

Effect of Molecular Weight on Turbulent Drag Reduction with Polyisobutylene Additives

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Abstract

Turbulent drag-reduction efficiency of polyisobutylene with three different, very high molecular weights was studied in a build-up closed loop gas oil circulation system. The turbulent mode was produced via a positive displacement gear pump to avoid mechanical degradation of polymer chains during the experimental period. Three molecular weights 2.9×10^6 , 4.1×10^6 , 5.9×10^6 g/mol dissolved in reformat were used as additives in order to investigate the effect of molecular weight on drag-reduction rate and flow capacity increase.

The effect of polymer concentration was investigated over a range up to 70 wppm. The gas oil flow conditions that were studied included Reynolds number 8341 to 17874 as well as inside pipe diameters 1.0, 1.25 and 2.0 inches. A gradual increase of drag reduction and throughput was achieved by increasing the polymer concentration and gas oil flow rate and decreasing the pipe diameter.

Friction factor was calculated from the experimental data. For untreated gas oil pipelining, friction factor values lies near Blasius asymptotes. While by addition of polymer drag reducer into the flow, the friction factor values were positioned towards Virk maximum drag-reduction asymptotes, noticeably for the highest molecular weight type. Furthermore the investigation showed that the degree of molecular weight is significantly in drag reduction performance.

Correlation equations were suggested to predict the effect of flow parameters, concentration, flow rate, pipe diameter and finally polymer

molecular weight on pressure drop reduction. The results of the correlations showed good agreement between the observed and predicted pressure drop reduction values, with a higher than 99.5 %.

The presented data should be useful in possible field applications, in order to increase the flow capacity for crude oil and fractions transportation pipelines system, specially by use the $5.9 \cdot 10^6$ molecular weight polyisobutylene additive.

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NOTATIONS

Variables Notations

%Dr	Percentage drag reduction	[-]
%TI	Percentage throughput increase	[-]
A	Area	[m ²]
C	Polymer concentration	[ppm]
<i>d</i>	Pipe diameter	[m]
<i>h_f</i>	head loss	[m]
ID	Inside Diameter	[m]
J _o	staudinger index	[cm ³ .g ⁻¹]
<i>L</i>	Length of Tube	[m]
L	Testing section length	[m]
Le	Entrance length	[m]
MW	Molecular weight	[g/mole]
N	Chain length	[m]
ppm	part per million	[g/cm ³]
Q	Volumetric flow rate	[m ³ /hr]
Re	Reynolds number ($\rho U d/\mu$)	[-]
<i>R_G</i>	Radius of gyration	[m]
<i>u</i>	Fluid velocity	[m/s]
wppm	weight part per million	[g/cm ³]
ΔP	Pressure drop	[N/m ²]

Abbreviations

API	Density by American Petroleum Institute
BHP	Pump horsepower
BPD	Barrel per day
CDR	Conoco drag reducer
CMC	SodiumCarboxymethylcellulose
DR	Drag Reduction
DRA	Drag Reduction Agent
DRE	Drag reduction effectiveness
GG	Guar gum
HEC	Hydroxyethylcellulose
HP	Horse power
MC	Minimum concentration
M_v	Average molecular weight
MW	Molecular weight
MWD	Molecular weight of degradation
PAA	polyacrylic acid
PAM	Polyacrylamide
PEO	Polyethylene oxide
PIB	Polyisobutylene
PMMA	Polymethyl methacrylate
PRD	Pressure drop reduction
RDA	Rotating disk apparatus
TAPS	Trans Alaska Pipeline System
XG	Xanthan gum

Greek Letters

ρ	Fluid density	[kg/m ³]
η	Dynamic viscosity	[poise]
μ	Viscosity	[poise]
Φ	Fanning friction factor	[-]
η_{sp}	Specific viscosity	[poise]
η_p	pump efficiency	[-]

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CHAPTER ONE

INTRODUCTION

A large amount of energy loss due to friction occurs in many cases of turbulent flow, generally. However, it is well known that turbulent drag reduction which is drastic reduction of frictional resistance can be easily observed by injection a minute amount of polymeric additives in turbulent flow ⁽¹⁾. Treated solvents undergoing a turbulent flow in a pipe thereby require a low pressure drop to maintain the same volumetric flow rate.

Effective polymeric Drag- reducing additives are considered to be flexible, linear with high molecular weight, such as polyethylene oxide, polyacrylamide and polyisobutylene ⁽²⁾.

The industrial application of drag reduction can be found in many areas such as pipelining of crude oil and its fractions, fire-fighting ⁽³⁾ and closed-circuit pumping installations, such as central heating systems ⁽⁴⁾. The first major application of drag reducers in oil pipelines has been in the Trans-Alaska oil pipeline system ⁽⁵⁾. Another major use of such chemicals had been in Iraq in the mid 1980s ⁽⁶⁾. These applications showed the high ability of polymers in reducing drag and increasing oil flow rate without the need for any additional pumping power or new pipelines.

Injected polymer solutions into a pipe flow does not usually quickly mix with the main flow. The turbulent mixing process as well as the interacting between polymer solution and turbulent flow determines the drag reduction effectiveness ⁽⁷⁾. Almost all the laboratory investigations on drag

reduction have been conducted for homogeneously premixed dilute solutions. Hence dissolving the polymer in the fluid is done before the experiment takes place. The onset shear stresses as well as the obtainable magnitude of drag reduction are essentially determined by the molecular parameters of the polymer⁽⁷⁾. The experimental work of the present investigation is of this type.

The dependence of drag reduction efficiency is known to be a function of polymer molecular weight, polymer concentration, and the degree of turbulence. However, the usage of these polymers is limited because of their susceptibility to flow induced mechanical and/or chemical degradation of the polymer molecules and marginal economic incentive, have slowed its exploitation⁽⁸⁾.

The rheological characteristics of drag-reducing polymeric solutions are not only quite complex, they are generally difficult to evaluate quantitatively because of the low concentration of polymer solution. These properties coupled with the complex character of turbulent flow, resulted in an exceedingly complex system which is virtually difficult to analyze precisely. Consequently, various approximations and simplifying assumptions are necessary in order to obtain a relationship between observable quantities⁽⁹⁾.

The major objective of the present work is concerned with the studying the effect of molecular weight of polymeric additives on effectiveness of drag reduction on gas oil. Three potentially economically available polyisobutylene polymers with different molecular weights ranging between 2.5 to about six million have been studied in a laboratory scale turbulent pipe flow loop.

Further aim of the experimental study is to evaluate the effect of polymer concentration, bulk velocity and pipe diameter on the drag reduction performance. The information obtained should be of value in themselves and should also assist in the consideration of the economic application of drag reducing additives for increasing the capacity of a given pipeline for oil products.

CHAPTER TWO

LITRETURE SERVEY

2.1 Pipeline Transportation of Oil Products

2.1.1 Pipelining

Crude oils and their fractions are often transported by pipelines over long distances from fields and storage to marketing and processing units. Approximate 75% of crude oil in the world and about 20% of petroleum products are transported by pipelines, with diameters ranging between 8.9 -121.9 cm (3.5-48) inches. Reasonable amounts of distinct products can be transported through the same pipeline with a very small loss due to the mixing at liquid boundaries. Pipeline management is a complex task, where planning and logistics are important issues, among others like maintenance and environmental safety.

During the pumping a substantial drop in pressure may be take in account in both the pipeline and in individual units themselves. It is necessary, therefore, to consider the problems concerned with calculating the power requirements, for pumping, with designing the most suitable flow systems, and frequently with controlling the flow at a steady state. The oil-stocks may consist of one or more phases and contain suspended solids, and considered sometimes as non-Newtonian properties, these often complicate the analysis ⁽¹⁰⁾.

The design and layout of pipe systems are an important factor in the planning of modern plants and may represent a significant part of the total cost.

The energy required by the pumping of oil-stocks will depend on the height through which the fluid is raised, the pressure required on delivery, the length and diameter of the pipe, the rate of flow and the physical properties of the fluids, particularly its viscosity and density ⁽¹¹⁾.

Heavy oils, characterized by their high viscosities, high pour point and low API gravities, are currently being transported to a limited extent by pipelines. Although there are some pipelines used for the transportation of heavy crude oils. Heavy oils present problems of pipelining usually due to there high pour point (wax crystallization) and viscosities (the ability to flow) ⁽¹²⁾.

The most relevant parameters effecting the pipelining oil products are viscosity, temperature, density and pour point.

The relationship between viscosity and temperature is important in the design of pipelines. This relationship is shown in figure 2.1 for a number of crude oils, both heavy and light ⁽¹¹⁾. Viscosity relates to the shear stress and shear rate. The greater the viscosity, the greater becomes the head loss along the pipeline, and therefore, more horsepower is required for pumping. Generally, the economic range of viscosities at pipeline temperatures is 10-1000 Cst, depending on pipeline length. The effect of viscosity on pipeline size and pumping power requirement is predominate ⁽¹²⁾.

