666	4.7	6.8301631
40	0.01905	2.730209	14396.08	6293.25	6528.3	5305.61	5114.61	4.540331209	3.6	26.120311
40	0.0254	3.290877	23136.55	7494.19	8326.9	9023.15	8120.835	8.85650343	10	11.434966
40	0.0254	3.071485	21594.11	6759.56	7460.9	8084.74	7324.776	8.318746111	9.4	11.502701
40	0.0254	2.852093	20051.68	5867.18	6461.7	7001.96	6357.783	8.177359755	9.2	11.115655
40	0.0254	2.632702	18509.24	5097.65	5595.7	6063.56	5523.9	7.951087011	8.9	10.661944
40	0.0254	2.303614	16195.59	4062.45	4396.6	4764.22	4402.142	6.958528503	7.6	8.4404144
40	0.0254	1.86483	13110.71	2731.75	2931.1	3176.15	2960.171	6.472932493	6.8	4.8098163
40	0.0254	1.535743	10797.06	2022.96	2131.7	2309.93	2192.12	5.462408792	5.1	7.1060547
40	0.03175	2.106161	18509.24	1900.26	2264.9	3067.87	2573.944	18.51976424	16.1	15.029592
40	0.03175	1.965751	17275.29	1666.71	1998.5	2706.94	2257.592	19.74291868	16.6	18.933245
40	0.03175	1.82534	16041.34	1528.81	1798.6	2436.25	2070.813	16.38815684	15	9.2543789
40	0.03175	1.684929	14807.39	1374.93	1598.8	2165.56	1862.378	14.63961575	14	4.5686839
40	0.03175	1.474313	12956.47	1107.47	1265.7	1714.4	1500.099	12.4155091	12.5	0.6759272
40	0.03175	1.193491	10488.57	719.442	799.38	1082.78	974.5001	9.517801764	10	4.8219824
40	0.03175	0.982875	8637.646	551.572	599.54	812.083	747.1168	7.716758245	8	3.5405219
40	0.0508	0.822719	11568.28	306.462	358.02	775.905	664.1746	15.8815648	14.4	10.288644
40	0.0508	0.767871	10797.06	274.348	314.26	681.072	594.5759	13.10714296	12.7	3.2058501
40	0.0508	0.713023	10025.84	234.807	266.52	577.618	508.8815	12.03279196	11.9	1.1158988
40	0.0508	0.658175	9254.62	214.81	238.68	517.27	465.5429	9.75962083	10	2.4037917
40	0.0508	0.575903	8097.793	175.094	190.94	413.816	379.4692	8.157331055	8.3	1.7189029
40	0.0508	0.466208	6555.356	127.271	135.25	293.12	275.8256	6.376152379	5.9	8.0703793

50	0.01905	5.850448	30848.73	25194.9	27445	22305.2	20476.2	7.390805581	8.2	9.8682246
50	0.01905	5.460418	28792.15	22970.7	24914	20247.9	18668.61	7.099995862	7.8	8.974412
50	0.01905	5.070388	26735.57	20378.2	21983	17865.8	16561.63	6.755270363	7.3	7.4620498
50	0.01905	4.680358	24678.99	17594.4	18919	15375.4	14299.17	6.574167337	7	6.0833238
50	0.01905	4.095314	21594.11	13592.7	14522	11802.3	11046.93	6.220774981	6.4	2.8003909
50	0.01905	3.315254	17480.95	9267.48	9859	8012.56	7531.803	6.040291725	6	0.6715288
50	0.01905	2.730209	14396.08	6260.61	6528.3	5305.61	5088.082	5.015675741	4.1	22.333555
50	0.0254	3.290877	23136.55	7194.42	8326.9	9023.15	7796.001	13.96472877	13.6	2.6818292
50	0.0254	3.071485	21594.11	6490.97	7460.9	8084.74	7033.726	13.08070697	13	0.6208228
50	0.0254	2.852093	20051.68	5660.41	6461.7	7001.96	6133.72	12.27262235	12.4	1.0272391
50	0.0254	2.632702	18509.24	4929.78	5595.7	6063.56	5341.993	11.65117694	11.9	2.0909501
50	0.0254	2.303614	16195.59	3930.55	4396.6	4764.22	4259.215	10.14805694	10.6	4.2636138
50	0.0254	1.86483	13110.71	2664.33	2931.1	3176.15	2887.119	8.713281547	9.1	4.2496533
50	0.0254	1.535743	10797.06	1973.94	2131.7	2309.93	2138.992	7.319797419	7.4	1.0838187
50	0.03175	2.106161	18509.24	1798.34	2264.9	3067.87	2435.889	33.68699377	20.6	63.529096
50	0.03175	1.965751	17275.29	1584.77	1998.5	2706.94	2146.607	34.25905637	20.7	65.502688
50	0.03175	1.82534	16041.34	1474.86	1798.6	2436.25	1997.725	24.60862925	18	36.714607
50	0.03175	1.684929	14807.39	1326.97	1598.8	2165.56	1797.411	21.88980716	17	28.763572
50	0.03175	1.474313	12956.47	1075.83	1265.7	1714.4	1457.239	17.39388209	15	15.959214
50	0.03175	1.193491	10488.57	703.454	799.38	1082.78	952.8446	12.4941803	12	4.1181692
50	0.03175	0.982875	8637.646	545.577	599.54	812.083	738.9959	9.026694255	9	0.2966028
50	0.0508	0.822719	11568.28	298.227	358.02	775.905	646.3288	21.86403159	16.7	30.922345