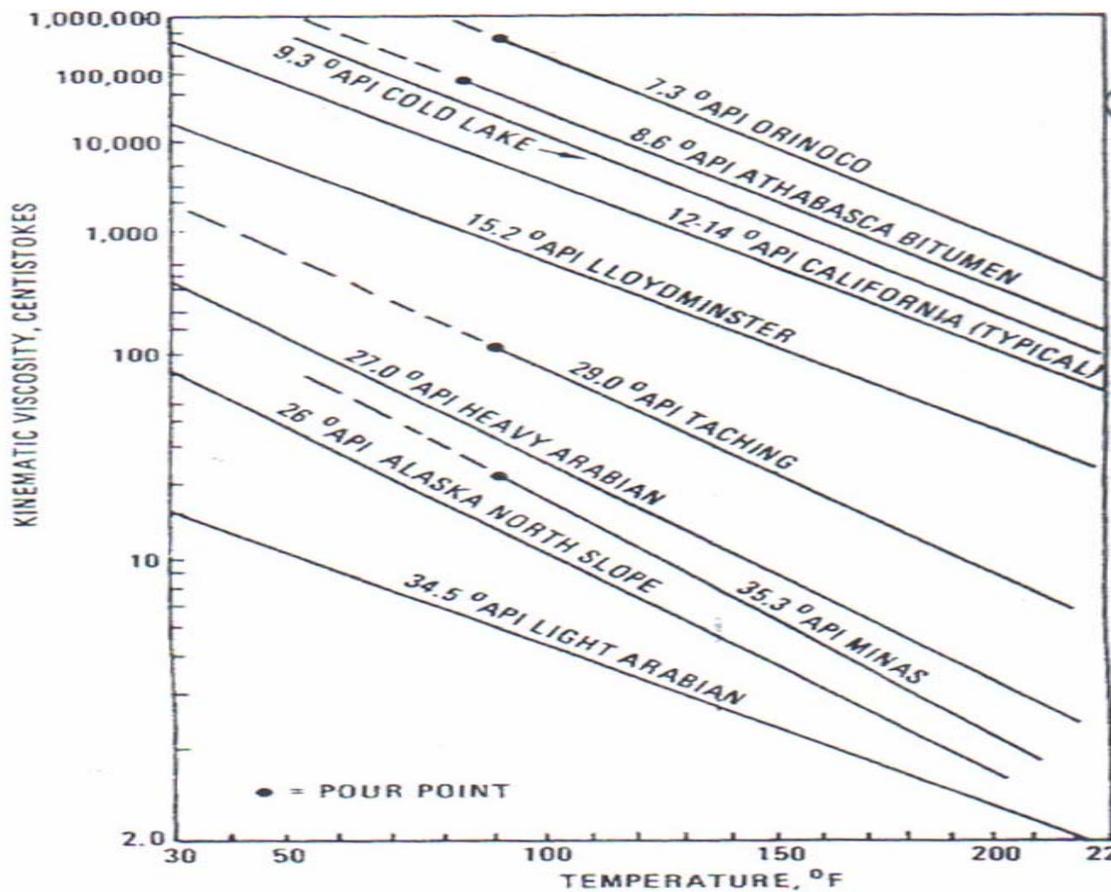


Figure 2.1 crude oil and bitumen viscosity data ⁽¹²⁾

Some idea of the effect of viscosity on pipeline size, pumping BHP requirement, and costs is shown in table 2.1. The data developed do not necessarily represent an economically "optimum" design for each case, but serve to illustrate the effect of viscosity.

Note that above approximately 100 Cst, there are larger incremental increase in pipeline size, pumping HBP, and costs. It is for this reason that most existing large and long oil pipelines have been designed for viscosities in the region of 100 Cst. However, it is feasible to consider designs for viscosities in the region of 1,000 cts if the economics are favorable ⁽¹²⁾.

Table 2.1 Effect of Viscosity on Pipeline Size and BHP

Viscosity, Cst	Gravity API	Pipeline I.D., inch	Psi/Mile	BHP per Mile
50,000 BPD capacity				
1	45	10.3	16	17
10	26	11.2	17.4	18.5
100	17	12.5	19.4	20.5
1000	10	17.0	26.5	28

The pour point is the lowest temperature at which a petroleum oil will flow or pour when it is chilled without disturbance at a controlled rate. At pour point temperature or below wax crystals will be precipitate and inhibit its ability to flow. Waxy oils will form wax sediment on the walls of pipelines sufficient, on time, to block the pipeline. Generally, pipelines are designed and operated at temperatures above the pour point.

2.1.2 Calculations

The head loss due to friction is expressed by Darcy's equation as follows:

$$h_f = 8\phi \frac{L u^2}{2dg} \quad \dots(2.1)$$

and in more conventional pipeline units, pressure drop:

$$\Delta P = 4\phi \frac{L}{d} \rho u^2 \quad \dots(2.2)$$

For turbulent flow and smooth pipe,

$$\phi = \frac{0.04}{\text{Re}^{0.25}} \quad \dots(2.3)$$

Where the Reynolds Number

$$\text{Re} = \frac{\rho u d}{\mu} \quad \dots(2.4)$$

Equation 2.2 can be written by considering equations 2.3 and 2.4 as follows:

$$\frac{\Delta P}{L} = \frac{0.16 \rho^{0.75} u^{1.75} \mu^{0.25}}{d^{1.25}} \quad \dots(2.5)$$

The oil velocity is calculated by equation 2.6

$$u = \frac{Q}{A} = \frac{Q}{\left(\frac{\pi}{4}\right) d^2} = 1.27 \frac{Q}{d^2} \quad \dots(2.6)$$

Therefore, the pressure drop is estimated by:

$$\frac{\Delta P}{L} = 0.244 \frac{Q^{1.75} \mu^{0.25} \rho^{0.75}}{d^{4.75}} \quad \dots(2.7)$$

The power required for pumping will be given by the product of the volumetric flow rate and the pressure difference between the pump and the discharge of the pipeline,

$$HP = \Delta P \frac{Q}{\eta_p} \quad \dots(2.8)$$

The required horse power is calculated by assuming constant volumetric flow rate, as follows:

$$HP = \frac{0.244 Q^{2.75} L}{d^{4.75} \eta_p} \rho^{0.75} \mu^{0.25} \quad \dots(2.9)$$

While, the volumetric flow rate is calculated by constant pumping horse power as follows:

$$Q = \left[\frac{d^{4.75} \eta_p HP}{0.244 \mu^{0.25} \rho^{0.75} L} \right]^{0.3637} \quad \dots(2.10)$$

2.1.3 Flow Improvement

There are a number of methods by which the pipelining of oil can be improved. One of these, is the addition of pour point depressants to reduce pour point and avoid wax crystallization ⁽¹²⁾.

It is well known that the viscosity of heavy petroleum fractions decreases as temperature increases. For short distance transportation of oil, through pipes the process of heating by steam would reduce the viscosity; making the flow easier. The disadvantage of this process are the added cost of heating devices, insulation of pipelines and energy requirement ⁽¹²⁾.

If heating is required, a direct-fired heater is usually used to raise the temperature of the oil. This heater is of conventional tube coil design fired with gas or fuel oil.

To minimize tube size, a by-pass stream, taken from the main flow, is heated to a higher temperature than required. When it re-enters the main flow, it mixes with the main temperature is met which is required. The temperature to which the oil is raised in the heater must obviously be kept below the coking range.

An alternative to hot oil pipeline transport of heavy crude oils at ambient temperature is the blending with a low-viscosity hydrocarbon such as condensate, natural gasoline, or naphtha. Figure 2.2 shows the reduction in viscosity that can be obtained by blending condensate with heavy crude oils.

Table 2.2 shows the effect of dilution on pipeline size, pumping BHP, and costs for pipeline transport of 1,000 cts oil with and without dilution. Note that in this case use of 10-20 percent approximates an "optimum" pipeline design ⁽¹²⁾.

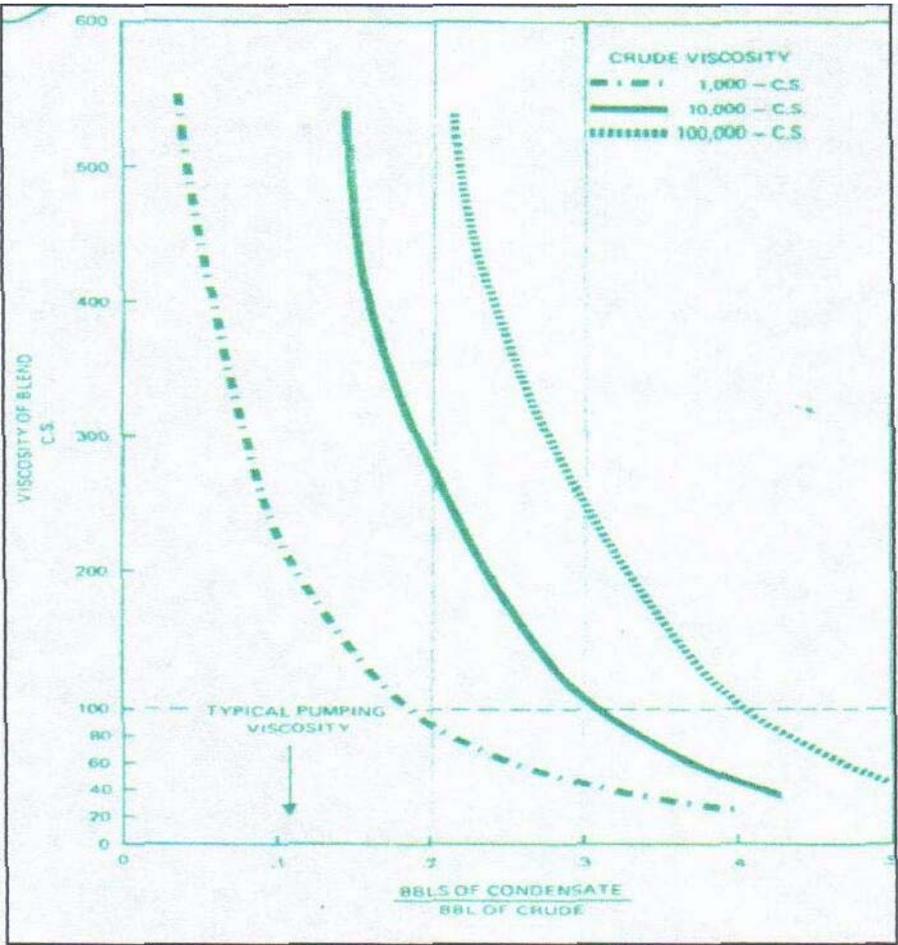


Figure 2.2 effect of dilution with condensate on viscosity ⁽¹²⁾

This technique is currently being practiced in Canada to move Lloydminster heavy crude oil through the Interprovincial Pipeline. The diluted, or blended, crude oil has a viscosity of 120-135 cts at pipeline temperature ⁽¹²⁾.

Table 2.2 Effect of dilution on pipeline sizes and transportation costs ⁽¹²⁾

Blend Stock Added to Crude oil Parts P/100	Total Capacity MBD	Blend		Pipeline I.D. in.	Psi/Mile	BHP per Mile	Investment \$1,000 per Mile	Costs of Service \$ per 100 Bbi-Mi		Station Spacing Miles
		Vise, Cst.	°API					Blend	crude	
0	100	1000	10	18.9	17.3	37	240	32	32	70
I	101	838	11	18.7	16.6	36	233	31	32	75
5	105	445	13	18.7	14.2	32	208	26	28	85
10	110	231	15	18.5	13.1	31	201	24	27	90
20	120	85	18	19.2	12.1	31	203	22	27	100
30	130	41	23	21.5	11.2	31	203	21	27	105
40	140	23	28	22.2	10.5	31	205	19	27	115
Bases										
Crude oil		Viscosity 1000 Cst, S-G. 0.61								
Blend Stock		Viscosity 0.4 Cst, S-G. 0.61								
Net Capacity, Crude oil 100,000 BPD										

Lowering the viscosities is achieved also by the preparation of unstable emulsion by mixing water ^(13, 14) or alcohol ^(15, 16) with oil. S. Marsden described a method of transporting crude oils at a temperature below 0 °C through pipelines in form of 50 to 40 volume percent in methanol or methanol-water dispersion in the presence of effective surfactants ⁽¹⁶⁾.

One of the modern techniques for reducing drag in oil pipelines is the addition of minute quantity of chemical additives to liquid transported in turbulent flow ^(17, 18).

2.2 Drag Reduction Phenomena

In the process of transferring a Newtonian fluid through a pipelining systems, considerable energy may be expended to overcome friction encountered in movement of the liquid. When a liquid is pumped under pressure a frictional pressure is apparent as a pressure drop along the pipeline ⁽¹⁹⁾. Such pressure drops are particularly noticeable under conditions where the velocity of liquid has surpassed the critical limit for laminar flow. To compensate for the loss of energy due to friction pressure, additional energy must be consumed. Consequently, a decrease in frictional 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 as in hydraulic fracturing of oil and gas wells ⁽¹⁹⁾.

A large amount of energy loss due to friction occurs in many cases of turbulent flow, generally. However, it is well known that turbulent drag reduction (DR) which is a drastic reduction of frictional resistance can be easily observed by injecting a minute amount of polymeric additives in a turbulent flow ⁽¹⁾. Polymer solutions undergoing a turbulent flow in a pipe thereby require a lower pressure drop to maintain the same volumetric flow rate. The addition of small amounts of additives to the flowing fluids can show significant effects on a lot of flow types, including the stability of laminar flow, transition to turbulence, vortex formation and break-up ⁽⁶⁹⁾.

The phenomenon in which drag of a dilute polymer solution is drastically reduced in turbulent flow by minute amount of suitable additives has been well documented ⁽²⁰⁾. This implies that fluid containing these additives requires a lower pressure drop than pure solvent to maintain the same flow rate in a pipe ^{(21), (22)}.

High molecular weight polymers and some surfactants are the most popular chemical drag reducing agents. The dependence of drag reduction efficiency is known to be a function of polymer molecular weight, polymer concentration and the degree of turbulence ^{(23), (24)}.

The addition of DR additive is done by two different method, resulting in two different types of drag reduction, homogeneous and heterogeneous ⁽²⁵⁾. Dissolving the polymer in the fluid before the experiments takes place is in the case of homogeneous DR. the onset shear stress as well as the obtainable magnitude of drag reduction are essentially determined by the molecular parameters of the polymer. While, by injection of moderately concentrated polymer solution into turbulent pipe flow resulted in a heterogeneous DR. the turbulent mixing process as well as the interaction between polymer solution and turbulent flow determine the drag reduction effectiveness.

2.3 Drag Reducing Additives

2.3.1 Polymers

Various drag-reducing additives are available, such as flexible long- chain macromolecules, colloidal surfactants and suspension of fine, insoluble fibers or particles ⁽²⁶⁾. Among these, macromolecules, which possess a linear flexible structure and a very high molecular weight, have been widely investigated as drag reducer ⁽²⁷⁾.

Drag reducer polymers are classified into two groups, water-soluble and oil soluble polymers, as listed in table 2.3.

Table 2.3 Drag-reducing polymer additives

Water-soluble (and brine soluble polymers)	Hydrocarbon-soluble
Poly (ethylene oxide)	Polyisobutylene
Polyacrylamide	Polystyrene
Guar gum	Poly (methyl methacrylate)
Xanthan gum	Polydimethyl siloxane
Carboxymethyl cellulose	Poly (Cis-isoprene)
Hydroxyethyl cellulose	Conoco drag reducer (CDR)

Polyethylene oxide (PEO) has been the most widely studied for both laboratory and commercial application, including fire fighting and Marine propulsion. (PEO) is a linear, flexible molecule which is available commercially in a range of molecular weight, its utility in multiple pass application is limited

due to its extreme sensitivity to shear degradation. Drag reduction similar to that obtained in water has been shown for PEO in other solvents such as, sea water, plasma, benzene, dioxane, and chloroform. Mixed (PEO) system, such as (PEG) graft polymer, polymer/soap and polymer/dye mixture, have shown to provide varying levels of (DRE) ⁽²⁸⁾.

Poly (acrylamide) (PAM) is the other synthetic water soluble additive which differs from PEO in that it has a side chain and is less susceptible to shear degradation. The related polymer poly (acrylic acid)(PAA) can be formed by hydrolysis of PAM. Most of the laboratory and commercial studies, however have focused on PEO and PAM due to their availability, their relatively low cost, and the large body of previously reported experiments describing their solution behavior available in the literature ⁽²⁸⁾.

One of the most widely used commercial drag reducing biopolymers is guar gum (GG). GG is a plant polysaccharide with a semi-rigid backbone. It has been used for a number of years in oil field application, and in the petroleum industry ⁽²⁹⁾. The major limitation of guar gum as drag reduction application is its susceptibility to biodegradation. It has been shown that resistance to shear and biodegradation can be increased by grafting acrylamide to guar gum molecules ⁽³⁰⁾.

Modified cellulose such as Carboxymethyl cellulose (CMC) and Hydroxyethyl cellulose (HEC) have been employed commercially and in laboratory studies. (CMC) was the first water-soluble polymer whose drag-reducing properties were reported in the literature ⁽³¹⁾.

The other biopolymer which has been widely used as a commercial drag reducer is Xanthan gum (XG). XG is an extracellular polysaccharide produced by the bacteria *xanthomonas*. XG shows variable rheological behavior with changes in solvent ionic strength, flow rate, and polymer concentration. Kenis⁽³²⁾ has demonstrated a greater shear stability for XG than for a number of other drag-reducing molecules. The shear stability, and resistance to shear degradation decreased as follow: PAM>XG>PEO>GG.

Polyisobutylenes are highly olefin hydrocarbon polymers, composed of long, straight chain macromolecules containing only chain- end olefin bonds. This molecular structure leads to chemical inertness and resistance to chemical or oxidative attack, and solubility in hydrocarbon solvents. All grades of polyisobutylene are a mixture of molecules of varies sizes⁽⁴⁹⁾.

Conoco drag reducer is a high molecular weight, linear polyolefin's, which supplied as up to 10% polymer and 90% solvent^{(33), (34)}. The first major application of CDR in oil pipeline has been in the Trans-Alaska oil pipeline system⁽³⁵⁾.

A range of new water-soluble polymers have been synthesized by McCormick and coworker⁽³⁶⁾. They have undertaken extensive analyses of polymers of widely different structures and compositions. These polymers include hydrophobically modified polyacrylamide polymers, anionic and cationic polyelectrolytes and polyampholytes. Applications of these water-soluble polymers to DR technologies have been investigated^(37, 38, 39). It was

discovered that all copolymers were found to conform a universal curve for DR, when normalized for hydrodynamic volume fraction polymer in solution.

Biopolymers such as high molecular weight polysaccharides produced by living organisms can provide effective DR ⁽⁴⁰⁾. Polysaccharides of several fresh water and marine algae, fish slimes, seawater slime and other fresh water biological growths have been found to be good drag reducers. Interestingly, as mentioned later these biological additives are also a source of fouling growth which can substantially reduce the DR effectiveness brought about by other DR technologies.

2.3.2 Surfactants

Surfactants are surface-active agents, which consist of a polar, Hydrophilic head and non-polar, hydrophobic tail. Depending on the electrical charge can be classified as anionic, cationic and nonionic.

Surfactants were used as drag reducing agents in many commercial applications. Surfactant molecules have the ability to form certain types of aggregates which are called "micelles". These micelles have the ability to reform their structure and region their drag reducing ability, when the fluid enters lower shear regions ^(41, 42). Also Surfactants are easier to handle during operation and they are commercially available. These advantages made the surfactant to be preferred to many types of polymers in some commercial applications, especially with aqueous media ⁽⁴³⁾.

2.4 Drag Reduction Applications

For many pipeline operations, increased throughput or pump station shutdown can be dealt economically by installation of higher capacity pumps or temporary portable pumping facilities, hence the use of polymer drag reduction is usually not an optimal utilization of capital resources. This evaluation can change drastically for large-scale, high volume pipelines in hostile environments, such as the Trans-Alaska pipeline, (TAPS) ⁽⁴⁷⁾.

The first major application of drag reducers in oil pipelines has been in the TAPS, another reported major use of such chemicals has been in Iraq in themed 1982 ⁽⁴⁸⁾.

The industrial applications of DR can be found in many areas such as transport of crude oil ⁽⁴⁴⁾, closed-circuit pumping installations such as central-heating systems ⁽⁴⁵⁾, sewage systems to prevent overflowing after heavy rain ⁽⁴⁴⁾, hydraulic transportation of solid particle suspensions ⁽⁴⁶⁾, fire-fighting to increase the range of water Jets, and water supply and irrigation systems ⁽⁴⁵⁾.

In addition to a drag reduction, the polymer also causes a reduction in heat transfer, which is advantageous in maintaining low oil viscosity ⁽⁵⁰⁾. A similar application is the addition of polymers to oil being pumped from offshore platforms to shore facilities ⁽⁵¹⁾. 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 in frequently use is required, this can be

much cheaper than constructing new pipes ⁽⁵²⁾. Another application is the increase in the range and coherence of water jets from firefighting hoses, but this idea has not been widely exploited ⁽⁵³⁾. A military application which has been patented is the reduction of the drag acting on a torpedo by ejecting a sea-water-polymer solution from the torpedo nose ⁽⁵⁴⁾. Finally, we mention a possible medical application: the addition of low concentrations of polymers might be capable of improving blood flow through stenotic vessels without altering flow through normal vessels, as is suggested by a study by Unthank et al. ⁽⁵⁵⁾.

Hydrotransport of solid such as clay sand and gravel, coal, iron ore, sewage sludge, and pulverized fly ash using drag reducing agents has been studied extensively. Polymer solution friction system such as hydraulic machinery, motor, gear cases, propellers and bearing ⁽⁵⁵⁾.