50	0.0508	0.767871	10797.06	266.491	314.26	681.072	577.5491	18.37521104	15.2	20.889546
50	0.0508	0.713023	10025.84	230.809	266.52	577.618	500.2173	14.98115741	13.4	11.799682
50	0.0508	0.658175	9254.62	210.752	238.68	517.27	456.7493	12.38341634	11.7	5.8411653
50	0.0508	0.575903	8097.793	171.084	190.94	413.816	370.7791	10.78277831	10.4	3.6805607
50	0.0508	0.466208	6555.356	127.271	135.25	293.12	275.8256	6.68716286	5.9	13.341743

APPENDIX F

EXPERIMENTAL DEGRADATION DATA

Table F-1: Degradation of oppanol 150, in 19.05 mm ID pipe and 2 m test section at 50 wppm

Q (m^3/min)	Time (min)					
	10	20	30	40	50	60
6	2.3	3	3.7	2.3	1.7	0.6
4.8	2	2.5	2.7	2.5	1	0.3
2.8	1.2	1.8	2.4	1.2	0.5	0

Table F-2: Degradation of oppanol 150, in 31.75 mm ID pipe and 2 m test section at 50 wppm

Q (m^3/min)	Time (min)					
	15	30	45	60	75	
6	4.5	8.9	6	4.5	3	
4.8	4	8	4	2		
2.8	1.7	4.6	3	1.3		

Table F-3: Degradation of oppanol 150, in 50.8 mm ID pipe and 2 m test section at 50 wppm

Q (m^3/min)	Time (min)					
	15	30	45	60	75	90
6	2.8	6.8	4.8	3.4	1.6	1
4.8	3.4	6.8	3.4	1.7		
3.4	3.1	4.6	1.6			

Table F-4: Degradation of oppanol 200, in 19.05 mm ID pipe and 2 m test section at 50 wppm

Q (m^3/min)	Time (min)									
	10	20	30	40	50	60	70			
6	3.2	4.8	4.1	3.2	2.3	1.3	0.7			
4.8	2.4	3.7	3	2.4	1.7	0.9	0.3	0		
2.8	2	3	2.3	1.5	0.8	0.1	0			

Table F-5: Degradation of oppanol 200, in 31.75 mm ID pipe and 2 m test section at 50 wppm

Q (m^3/min)	Time (min)									
	15	30	45	60	90	120	150	180	210	240
6	1.5	2.9	5.9	11.8	8.8	7.1	4.2	2.9	1.5	0
4.8	2.1	4.1	8.4	6.3	4	4	2.1	0		
2.8	1.5	3	3	3.8	6	3.8	1.5			

Table F-6: Degradation of oppanol 200, in 50.8 mm ID pipe and 2 m test section at 50 wppm

Q (m^3/min)	Time (min)									
	15	30	45	60	90	120	150	180	210	240
6	4.1	5.9	5.9	8.1	10.7	7	4.5	2.3	1.2	0
4.8	3.5	5.3	7.1	8.8	5.3	3.5	0.8	0		
3.4	2.1	3.9	3.9	5.9	2.1	0				

Table F-7: Degradation of oppanol 250, in 19.05 mm ID pipe and 2 m test section at 50 wppm

Q (m^3/min)	Time (min)								
	0	10	25	40	55	70	100	115	
6	8.3	7.3	4.1	1.7	1.2	1	0.5	0.5	
4.8	7	7	4.9	3.5	3.5	3.5	2.1	2.1	
2.8	4.1	3.1	2.6	2	2	1	1	0.5	

Table F-8: Degradation of oppanol 250, in 31.75 mm ID pipe and 2 m test section at 50 wppm

Q (m^3/min)	Time (min)								
	0	30	60	90	120	150	180	270	300
6	20.7	20.6	17.6	14.7	11.8	11.8	8.8	8.8	5.9
4.8	16.7	14.6	10.4	8.3	6.3	4.2	4.2	0	
2.8	8.9	6.7	5.6	5.6	4.4	0			