Biomedical studies of drag reducing polymers have been conducted for the past forty years. The possibility of improving blood flow in partially blocked arteries, and thus treating or preventing circulatory disease is one of such applications ⁽⁵⁵⁾.

2.5 Factors Affecting the Drag Reduction

2.5.1 Drag Reducer Concentration

The effect of polymer concentration on drag reduction is shown in Fig. (2.3), which displays data taken in the same pipe for solutions of the same polymer ranging in concentration from 50 to 1000 w ppm. This figure shows that at the same Reynolds number, $1/\sqrt{f}$ increases as concentration is increased. It is necessary to mention here that as the value of $1/\sqrt{f}$ increases, the value of f is decreased, therefore, the drag reduction is increased. Also it is noted that as concentration of polymer or surfactant increases, the critical solution Reynolds number is decreased⁽⁵⁶⁾.

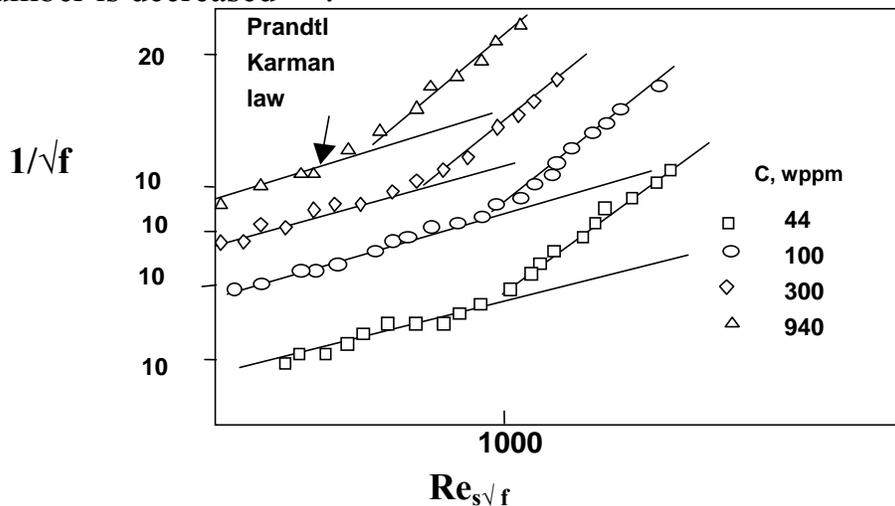


Figure: (2.3) Aspects of the polymeric regime. Effect of concentration. Pipe I.D. 8.46 mm temperature 25 °C, solvent distilled water, polymer PEO, $M=0.57 \cdot 10^6$ ⁽⁵⁶⁾.

Fig. (2.4) shows the effect of polymer concentration on % DR at constant rotational speed related to two competitive mechanisms⁽⁵⁷⁾. It was found that initially, % DR increases as the concentration increases due to an increase in the number available drag reducers. However, as the polymer concentration increases further, the solution viscosity drastically increases, leading to a

decrease in the turbulent strength. Therefore, exists a critical concentration at which the drag reduction is maximized.

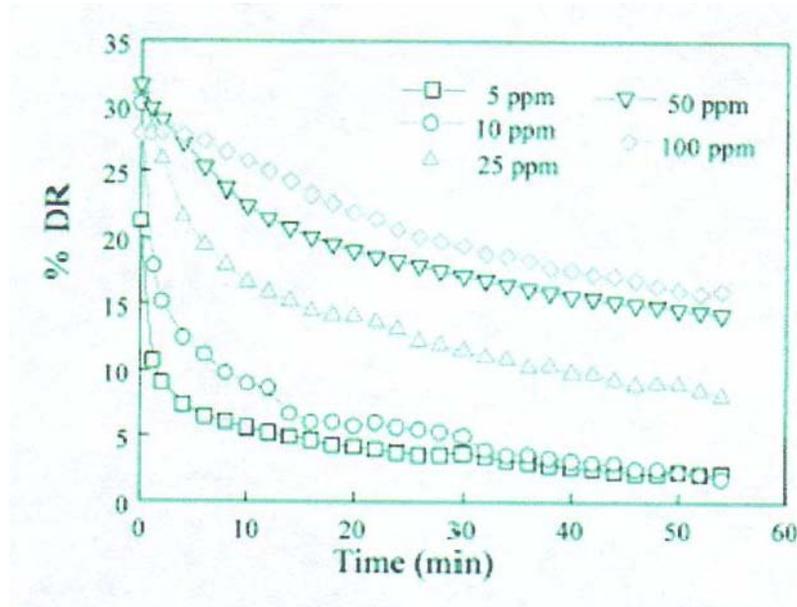


Fig. (2.4) Time dependence of % DR for PEO 345 ($AW=5 \cdot 10^6$) with five different concentrations in deionized water at 2040 rpm and 25°C ⁽⁵⁷⁾.

In general, drag reduction increases initially with increasing concentration but tends to be constant at critical concentration because high doses of surfactant or polymer cause decrease in the activity of the surfactant or polymer. Toms ⁽⁵⁸⁾ observed that drag reduction increases with an increase in the concentration, beyond which, due to the increased viscosity of the solutions, the drag reduction decreases with an increase in concentration.

A remarkable aspect of polymers as a drag reducer is that DR occurs at very low concentrations in the ppm region. Increasing the concentration beyond 30-40 ppm lowers DR for PEO in a small tube owing to increase of the viscosity with increasing concentration. Interestingly, DR can be observed in

concentration as low as 0.02 ppm ⁽⁵⁹⁾. Using a rotating disk apparatus ⁽⁶⁰⁾ or a rotating cylinder ⁽⁶¹⁾, DR induced by water-soluble polymers (PEO, guar gum) and solvent-soluble polymers (polyisobutylene) showed similar results to the experiments performed with a small tube.

2.5.2 Effect of Flow Rate

In general, drag reduction is increased, as the fluid flow rate increased. Because increasing the fluid velocity means increasing the degree of turbulence inside the pipe, this will provide a better media to the drag reducer to be more effective as shown in fig. (2.5). Further observations about flow rate effect are as follows:

- 1- At high flow rate degradation may occur in drag reducer ⁽⁶²⁾.
- 2- Decrease in drag reduction is expected in a pipe of high roughness ⁽⁶²⁾.
- 3- According to elastic theory, drag reducer doesn't stretch fully at high flow rate ⁽⁶³⁾.

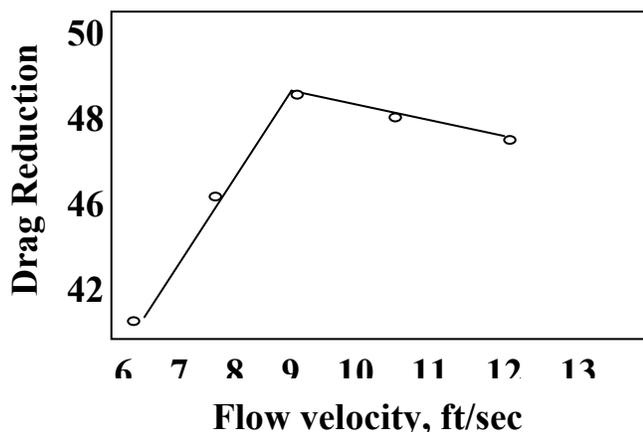


Figure: (2.5) Flow velocity. Vs. drag Reduction% ⁽⁶²⁾

2.5.3 Effect of Temperature and Viscosity

Drag reduction by surfactant increases when temperature is increased because the length of rod-like micelles (collection of micelles) becomes longer. Above some critical temperature, the length of the rod-like micelles will decrease and drag reduction is decreased⁽⁶⁴⁾. The effect of temperature on drag reduction is shown in fig (2.6). When the surfactant has long chain alkyl groups it will be more effective in drag reduction at high temperature as compared with short chain surfactant, on the other hand short chain surfactant will be more effective at low temperature as compared with long chain surfactant⁽⁶⁵⁾.

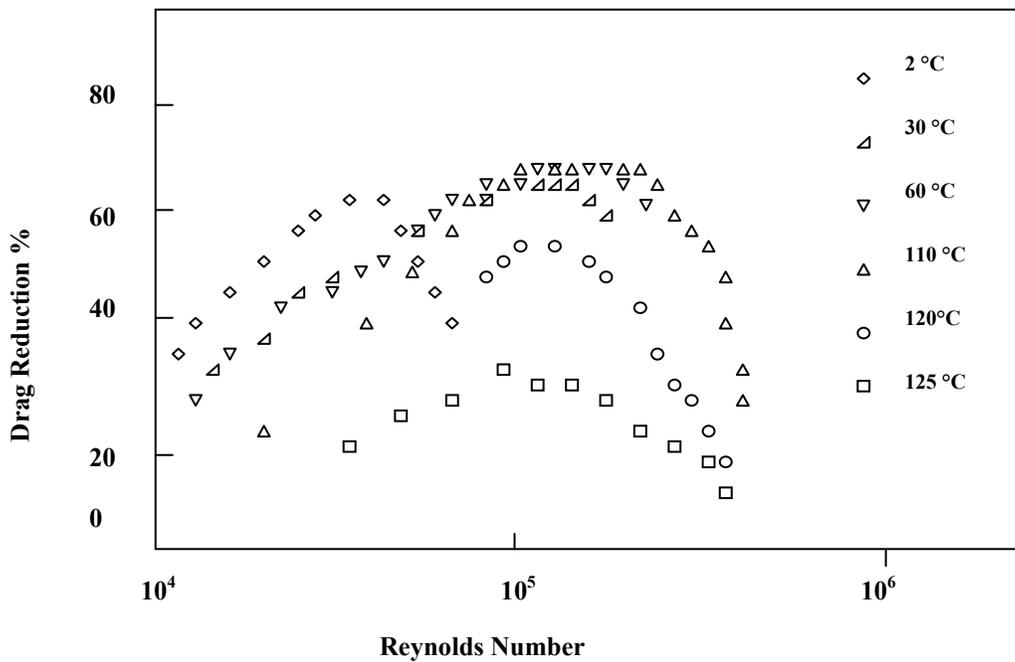


Fig.(2.6) Drag Reduction of Cationic Surfactant at Different Temperatures⁽⁶⁵⁾.

The apparent viscosity of drag reducing solutions changes with temperature and concentration. Viscosity may reveal the existence of structures in the solution and even though it does not directly predict the drag reduction ability. It can help in the characterization of some processes, which take place in the solution. The concentration of the polymer and surfactant in a drag reduction solution is usually low and viscosity measurements of such system are often problematic because of low instrument sensitivity, some references revealed that the drag reduction increases with an increase in the concentration, beyond which, due to the increased viscosity of the solutions, the drag reduction decreases with an increase in concentration⁽⁶⁶⁾. Tap water or the presence of different ions in the water decreases the viscosity of drag reducing surfactant in comparison to the distilled water solution of that surfactant⁽⁶⁵⁾.

2.5.4 Effect of Pipe Diameter and Pipe Roughness

Investigators were differed in determining the effect of pipe diameter. Some Investigators explained that drag reduction increases with decrease in tube diameter when Reynolds number is holding constant⁽⁶⁷⁾, as shown in fig. (2.7). This figure shows that at the same Reynolds number, the $1/\sqrt{f}$ increase as diameter decreases (when $1/\sqrt{f}$ increases, f will decrease and consequently drag reduction will increase). Others showed that the effect of diameter is small. Most investigators showed that drag reduction increases with increasing pipe diameter⁽⁶⁷⁾.

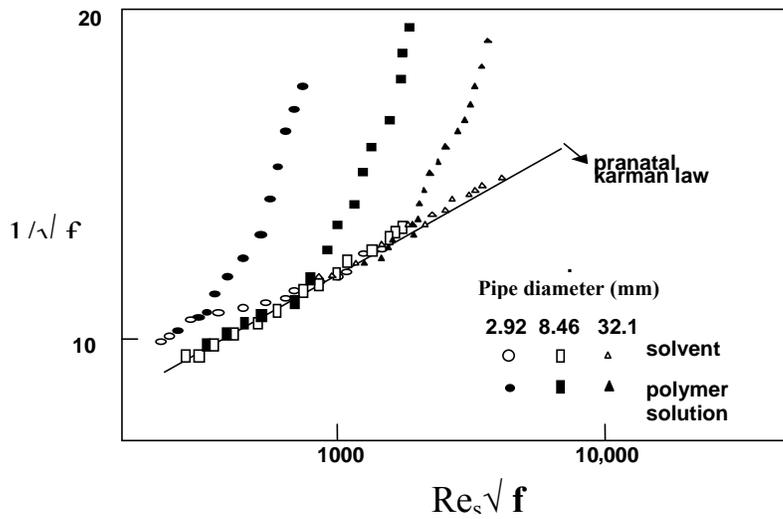


Figure (2.7): effect of pipe diameter. Pipe I.D. 2.92, 8.46, and 32.1 mm, temperature 25 °C, solvent distilled water, polymer solution PEO⁽⁶⁷⁾.

From experiments in a smooth and highly rough pipe of nearly the same inside diameters and polymer type, there was a significant drag reduction in smooth pipe, while rough pipe did not show any drag reduction with increasing flow rate. The drag reduction observed in the rough pipe increased to a maximum, and then decreased and almost disappeared. This decrease was not attributed to polymer degradation but was caused by rough pipe, since the tested polymer structure did not show any degradation⁽⁶⁸⁾.

2.5.5 Stability

The drag-reducing additives demonstrate a desirably high drag reduction efficiency 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 chain can indeed be fully extended by turbulent flow and experience the chain midpoint scission of macromolecule. The mechanical degradation of high molecular weight polymers such as PEO and PIB under turbulent flow by various conditions of temperature, polymer concentration and rotation speed. Since the long chain polymer experiences midpoint degradation, the polymer chains having different molecular weights will show different time dependent existence. In other words, longer molecules are more susceptible to mechanical degradation, accompanying more rapid degradation.

The stability of some drag-reducer additives such as polyethylene oxide, acrylamide, sodiumacrylate and polyvinyl pyrrolidones in water and polyisobutylene in mineral oil was studied on bent tubes of various geometries. It can be concluded that the efficiency of the polymers is strongly dependent on their mechanical degradation ⁽⁶⁹⁾.

Turbulent drag reduction with PEO in RDA was investigated with two different molecular weights. A higher molecular weight of PEO ($MW=5.0 \times 10^6$ g/mol) showed less mechanical degradation than that with a lower molecular weight ($MW=4.0 \times 10^6$ g/mol) at the same concentration. The susceptibility of PEO to degradation increases dramatically with increasing temperature ⁽⁶⁹⁾.

2.5.6 Effect of Polymer Structure and Polymer Molecular Weight

The chemical nature of the polymer is important in terms of its relation to other DR parameters. The molecular linkage in the polymer backbone affect shear stability, obtained flexibility, intermolecular association and polymer/solvent interaction, which in turn affect DRE. Polymer molecular composition and architecture can be tailored to provide desired combination of the above properties. McCormick ⁽⁷⁰⁾ and Morgan ⁽⁷¹⁾ have shown that slight modification of polymer chemical composition can dramatically alter drag reduction effectiveness (DRE). Although originally it was thought that branching decreased DRE, high molecular weight branched and graft copolymer have been synthesized which affect DR and enhanced shear stability. Kim synthesized a high molecular weight, highly branched acrylamide polymer which showed enhanced shear stability ⁽⁵⁷⁾. Deshmukh have shown greater DRE and shear stability for (PAM) grafted to Xanthan gum and guar gum. Hoyt ⁽⁷³⁾ reported that branched polysaccharides are generally not able to reduce drag.

In early drag reduction studies it was observed that DR increased with increasing (MW), but the quantitative understanding of the effect has not yet been obtained. It is unclear whether the parameter providing best correlation of (MW), chain length (N), or radius of gyration (Rg). Correlates onset of DR with polymer radius of gyration which is a function of both polymer molecular weight and polymer/ solvent interaction. Zakin ⁽⁷⁴⁾ showed that a minimum molecular weight is required before a polymer can effectively reduce drag. The minimum is defined in term of (MC), the critical (MW), at which chain entanglements become important in polymer melts, (MC) is unique for each polymer.

Shear degradation greatly complicates the understanding of the effect of (MW) on DR effectiveness. In many DR experiments, (MW) and (MW) distribution are constantly changing due to shear degradation. (MWD) experiments have demonstrated that the high molecular weight fraction responsible for the greatest amount of DR is also susceptible to shear degradation, and thus the first to lose DR effectiveness. Several studies have been performed to clarify the mechanism and characteristics of shear degradation in dilute polymer flows.

The effect of polymer's molecular weight is illustrated in Fig. (2.8). It is noted that as molecular weight is increased, the onset drag reduction occurs at lower Re_s/\sqrt{f} , which, in turn, leads to the fact that drag reduction increases as the molecular weight increases⁽⁵⁶⁾.

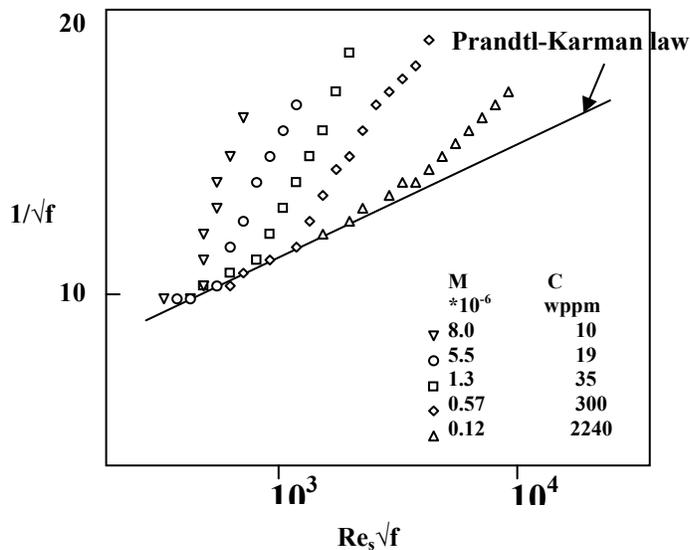


Figure (2.8) Effect of molecular weight pipe I.D. 8.46 and 9.45 mm, temperature 25 °C, solvent distilled water, polymer PEO⁽⁵⁶⁾.

Experiments show that the higher the molecular weight (MW), the more effective a given polymer as a drag reducer⁽⁷⁵⁾. Polymers with a MW below

100000 seem to be ineffective. As the average MW of poly(ethylene oxide) (PEO) is increased from 2×10^5 to above 5×10^6 , the solution concentration to achieve about 70 % drag reduction on a rotating disk is reduced from 600 to 100 ppm⁽⁷⁵⁾. In other words, the higher the MW, the greater the drag reduction for a given concentration and Re number. The longer polymer chain provides more chance for entanglement and interaction with the flow. It has been confirmed that the extension of the polymer chain is critical for drag reduction. The most effective drag reducing polymers are essentially in linear structure, with maximum extensivity for a given molecular weight. Poly(ethylene oxide), polyisobutylene and polyacrylamide are typical examples of linear polymers. Polymers lacking linear structure, such as gum arabic and the dextrans, are ineffective for drag reduction⁽⁷⁵⁾.

2.6 Drag Reduction Mechanism

2.6.1 Introduction

Drag reduction was discovered almost half a century ago, the physical mechanisms responsible for the phenomenon of drag reduction are not completely understood and remain a subject of debate. Nevertheless, it is generally accepted that both the viscoelastic property including elastic behavior and energy dissipation phenomena of polymer solutions and the interaction between polymer molecules and turbulence generate the drag reduction phenomenon. The role of stress anisotropy due to polymer extension versus elasticity is also still an ongoing subject of controversy in the drag reduction mechanism ⁽⁶⁹⁾.

The mechanism for drag reduction has been the subject of extensive research, a complete and satisfactory explanation has not been reported ⁽⁵⁷⁾.

2.6.2 Techniques

The precise mechanism describing how a DRA works to reduce friction is not established. It is believed these agents work by directly reducing turbulence or by absorbing and later returning to the flowing stream energy which otherwise would have wasted in producing the cross flows which comprise turbulence. The "absorb-and-return theory" has a certain intuitive attractiveness because one of the characteristics of a viscoelastic fluid is its ability to do this on a physically large scale. Whether the effect exists at the molecular scale is unknown.