Table F-9: Degradation of oppanol 250, in 50.8 mm ID pipe and 2 m test section at 50 wppm

Q (m^3/min)	Time (min)								
	0	15	30	60	90	120	150	180	210
6	16.7	16.7	16.7	16.7	15.6	13	11	10	10
4.8	11.7	11.7	10	10	8.2	5.7	4.9	3.2	3.2
3.4	5.9	5.9	4.3	2.9	0	0	0	0	0

REFERENCES

1. Fabula, A. G., "Fire-Fighting Benefits of Polymeric Friction Reduction," *ASME J. Basic Eng.*, **93**, pp 453-455 (1971).
2. Kim, C.A., J. H. Sungh, H. J. Choi, C. B. Kim, W. Chum, and M. S. John, "Drag Reduction Characteristics of Poly(ethylene oxide) in Seawater," *J. Chem. Eng. Japan*, **32**, pp 803-811 (1999).
3. Burger, E., W. Munk, and H. Wahl, "Flow Increase in the Trans-Alaska Pipeline Using a Polymeric Drag Reducing Additives," *Society of Petroleum Engineers*, SPE 9419 (1981).
4. Shao, X. L., "Experimental Research on Drag Reduction by Polymer Additives", Zhejiang University, 310027, Hanzhou, P. R. Chain, mecxm@public.zju.edu.cn
5. Rho, T., J. Park, C. Kim, H. K. Yoon, and H. S. Suh, "Degradation of Polyacrylamide in Dilute Solution," *Polym. Degrad. Stab.*, **51**, pp 287-293 (1996).
6. Townsend, A.A., "The Structure of Turbulent Shear Flow", 2nd Edition, Cambridge University, Cambridge, (1976).
7. McComb, W.D., "The Physics of Fluid Turbulence", Oxford University, Oxford, (1990).
8. Schlichting H.,*Boundary Layer Theory*, 6th Edition, McGraw – Hill, New York, (1987).
9. Wilson, N.W., and Azad R.S., "A Continuous Prediction Method for Fully Developed Laminar, Transition and Turbulent Flows in Pipes", *J. Applied Mech.*, **42**, pp.51-57 (1975).
10. Nikuradse J., "Stromungsgesetze in Rauhen Rohren" *Ver Deutch Ing.*, Forshungsheft, **361**, (1933).

11. Toms, B.A., “Some Observations on The Flow of Linear Polymer Solutions Through Straight Tubes at Large Reynolds numbers”, *Proc. 1st Intern. Congr. Rheol.*, **II**, pp 135-141, North Holland, (1948)
12. Toms, B. A.,”The Early Experiments on Drag Reduction by Polymers,” *Phys. Fluids*, **20**, pp s3-s5 (1977).
13. Mysels, K. J., “Flow of Thickened Fluids,” U.S. Patent no. 2, 492, 173, Dec., **27**, (1949).
14. Zagustin, A., and K. Zagustin, “Mechanics of Turbulent Flow in Sediment Laden Streams,” *Inter. Cong. Hydr. Res.*, Kyoto, Japan, B33, **2**, (1969).
15. Mahmood, K., “Flow in Sand-Bed Channels,” Ph.D. Thesis , Colorado State-University, (Feb. 1971).
16. Imae, T., R. Kamiya, and S. Ikeda, *J. Colloid and Iterface Sci.*, **108**, pp 215 (1985).
17. Ohlendrof, D., W. Interthal, and H. Hoffman, *Rheol. Acta*, **25**, pp 486 (1986).
18. Gyr, A., and H. W. Bewersdorff, “Drag Reduction of Turbulent Flows by Additives,” Kluwer Academic Publishers, Dordrecht, Nethlands, (1995).
19. Zakin, J. L., “Variables affecting drag reduction by non-ionic surfactant additives”, Chem. Eng., Common., 23, pp 77-88, (1983).
20. Myska, J.; Zakin, J.L., “Difference in the Flow Behaviours of Polymeric and Cationic Surfactant Drag – Reducing Additives”, Ind. Eng. Chem. Res., 36, pp 5483 – 5487 (1997)
21. Zakin, J. L., J. Myska,. and Z. Chara, “New Limiting Drag Reduction and Velocity Profile Asymptote for Polymeric and Non-Polymeric Additives Systems”, AICHE J., 42, pp 3544-3546, 1996.
22. Rose, G. D., K. L. Faster, V. L. Slocum, and J. G. Lenhart, “Drag Reduction and Heat Transfer Characteristic of Viscoelastic Surfactant Formulations”, 3rd Int. Conf. on the drag reduction, Bristol, paper D6, (1984).