Pipe liners generally work with the rational flow formula. The friction factor therein, which is a scaling factor applied to velocity head to yield friction loss, is a macro-factor in that it lumps all of the friction-producing effects acting in a flowing system in a single numerical value. The friction factor concept does not provide an insight into how a DRA might work. It is necessary to look at the velocity distribution pattern in a pipeline in turbulent flow to understand the bases which support the concept of the friction factor and understand better how drag reduction might take place.

The concept of turbulent flow in pipelines provides that the point flow may be directed in any direction while maintaining net pipe flow in the direction of decreasing pressure. All flow not in the direction of net pipe flow absorbs energy; the more turbulent the flow becomes, the more energy absorbed in these cross flows, flow in hydraulically rough pipes, the friction factor does not vary with increasing flow, but the unit friction loss increases as the square of the velocity of fluid ⁽⁶⁹⁾.

The model of turbulent pipe flow we used is based on the Universal law of the wall which applies to both smooth and rough pipe flow. It presumes two general modes of flow in a pipe: the wall layer, and the turbulent core. The wall layer is presumed to contain all of the flow where the point velocity varies with distance of the point from the pipe wall. The turbulent core carries all of the flow where variations in point velocity are random and independent of this distance. The wall layer itself is presumed to be comprised of three sublayers: the laminar sublayer; the buffer zone; and the turbulent sublayer. The laminar sublayer has as its outer boundary the wall of the pipe, and flow in the entire sublayer is laminar.

This definition requires that, immediately at the wall lie a film of liquid which is not moving.

The increase in point velocity as the point moves away from the wall, is a linear function of the distance from the wall, and directed parallel to the wall in the direction of the pipe flow. There are no cross flows in this sublayer. The contribution of the laminar sublayer to total friction arises in viscous shear generated in the sublayer. Pipe roughness acts to inhibit laminar flow; therefore, the definition is only statistically true for rough or partially rough pipe.

In the turbulent sublayer, which has as its inner boundary the turbulent core, it is presumed that the velocity varies logarithmically with distance from the wall but that crossflows in the sublayer may be statistically large and nearly as great as in the core. The contribution of the turbulent sublayer to total friction lies in the turbulent shear generated in this sublayer.

In the buffer zone, which lies between the laminar and turbulent sublayers, variation of point velocity with point position is not established. Ideally, it should be the same as the laminar sublayer at the outer boundary and the same as the turbulent sublayer at the inner boundary.

Any number of mathematical functions can be written to approximate these two requirements. Both viscosity and density contribute to shear losses in the buffer zone.

The contribution of the turbulent core to total friction loss lies entirely in turbulent shear; DRA's are presumed not to act on this component of total friction. Therefore the action of a DRA must take place in the laminar sublayer, the buffer zone, or the turbulent sublayer.

That the action of a DRA increase with increasing flowing velocity would indicate that DRA action could not be primarily in the laminar sublayer. It sometimes would appear that this is so: liquids treated with a DRA flowing under conditions in which the pipe is hydraulically rough and viscosity presumed to make no contribution to total friction can yield excellent drag reduction. This kind of result would lead to the presumption that a DRA works in the buffer zone.

On the other hand, large doses of a DRA have been observed to keep a liquid in the laminar flow at Reynolds numbers much higher than those expected of the same liquid without DRA, which leads to the conclusion that a DRA acts in the laminar sublayer.

The conclusion suggests that a DRA may inhibit the action of crossflows, whether generated in the laminar sublayer or the buffer zone, which move inward into the turbulent sublayer and core and absorb energy which otherwise would go toward producing pipe flow.

Reduction in the energy absorbed by crossflows originating at the pipe wall can be accomplished by reducing their number, size, or velocity. Or, the energy in the crossflows may be absorbed by a DRA and later returned to the

flowing stream for reuse which, in effect, means reducing their effect if not their size, number, or velocity. And it is here that theory breaks down; no one really knows which effect predominates-if either does.

2.6.3 Mechanisms

The Mechanisms of drag reduction are not known exactly, however, the following five types of mechanisms are proposed;

2.6.3.1 Wall Layer Theory

This theory suggests the existence of abnormally mobile laminar sub- layer whose thickness is comparable to polymer type and its properties, which cause apparent slip at the wall ⁽⁷⁶⁾. It is noted that the viscosity in a boundary layer at the wall is several times higher than in the bulk of the fluid and this tendency is increased with the increase in chain length of polymer. These observations lead to conclude that fluid friction reduction is the result of boundary sub layer modification, and this effect persists even in the fully developed turbulent flow.

The direct method of determining the presence or absence of wall effects is the comparison of velocity profile in ordinary fluid with velocity profiles in drag reducing fluid. If there are slip at the wall, the velocity profiles would have to more blunt ⁽⁷⁶⁾ as shown in Fig (2.9), where proposed model (three zone model) scheme represented by the mean velocity profile, in which drag reduction

associated with an (interaction zone) between a viscous sub layer and Newtonian outer flow.

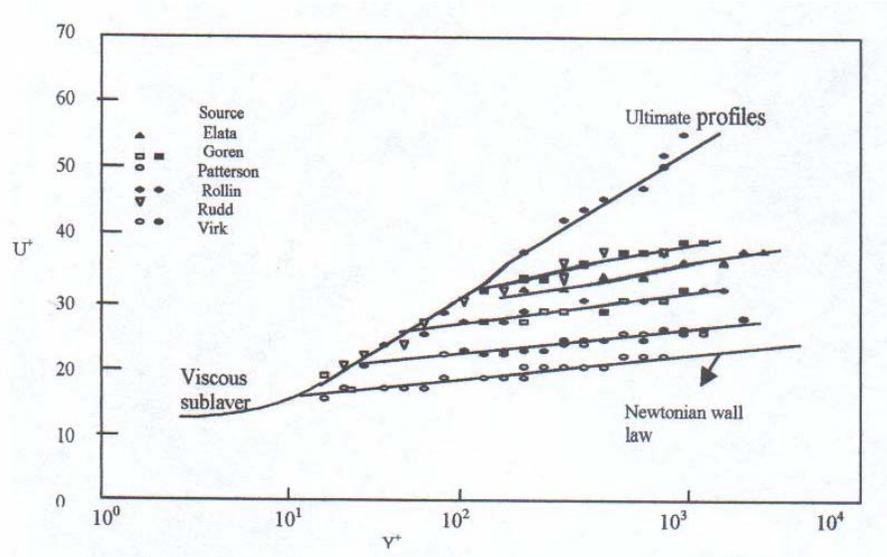
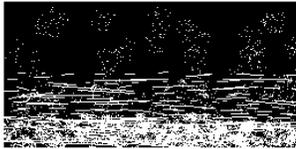


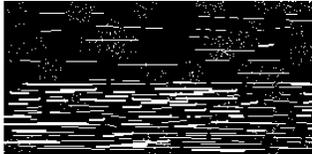
Figure (2.9) Mean velocity profiles drag reduction for experimental details ⁽⁷⁶⁾.

2.6.3.2 Turbulent Suppression Theory

Generally, most of the dissipation of energy associated with turbulence is caused not by the eddies largest in size but by the eddies at higher frequencies. Figure (2.10) reveals a boundary layer extending over most of the tube and the virtual absence of velocity fluctuations. The two photographs in Fig (2.10) show (in non drag reducing systems) large radial velocity fluctuations and a thin wall region. The later implying low velocity gradients and hence equal streak lengths over the major of the velocity field ⁽⁷⁷⁾.



(a) -Non drag reducing conditions
NRe = 13,500, V= 1.87 ft/sec



(b) Drag reducing conditions
NRe = 13,400, V = 10.0 ft/sec

Figure: (2.10) streak photographs for non-drag reducing and drag reducing conditions ⁽⁷⁷⁾

The maximum in the intensity of the streamwise velocity fluctuations is shifted farther way from the wall with increasing drag reduction. The intensity of the turbulent velocity component normal to the wall is found to be reduced by about 50% ⁽⁷⁸⁾. Drag reducer does not treat or coat the pipe wall or change the bulk hydrocarbon fluid properties but only change the hydraulics of the flow stream ⁽⁷⁹⁾. These agents work by absorbing and later returning to the flowing stream energy which otherwise would have been wasted in producing me crossflows which comprise turbulence ⁽⁸⁰⁾. As well as inhibiting the growth of turbulent eddies and reducing momentum transport normal to the flow direction will cause drag reduction ⁽⁸¹⁾.

2.6.3.3 Viscosity Gradient Theory

This theory is well defined through the following explanation:

On injecting a dye into a CMC (polymer) solution in turbulent motion, it was observed that fluid layers adjacent to the wall were much thicker than in the flow of water under turbulent conditions. Further, vortices leaving the layer were relatively few in number. The damping effect was attributed to a positive gradient of viscosity (for a non-Newtonian flowing, the viscosity is generally at a minimum at the boundary and a maximum in the region remote from the wall, owing to the distribution of shearing stress across the tube cross section) encountered by the vortices on forming at the wall and moving toward the region remote from the boundary. It was concluded that the lower energy dissipation resulted from a repressing effect by the viscosity on the formation of the vortices.

It was also proposed that the decreased friction factors and sharper velocity profiles, which were measured, could be attributed to the viscosity damping effect. But, however, this is only partly correct, because there are typical non-Newtonian solutions which exhibit the viscosity gradient effect and yet some of them exhibit drag reduction properties. Example of these solutions are one grade of CMC, a poly (acid), poly (vinyl) alcohol all in water solutions, a polyisobutylene in cyclohexane)⁽⁷⁶⁾.

2.6.3.4 Viscoelasticity

It has been observed that dilute solutions of poly (methacrylate) in selected organic liquid, moderate concentrations of aluminum soap of fatty acids in gasoline and low concentrations of the higher viscosity grades of CMC (polymer) in water as well as surfactant solutions, exhibit viscoelastic properties. All of these solutions are characterized by drag reduction properties in turbulent flow^{(76), (78)}.

Viscoelastic property of the dilute polymer and surfactant solutions may be shown to reduce the radial transport rate in eddies near the wall⁽⁸²⁾, As well as viscoelastic properties influence the rate of energy dissipation in turbulent eddies⁽⁸³⁾.

2.6.3.5 Elastic Theory

Drag reducer solutions having elastic deformations might, occur which would modify the type of turbulence, where found CMC (polymer) and polyisobutylene solutions have swelling of a liquid jet emerging from a capillary. There was also some evidence of the presence of low level of elasticity in a poly (acid)⁽⁷⁶⁾.

At turbulent flow, eddies will strike with elastic material. Strike energy will be stored as strain in elastic material (polymer coil and micelles surfactant) and return to flow stream.

Some solutions might not exhibit much elastic deformation under ordinary conditions; it is possible that elastic behavior might be of importance under turbulent flow condition. Drag reducing polymer molecules in turbulent boundary layers are stretched by the flow, resulting in an increase in the total increase in the local fluid viscosity, in this extended state, the elongational viscosity increases by a factor of the order often thousands. This phenomenal increase in elongational viscosity near die wall is because the extensional strain rates are the highest there, the increased elongational viscosity suppresses turbulent fluctuations, increases the buffer layer thickness and reduces wall friction⁽⁸⁴⁾.

CHAPTER THREE

EXPERIMENTAL WORK

3.1 Materials

The drag-reducing polymers were polyisobutylene types Oppanol B 150, 200, and 250 with three different average molecular weight of 2.6, 4.1 and 5.9×10^6 respectively which were acquired from BASF company, Germany. Their main properties are listed in table (3.1) ⁽⁸⁵⁾.

Table (3.1) Some Properties of Oppanol B Polymers

Oppanol B Type	150	200	250
Viscosity of solutions in isooctane at 20°C:			
Concentration, g.cm ⁻³	0.001	0.001	0.001
Staudinger Index, J _o [*]	416-479	551-661	>770
Relative molar mass:			
Weight average Mw	2500000	4100000	>5900000
Viscosity average Mv ^{**}	2600000	4000000	>5900000
Volatile matter, 105°C, 2hr, wt.%	0.01	0.01	0.005
Ash Content, ppm	<100	<100	<100
Stabilizer content, ppm	250-500	250-500	250-500

* The staudinger index $J_o \text{ cm}^3 \cdot \text{g}^{-1}$ is calculated from the flow time at 20 C through capillary of an Ubbelohde viscometer ⁽⁸⁵⁾

$$J_o = \mu_{sp} / C (1 + 0.31 * \mu_{sp}) \quad \dots(3.1)$$

Where:

$$\mu_{SP} = \frac{t}{t_0} - 1 \text{ (Specific viscosity)}$$

t = flow time of solution

t₀ = flow time of solvent

C = concentration of the solution in kg/cm³

** The viscosity average relative molecular mass, M_v is obtained from the following equation ⁽⁸⁵⁾

$$M_v = 0.65 \sqrt{\frac{J_o * 10^2}{3.06}} \dots(3.2)$$

Reformate, supplied from Al- Durra Refinery was used to dissolve the three Oppanol B polymers. Its general properties are about 58 API gravity, initial boiling point 40°C , end point 200°C, an octane number by research of about 91.

Light gas oil supplied from Al-Durra Refinery, was used as pipelining liquid, its general properties are, 38.3 API gravity, 158° C initial boiling point, 365 °C end point and 64 °C flash point.

3.2 Preparation of Polymeric Solution

The method of solution preparation adapted here was to make 2 % by weight concentration in a separate container. Thus 10 g of corresponding polymer is mixed with 650 ml of reformate at laboratory temperature. The container was placed in an electrical shaker, type KOTTERMANN 4010, GERMANY, 100 rpm. The shaker was used instead of mechanical stirrer to avoid polymer degradation; hence the shaker has no sharp edge that could

expose to high shear force. The shaker was started at 40 rpm and increased with 10 rpm after every 24 hours. A homogenous solution was obtained, after 2 days for Oppanol B 150, 3 days for Oppanol B200 and 5 days for Oppanol B 250 types ⁽⁸⁶⁾.

The solution is allowed to stand for 24 hours at room temperature prior to its uses, that made by mixing the required concentration with one liter of gas oil and then carefully transferred to the test apparatus, care should be taken also to avoid degradation of polymer during mixing and transfer.

3.3 Flow System

The drag reduction experiments were carried out in a laboratory circulation loop ⁽⁸⁷⁾, as shown in figure (3.1). It consists of a reservoir tank as feed tank for gas oil with dimensions 100*70*70 cm and a capacity of one m³. The reservoir tank was supported with four seamless carbon steel pipes of inside diameter 19.05, 25.4, 31.75 and 50.8 mm to perform the flow measurements. A gear pump of 50.8 mm diameter, 1440 rpm and a total head of 6 m was used to deliver the fluid at high turbulence. Gear pump was used to avoid polymer mechanical degradation and thus reduce the drag- reducing effectiveness.

A by- pass about 2 m length and 50.8 mm diameter was installed to control the flow and to obtain the desired flow rate.

The test sections of 3 m long were placed away from the entrance length required, as shown in table (3.2) for each pipe diameter. The minimum

entrance length required for a fully developed velocity profile in turbulent flow was calculated from the relationship suggested by Desissler⁽⁸⁸⁾:

$$L_e = 50D \quad \dots(3.3)$$

Where:

L_e = entrance length, m

D = pipe diameter, m.

3.4 Experimental Procedure

In order to obtain flow data against which the various predicate methods could be tested experiments were carried out in pipes whose nominal diameter were (1, 1.25 and 2) inch. The polymer solution concentrations tested were (0, 10, 20, 30, 40, 50 and 70) ppm at flow rates ranging between (2.8 to 6) m³/hr.

At start the experiment, the reservoir was filled about 130 liters gas oil. After operating the pump the fluid is allowed to flow through only one of the three pipe sizes by closing the other valves. Then connect each tube end of the pressure taps in the upstream and down stream with U- tube manometer, and allow the bubbles in the connecting vinyl tubes to flow away, to avoid any error by reading. Then open the by- pass valve and closed pipe valves to check the manometer so when the level of the mercury in manometer is in one level that indicate the reading of manometer is right (no bubbles in vinyl

tubes). Then add the required concentration prepared in one liter gas oil allow to mix with gas oil for about 20 min. circulation, then open the pipe valves and record the flow rate Q in (m^3/hr) and the pressure drop for each flow rate in (mmHg). The same procedure is repeated in order to obtain more data at various Reynolds number and for other pipes diameter and other molecular weight polymer.

Table (3.2) Minimum entrance length for the pipe used

Pipe diameter, m	Minimum entrance length (L_e), m
0.02540	1.2700
0.03175	1.5875
0.05080	2.5400

In each testing section, the pressure drop reading was taken using U-tube manometers filled with mercury for moderate flow and an inverted manometer for high flow rates.

Furthermore, a float flow meter of 50.8 mm diameter and flow indication range between 0.6-6.0 m^3/hr was used to measure the flow rates. Ball type valves, which can be opened and closed in one quarter of a cycle only, were used to control the flow in the pipes. The flow meter calibration is shown in figure (3.2).