23. Steiff A., W. Althans, M. Weberand and P.M. Weinspach, " Drag Reduction in Fluid Flow", Edition by R.H.J. Sellin and R.T. Moses, Ellis Horwood Pub., Chichester, England, **247**, (1989).
24. Shaver, R.G., Merrill, E.W. Amer., *Inst. Chem. Eng. J.*, **5**, pp 181 (1959).
25. Shin, H., "Reduction of Drag in Turbulent by Dilute Polymer Solutions," Ph. D. Thesis, Mass. Inst. Tech., Cambridge, (1965).
26. Gadd, G. E., "Turbulence Damping and Drag Reduction Produced by Certain Additives in Water," *Nature*, **206**, pp 463-467 (1965).
27. Elata, C., J. Leher, and A. Kahanovitz, "Turbulent Shear Flow of Polymer Solution," *Israel J. Technol.*, **4**, pp 87 (1966).
28. Pruitt, G. T., B. Rosen, and H. R. Crawford, "Effect of Polymer Coiling on Drag Reduction," Western Co., Dallas, Texas, Report No. DTMB-2 (1966).
29. Rodrigues, J.M., J. L. Zakin, and G. K. Patterson, "Correlatio of Drag Reduction with Modified Deborah Number for Dilute Polymer Solutions," *Soc. Petrol. Eng. J.*, **7**, pp 325 (1967).
30. Virk, P. S., E. W. Merrill, H. S. Mickely, K. A. Smith, and E. L. Mollo-Christensen, "The Toms Phenomenon-Turbulent Pipe Flow of Dilute Polymer Solutions," *J. Fluid Mech.*, **30**, pp 305 (1967)
31. Hershey H. C., and J. L., Zakin, "Existence of Two Types of Drag Reduction in Pipe Flow of Dilute Polymer Solutions", *Chem. Eng. Sci.*, **6**, pp 381, (1967).
32. Liaw G.C., "Effect of Polymer Structure on Drag Reduction in Non – Polar Solvents", Ph.D. thesis, University of Missouri, Rolla, (1968).
33. Whitsitt, N. F., L.J. Harrington, and H.R. Crawford, "Effect of Wall Shear Stress on Drag Reduction of Viscoleastic Fluids", Western Co., Dallas Texas, Report No. DTMB – 3, (1968).

34. Patterson G.K., J.L. Zakin and J.M. Rodrigues, “Drag Reduction – polymer solutions, Soap Solution and Solid Particles Suspensions in Pipe Flow”, *Ind. Eng. Chem.*, **61**, pp 22, (1969).
35. Seyer F.A., and A.B Metzner, “Turbulence Phenomena Drag Reducing Systems”, *AICHE J.*, **15**, pp 426, (1969).
36. Virk P.S., and H. Baher, “The Effect Of Polymer Concentration on Drag Reduction”, *Chem. Eng. Sci.*, **25**, pp 1183, (1970).
37. Virk P.S., “ Drag Reduction in Rough Pipes”, *J. Fluid Mech.*, **45**, pp 225, (1971).
38. Zakin, J. L., and D. L. Hunston, ”Effesct of Solvent Nature on the Mechanical Degradation of High Polymer Solutions,” *J. Appl. Polym. Sci.*, **22**, pp 1763-1766 (1978).
39. Marlin, D. H., and J. Chatterji, “Study of Oil Soluble Polymers as Drag Reducers,” *Polym. Eng. Sci.*, **20**, pp 473-477 (1980).
40. Hunston, D. L., and J. L. Zakin, “Effect of Molecular Parameters on the Flow Rate Dependence of Drag Reduction and Similar Phenomena,” Viscous Drag Reduction, edited by G. R. Hough, Progress in Astronautics and Aeronautics, **72**, (1980).
41. Burger, E. D., L. G. Chorn, and T. K. Perkins, “Studies of Drag Reduction Conducted over a Bord Range of Pipeline Conditions when Flowing Prudhoe Bay Crude Oil,” J. Rheology, **24** (5), pp 603-626 (1980).
42. Munstedt, H., Kunststofflaboratorium, BASF Aktiengesellschaft, Ludwigshafen am Rhein, Eingegangen am 18, (1981).
43. Sellin, R. H. J., and M. Oills, “Effect of Pipe Diameter on Polymer Drag Reduction,” *Ind. Eng. Prod. Res. Dev.*, **22**, pp 445-452 (1983).
44. Backtiyarov, S. I., and D. R. Oliver, “Drag Reduction in Exceptionally Dilute Polymer solutions”, J. non-Newtonian fluid Mech., 12, pp 113-118, (1983).

45.Horn, A. F. , C. D.Wu, D. J. Prilutski, and F. M. John, “High Viscosity Crude Oil Drag Reduction”, Pipelines & gas J., 55, pp 22-25, June, (1986).

46.Emad, S. A., “Prediction of Turbulent Drag Reduction With polymer Additives”, Ph.D. thesis, University of Technology, Baghdad (1996).

47.Kim C.A., J.T. Kim, K. Lee, H.J. Choi, and M.S.Jhon, “Mechanical Degradation of Dilute Polymer Solutions Under Turbulent Flow”, *Polymer J.*, **41**, pp 7611 – 7615, (2000).

48.Kim C.A., J.T. Kim, K.Lee, H.J. Choi, and M.S.Jhon, “A High – Precision Rotating Disk Apparatus For Drag Reduction Characteristic”, *Polymer Testing*, **20**, pp 43 – 48, (2001).

49.Choi, H. J., J. H. Sung, S. T. Lim, C. A. Kim, and H. Chung, “Mechanical Degradation Kinetics of Polyethylene Oxide in A Turbulent Flow”, *J. Korea – Australia Rheology*, **16 (**2), pp 57-62 (2004).

50.Jovanovic, J., and B. Frohnapfel, “The Effect of Polymers on the Dynamics of Turbulence in A Drag Reduced Flow”, *Thermal Science J.*, **9** (1), pp 31-14, (2005).

51.Barzinm, J. S. Lee, and S. Maurer, “The Effect of Diameter on Polyethylene Oxide Degradation during Turbulent Drag Reduction”, (Proposal) (2006).

52.Deshmukh, S. R., K. Sudhakar, and R.P. Singh, “Drag Reduction Efficiency, Shear Stability, and Biodegradation Resistance of Carboxymethyl Cellulose-Based and Starch-Based Graft CoPolymers,” *J. Appl. Polym. Sci.*, **43**, p 1091-1101 (1991).

53.Virk, P. S., “Drag Reduction Fundamentals,” *AIChE J.*, **21**, pp 625-656 (1975).

54.Morgen, S. E., Ph.D. Dissertation, University of Mississippi, (1988).

55.Virk, P. S., and D. L. Wagger, “Aspects of Mechanisms in Type B Drag Reduction,” GYR,A. (ed), Structure of Turbulence and Drag Reduction. Springer Verlag. IUTAM Symp., pp 201-213 (1989).

56. Sasaki, S., “Drag Reduction Effect of Rode-Like Polymer Solution,” *J. Phys. Soc.* Japan, **60**, pp 868-878 (1991)
57. Guillermo, A., K. Gasljevic, and E.F. Matthyas, “Experimental Investigation into the Reduction of Friction in Fluid Transport,” Univ. California, Irvine, CA 92697, U.S.A.: gaguilar@bli.uci.edu
58. Mansour, A. R., O. Swaiti, T. Aldoss, and M. Issa, “Drag Reduction in Turbulent Crude Oil Pipelines Using a New Chemical Solvent,” *Int. J. Heat and Fluid Flow*, **9**(3), pp 316-320 (1988).
59. Berman, N. S., “Drag Reduction of the Highest Molecular Weight Fractions of Polyethylene Oxide,” *Phys. Fluids*, **20**, pp 715 (1965).
60. Brod, M., B. C. Deane, and F. Rossi, “Field Experience with the Use of Additives in the Pipeline Transportation of Waxy Crudes,” *J. Inst. Petrol.*, **57** (554), pp 110-116 (1971).
61. Lescarboura, J. A., J. D. Culter, and H. A. Wahl,” Drag Reduction with a Polymeric Additives in Crude Oil Pipelines,” *Soc. Petol Engrs J.*, **11** (3), pp 229-235 (1971).
62. Hoyt, J. W., “Drag Reduction by Polymer and Surfactants,” *AIAA Inc.*, pp 413-432 (1990).
63. Oldroyd, J. G., “A Suggested Method of Deteching Wall Effects in Turbulent Flow Through Pipes,” in *Proc. 1st Intern. Congr. Rheol.*, North Holland, **2**, pp 130-134 (1948).
64. Toms, B. A., *J. Colloid Sci.*, **4**, pp 511 (1949).
65. Savins, J. G., “Drag Reduction Characteristics of Solutions of Macromolecules in Turbulent Pipe Flow,” *Soc. Petrol. Eng. J.*, **4**, pp 203 (1964).
66. Dodge, D. W., and A. B. Metzner, *AIChE J.*, **5**, pp 189 (1959).
67. Astarita, G., Ind. Eng. Chem. Fundementals, **4**, pp 354 (1965).
68. Ernst, W. D., LTV Research Center, Rept. **0-71000/5R-14** (1965).

69. Fabula, A. G., J. L. Lumely, and W. D. Taylor, “Some Interpretations of the Toms Effect,” Syracuse Univ. Rheology Conference, Saranac Lake, (1965).
70. Metzner, A. B., and M. G> Park, “Turbulent Flow Characteristics of Viscoelastic Fluids,” *J. Fluid Mech.*, **20**, pp 291 (1964).
71. Wells, C. S., “Anomalous Flow of Non-Newtonian Fluids,” *AIAA J.*, **3**, pp 1800 (1965).
72. Shaver, R. G., Ph.D. Thesis, Massachusetts Institute of Technology, (1957).
73. Hershey, H. C., and J. L. Zakin, “Study of the Turbulent Drag Reduction of Solutions of High Polymers,” *AIChE J.*, **7**, (1965).
74. Zimm, B. H., *Rheology*, **3**, pp 1-6 (1960)
75. Ram, A., E. Finkelstein, and C Elata, “Reduction of Friction in Oil Pipelines by Polymer Additives,” *Ind. Eng. Chem., Process Design Develop.*, **6**, pp 381 (1967).
76. Elperin, I. T., B. M. Smolskii, and L. I. Leventhal, “Decreasing the Hydrodynamic Resistance of Pipelines,” *Int. Chem. Eng.*, **7**, pp 276-295 (1967).
77. Spangler, J. G., “Studies of Viscous Drag reduction with Polymers Including Turbulence Measurements and Roughness Effects,” *Viscous Drag Reduction,* pp 131-155 (1969).
78. Little, R. C., “Drag Reduction in Capillary Tubes as a Function of Polymer Concentration and Molecular weight,” *J. Colloid Inter. Sci.*, **37**, pp 811-818 (1971).
79. Lumely, J. L., “Drag Reduction by Additives,” *Anu. Rev. Fluid Mech.*, **1**, pp 369 (1969).
80. Lumely, J. L., “Drag Reduction in Turbulent Flow by Polymer Additives,” *J. Polym. Sci., Macromol. Rev.*, **7**, pp 263-290 (1973).

81. Landahl, M. T., “Drag Reduction by Polymer Additives,” *Proc. 13th Intern. Congr. Theor. and Appl. Mechanics*, Moscow, pp 177-199 (1973).
82. Landahl, M. T., and F. Bark, “Application of a Two-Scale Boundary Layer Turbulence Model to Drag Reduction,” *Inter. Polym. Lubrification*, Brest (1974).
83. Berman, N. s., and W. K. George, “Onset of Drag Reduction in Dilute Polymer Solutions,” *Phys. Fluids*, **17**, pp 250 (1974).
84. Chorn, L. G., Msc. Thesis, Univ. Illinois at Urbana-Champaigu, (1975).
85. Ting, R. Y., and D. L. Hanston, “Some Observations on the Anomalous Flow Behavior of Dilute Polymer Solutions,” *Polymer*, **18**, pp 723-728 (1977).
86. Achia, B. V., and D. W. Thompson, “Structure of the Turbulent Boundary in Drag Reducing Pipe Flow,” *J. Fluid Mech*., **81**, pp 439-464 (1977).
87. Hanson, R. J., “The Reduced Drag of Polymer Solutions in Turbulent and Transient Laminar Shear Flow,” *ASME J. Fluids Eng*., **1**, pp 23 (1973).
88. Metzner, A. B., and A. P. Metzner, “Stress Levels in Rapid Extensional Flows of Polymeric Fluids,” *Rheol. Acta.*, **9**, pp 174 (1970).
89. Savins, J. G., and F. A. Seyer, *Phys. Fluids*, **20** (10), pp 578 (1977).
90. Motier, J. F., and D. J. Prilutski, ”Case Histories of Polymer Drag Reduction in Crude Oil Pipelines,” *Proceeding of the 3rd Inter. Conf. on Drag Reduction*, Univ. of Bristol, Bristol (1984).
91. McComb, W. D., and L. H. Rabie, “Local Drag Reduction Due to Injection of Polymer Solutions into Turbulent Flow in a Pipe,” *AIChE J.*, **28**, pp 547-565 (1982).
92. Darby, R. and H. D. Chang, ”Generalized Correlation for Friction Loss in Drag Reducing Polymer Solution,” *AIChE J.*, **30** (2), pp 274-279 (1984).
93. Usui, H. K. Maeguchi, and Y. Sano, “Drag Reduction Caused by the Injection of Polymer Thread into a Turbulent Pipe Flow,” *Phys. Fluids*, **31** (9), pp 2518-2523 (1988).

94. Sreenivasan, K. R., and C. M. White, “The Onset of Drag Reduction by Dilute Polymer Additives, and the Maximium Drag Reduction Asymptote,” *J. Fluid Mech.*, **409**, pp 149-164 (2000).
95. Tabor, M., and P. G. DeGennes, “A Cascade Theory of Drag Reduction,” *Europhys. Lett.*, **2**, pp 519-522 (1986).
96. Min, T., J. Y. Yoo, H. Choi, and D. D. Toseph, “Drag Reduction by Polymer Additives in a Turbulent Channel Flow,” *J. Fluid Mech.*, **486**, pp 312-238 (2003).
97. L′vov, V. S., A. Pomyalov, I. Procaccia, and V. Tiberkevich, *Phys. Rev. Lett.*, **92**, pp 244503 (2004)
98. Paschkewitz, J. S., C. D> Dimitropoulos, Y. X. Hon, V. S. R. Somandepalli, M. G. Mangal, E. S. G. Shaqfeh, and P. Moin, “An Experimental and Numerical Investigation of Drag Reduction in a Turbulent Boundary Layer Using A Rigid Rod-Like Polymer,” *Phys. Fluids*, **17**, pp 085101 (2005).
99. Patterson, R. W., and F. H. Abernalty, “Turbulent Flow Drag Reduction and Degradation with Dilute Polymer Solutions,” *J. Fluid Mech.*, **43**, pp 689-710 (1970).
100. Culter, J. D., J. L. Zakin, and G. K. Patterson, ”Mechanical Degradation of Dilute Solutions of High Polymers in Capillary Tube Flow,” *J. Appl. Polym. Sci.*, **19**, pp 3225-3240 (1975).
101. Horn, A. F., and E. W. Merrill, “Midpoint Scission of Macromolecules in Dilute Solution in Turbulent Flow,” *Nature*, **312** (8), pp 140 (1984).
102. Brostow, W., “Drag Reduction and Mechanical Degradation of Polymer Solutions in Flow”, *Polymer*, **24**, pp 631 (1983).
103. Brostow, W., H. Ertepinar, and R. P. Singh, “Flow of Dilute Polymer Solutions; Chain Conformations and Degradation of Drag Reducers,” *Macromolecules*, **23**, pp 5109-5118 (1990).

104. Brostow, W., S. Majumdar, and R. P. Singh, “Drag Reduction and Solvation in Polymer Solutions,” *Macromol Rapid Commun*, **20**, pp 144-147 (1999).
105. Bello, J. B., A. J. Müller, and A. E. Sa′ez, “Effect of Intermolecular across link on Drag Reduction by Polymer Solutions,” *Polym. Bulletin*, **36**, pp 111-118 (1996).
106. Lee, K., C. A. Kim, S. T. Lim, D. H. Kwon, H. J. Choi, and M. S. Jhon, ”Mechanical Degradation of Polyisobutylene under Turbulent Flow,” *Colloid Polym. Sci.*, **280**, pp 779-782 (2002).
107. Nakano, A., and Y. Minoura, “Effects of Solvent and Characterization on Scisson of Polymer with High-Speed Stirring,” *J. Appl. Polym. Sci.*, **19**, pp 2119-2130, (1975).
108. Cebeci, T., and A. M. O. Smith, “Analysis of Turbulent Boundary Layer,” Academic Press, New York, (1974).
109. Brodkey, R.S., and H. C. Hershey, “Transport Phenomena: A Unified Approach”, (1988).
110. Deissler, R. G., NASA TN 2138, (1950).
111. Elson, T.P., and J. Garside, “Drag Reduction in Aqueous Cationic Soap Solutions,” *J. of Non-Newtonian Fluid Mech.*, **12** (2), pp 121-133 (1983).
112. Sellin, R. H. J., ”Experiments with Polymer Additives in a Long Pipeline,” Int. Conf. Drag Reduction, Cambridge, Paper G2, (1974).
113. Berman, N.S., S.T. Griswold, S. Elihu, and J. Yuen, “An Observation of the Effect of Integral Scale on Drag Reduction,” *AIChE J.*, **24** (2), pp 124 (1978).

الخلاصة

ان استخدام المحلول البوليميري في ظاهرة تقليل الاعاقة يعد الوسيلة الاكثر فعالية في تقنيات تقليل الاعاقة عند الجريان المضطرب في الانابيب. من الناحية العملية، يمكن استخدام ظاهرة تقليل الاعاقة لغرض الاقتصاد وتوفير طاقة الضخ. ان التطبيق التجاري لتثليل اعاقة الموائع اثبت نجاحه في عمليات النقل بالانابيب.

تم في هذا البحث العلمي دراسة فاعلية تقليل الاعاقة باستخدام نوع خاص من البوليمر (Polyisolybutylene, type oppanol B 250) في منظومة تدوير مختبريه مغلقه وعند ظروف جريان مختلفهز تم الحصول على الجريان المضطرابي بواسطة مضخة الإزاحة الموجبة (مضخة التروس) لتجنب حصول إنحلال السلاسل البوليميريه أثناء الضخ. تم إستباط نتائج تقليل الإعاقة من قياسات هبوط الضغط في مقطعين مختلفين من ألاختيار في ألانبوب.

تم دراسة تركيز المواد البوليميرية المضافة بمعدل يتراوح بين صفر – ٥٠ جزء لكل مليون / نسبة وزنية، وبمعدل جريان يتراوح من ٢,٤ الى ٦,٠ (م^3/ساعة)، ومقطعي لختبار، اضافة الى اربعة انابيب مختلفة الاقطار من ١٩,٠٥ ملم الى ٥٠,٨ ملم بينما درس نوع اخر من المذيب (النفط الابيض) في انبوب ذي قطر داخلي ٥٠,٨ ملم ومقطع لختبار ٢م لاغراض المقارنة.

تم ملاحظة زياده مستمره في تقليل إلاعاقة مع زيادة تركيز البوليمر ومعدل سرعة الجريان.

يعطي الأنبوب ذو قطر ٣١,٧٥ mm تقليل إعاقة ألانبوب ذي قطر mm ١٩,٠٥ عند سرعة جريان ثابتة. كما أن قيم تقليل إلاعاقة المستصلة في جريان الكيروسين أعلى قليلا من نضيراتها لزيت الغاز، بسبب الفرق في لزوجتهما.

تقع قيم معامل ألاحتكاك لزيت الغاز المعامل مع wppm ٥٠ بوليمر بأتجاه محاذي للحدود القصوى لتقليل إلاعاقة، خاصة في ألانبوب بقطر ٣١,٧٥mm. تم تقدير معامل ألاحتكاك كدالة لرقم الرينولدز، وأعطت نتائج مطابقه الى حد ما للنتائج المستحصله عمليا.

تم ربط نتائج تقليل الاعاقة بادخال تطوير على الموديل الرياضي المتوفر في الادبيات وان الدالة الشكلية للموديل تطلب معرفة الشد السطحي، هبوط الضغط وتركيز المضافات كمتغير. النتائج تؤشر الى توافق مقبول مع القيم المستحصله عمليا، للانابيب المختلفة القطر.

تم دراسة تأثير الزمن على فعالية البوليمرات في تقليل الاعاقة بـــهدف أختيار أحتمال حصول إنحلال المضافات البوليميريه أثناء عمليات تدويرالمحاليل. تم أجراء التجارب باستخدام بوليمرات البولي أيزوبيوتيلين بثلاث أوزان جزيئيه مختلفة وهي النوعين B 150, B 200 بتركيز 50 wppm والنوع B 250 عند تراكيز مختلفه تصل الى 50wppm.

أوضحت النتائج، أن البوليمرات ذات ألاوزان الجزيئية ألاوطىء تفقد فعاليتها مع زمن التشغيل أسرع من النوع B 250 ذي الوزن الجزيئي العالي. علاوة على ذلك يتأثر أنحلال البوليمرات بوضوح على قطر الانبوب المستخدم.

. وقد تم تحليل سلوك الانحلال الميكانيكي للانواع البوليمرات الثلاثة المذكورة اعلاه كدالة للزمن، من خلال تطوير معادلة fractional exponential decay واتضح ان المعادلة المطورة تطابق النتائج العملية بدرجة افضل من المعادلة قبل تطويرها

شكـــــر وتقــــدير

قبل كل شيء وبعد كل شيء أن الحمد والشكر لله عز وجل والصلاة والسلام على سيد ألانام الرسول الكريم محمد صلى الله عليه وسلم .

بتقديمي هذه الاطروحة، وبالرغم من كل الجهد المبذول فيها، لا يسعني إلا التعبير عن بالغ الشكر والعرفان الى الأستاذ الدكتور جابر شنشول جمالي الذي كان الأب الروحي لجهدي العلمي لما ابداه من مساعدة قيمة في إنجاز هذا البحث العلمي. كما أعبر عن عميق شكري للأستاذ الدكتور قاسم جبار سليمان، رئيس قسم الهندسة الكيمياوية، لدعمه وتوجيهه المستمر، والى جميع أساتذتي وزملائي الكرام في قسم الهندسة الكيمياوية الذين كانوا دائما جاهزين لتقديم اي مساعدة أو مشورة أحتجت اليها.

كما أود أن أقدم شكري الخاص لأفراد عائلتي الكرام لصبرهم ودعمهم الذي قدموه لي طوال فترة حياتي الدراسة.

عزت نيازي سليمان

فعالية البولي ايزو بيوتيلين كماده مقللة للاعاقة في الجريان المضطرب في ألانابيب

أطروحة
مقدمة إلى كلية الهندسة في جامعة النهرين كجزء من متطلبات نيل درجة الدكتوراه فلسفة في الهندسة الكيمياوية

من قبل
عزت نيازي سليمان
بكلوريوس هندسة كيمياوية ١٩٩٧
ماجستير هندسة كيمياوية ٢٠٠٠

ذى الحجه ١٤٢٧ هـ
كانون الثاني ٢٠٠٧ م