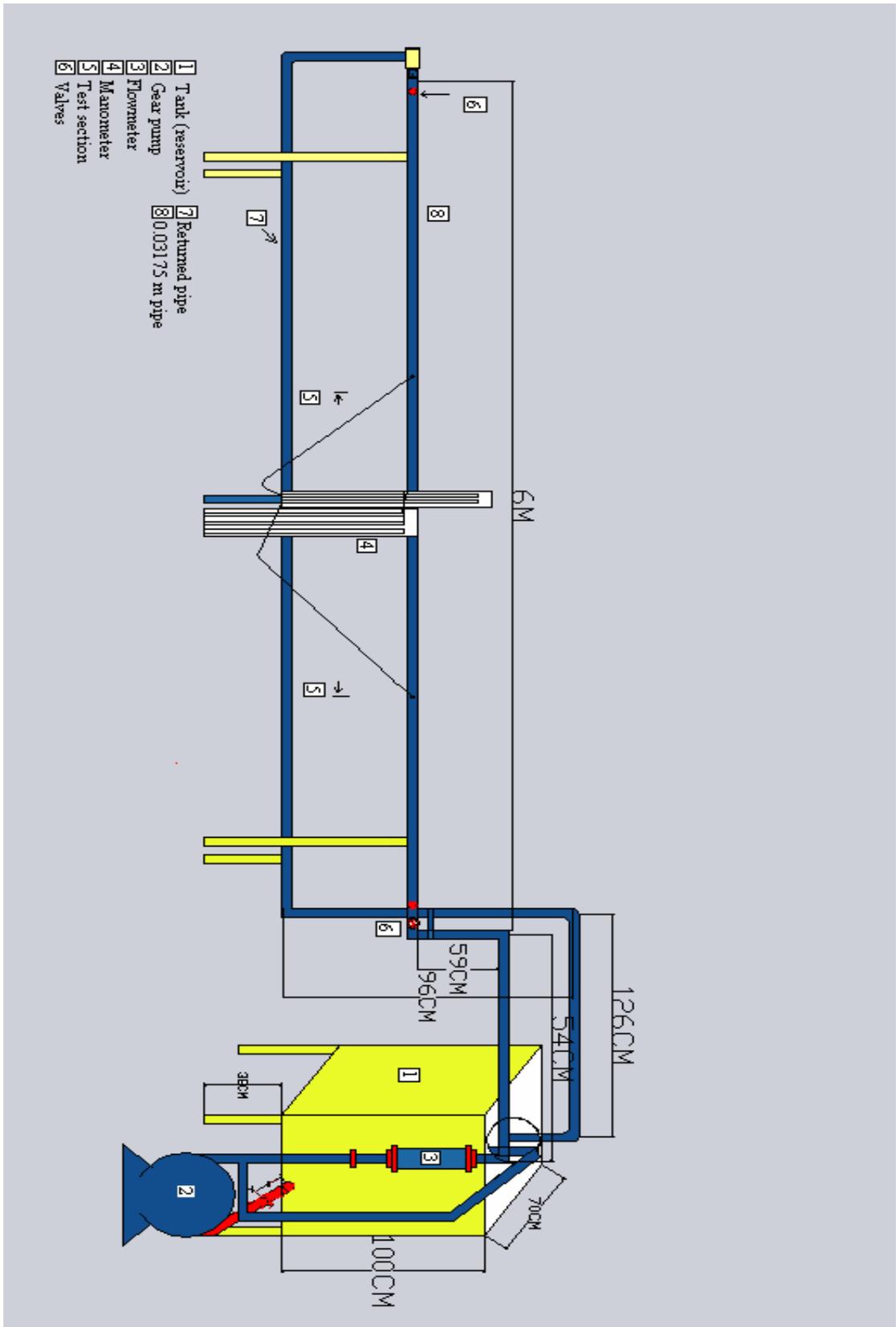


Fig. (3.2) Schematic diagram for the rig

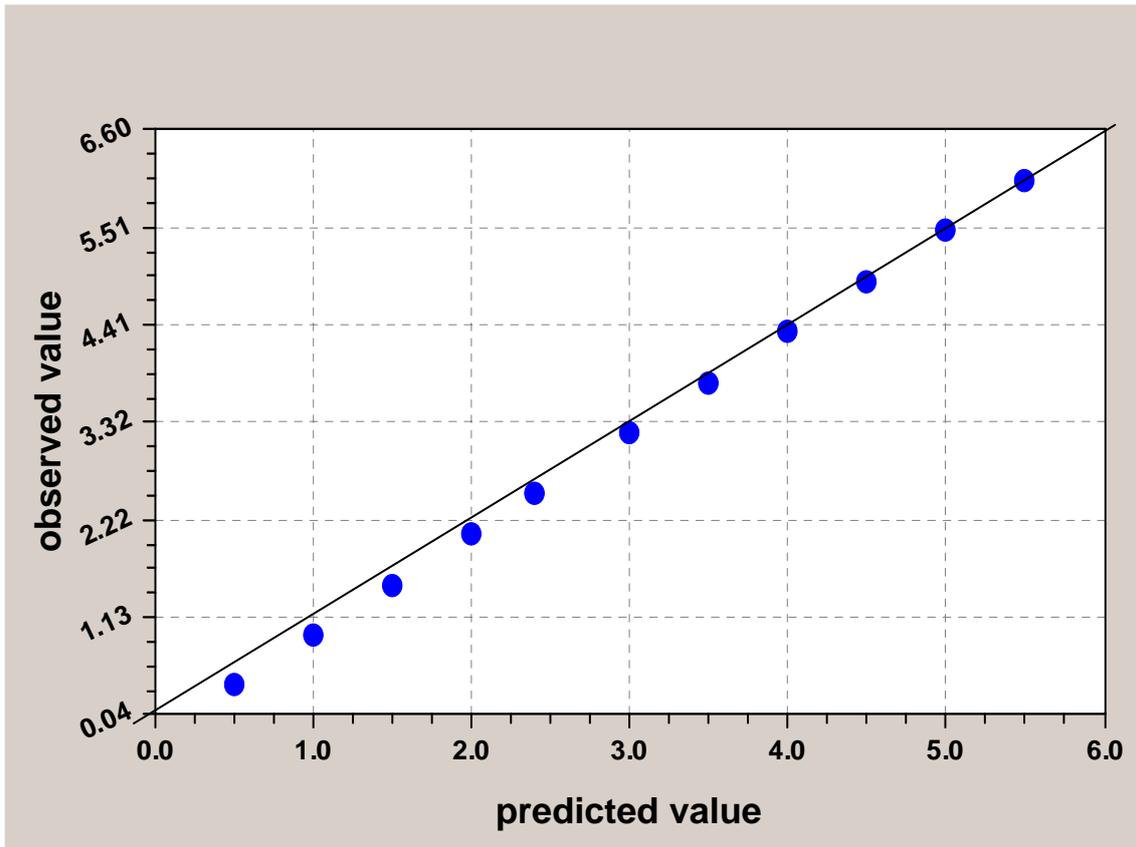


Fig. 3.2 Calibration of flow meter for gas oil

3.5 Calculations

The weight of polymer required to prepare (x) ppm in 125 liter of gas oil is obtain from following equation

$$\text{Weight of polymer} = \frac{\rho_{gasoil} * 125 * x}{10^6} \quad \dots(3.4)$$

Where ρ_{gasoil} = density of gas oil in g/lit.

For example to obtain 20 ppm:

$$\begin{aligned}\text{Weight of polymer} &= \frac{835 * 125 * 20}{10^6} \\ &= 2.0875 \text{ g polymers}\end{aligned}$$

For 2 % polymer solution

$$\begin{aligned}&= \frac{2.0875 * 100}{2} \\ &= 104.375 \text{ g solution}\end{aligned}$$

Pressure drop reducing through testing sections before and after drag reducer addition were used to calculate the percentage drag reduction % DR, as follows ⁽⁵⁾.

$$\%DR. = \frac{\Delta P_{untreated} - \Delta P_{treated}}{\Delta P_{untreated}} * 100 \quad \dots(3.5)$$

Percentage, throughput increase, % TI estimated from the following equation ⁽⁸⁹⁾.

$$\%TI = \left(\frac{1}{\left(1 - \frac{\%Dr}{100}\right)^{0.55}} - 1 \right) * 100 \quad \dots(3.6)$$

This equation assumes that pressure drop for both the treated and untreated fluid is proportional to flow rate rise.

Fanning friction factor was calculated by using the following equation (90).

$$f = \frac{\Delta P . D / 4 L}{\rho . U^2 / 2} \quad \dots(3.7)$$

Where:

f = fanning friction factor.

D = pipe inside diameter, m.

L = distance between the pressure taps, m.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Scope of the investigation

In this study, the turbulent drag-reduction efficiency which has been investigated by dilute solutions of polyisobutylenes (Oppanol B series) with three molecular weights in a laboratory flow loop was analyzed focusing mainly on their molecular weight effect. The additives provide a wide range of molecular weights, ranging $2.5 * 10^6$ to $5.9 * 10^6$ g/mol. Furthermore, the screening study evaluated the additives in gas oil with respect to their concentrations, pipe diameter and degree of turbulent.

Since turbulent flow is necessary for drag reduction to occur, the system was operated for Reynolds number greater than 17874, which produced by a positive displacement gear pump, to avoid mechanical degradation of polymeric chains.

Calibration of each pipeline in the laboratory test loop was performed with untreated gas oil prior to testing any drag-reduction additives. Figure 4.1 shows the calibration pressure drop data for the three laboratory test loops of 1, 1.25 and 2.0 inches diameter. As illustrated in fig. 4.1, a gradual increase of pressure drop is observed with increasing the bulk velocity. The two inches pipe shows lower pressure drop as that for 1 inch pipe at the same velocity.

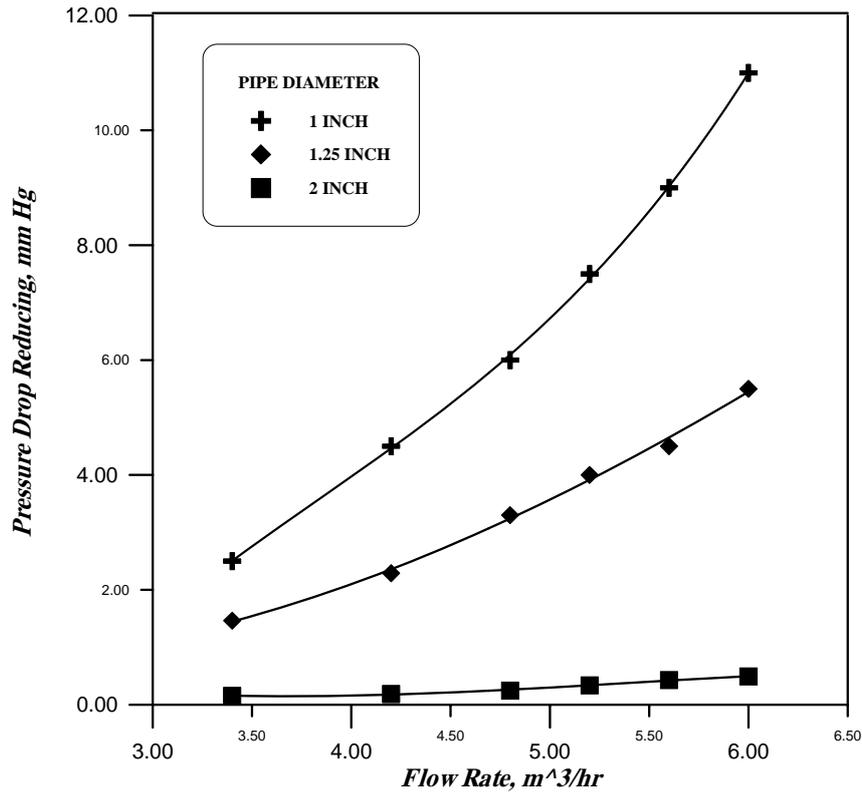


Fig. 4.1 laboratory test loop calibration data

Percentage drag-reduction was calculated based on pressure drop data, as follows

$$\%DR. = \frac{\Delta P_{untreated} - \Delta P_{treated}}{\Delta P_{untreated}} * 100 \quad \dots(3.5)$$

Where $\Delta P_{untreated}$ is the friction pressure drop for untreated gas oil and $\Delta P_{treated}$ for treated gas oil, both measured at the same volumetric flow rate.

4.2 Effect of Additives on Pressure Drop Reduction

Pressure drop of flowing treated gas oil was measured at the two points of the test section. The values of pressure drop saving are calculated between measured pressure drop in the test section for

untreated gas oil and those for gas oil at a given flow rate and pipe diameter, as follows

$$\Delta P_{\text{decrease}} = \Delta P_{\text{untreated}} - \Delta P_{\text{treated}} \quad \dots (4.1)$$

The data of pressure drop decrease are illustrated in figs. 4.2, 4.3 and 4.4 for polyisobutylene of $2.5 * 10^6$ g/mol molecular weight, figs. 4.5, 4.6 and 4.7 for polyisobutylene of $4.1 * 10^6$ g/mol and figs. 4.8, 4.9 and 4.10 for highest molecular weight additive of $5.9 * 10^6$ g/mol. All data are measured at different concentrations, flow rates and three diameters.

The figures show, that the achieved decrease in pressure drop is a function of additive concentration, its molecular weight and fluid flow rate. While pipe diameters of 1 inch show highest decrease than the 1.25 and 2 inch diameter at constant other variables.

It was noticed that, the degree of molecular weight is predominate in saving of pressure drop values. Those the highest molecular weight additive gives the lowest pressure drop required for pipelining of gas oil and resulted in more energy saving compared with those of lower molecular weight.

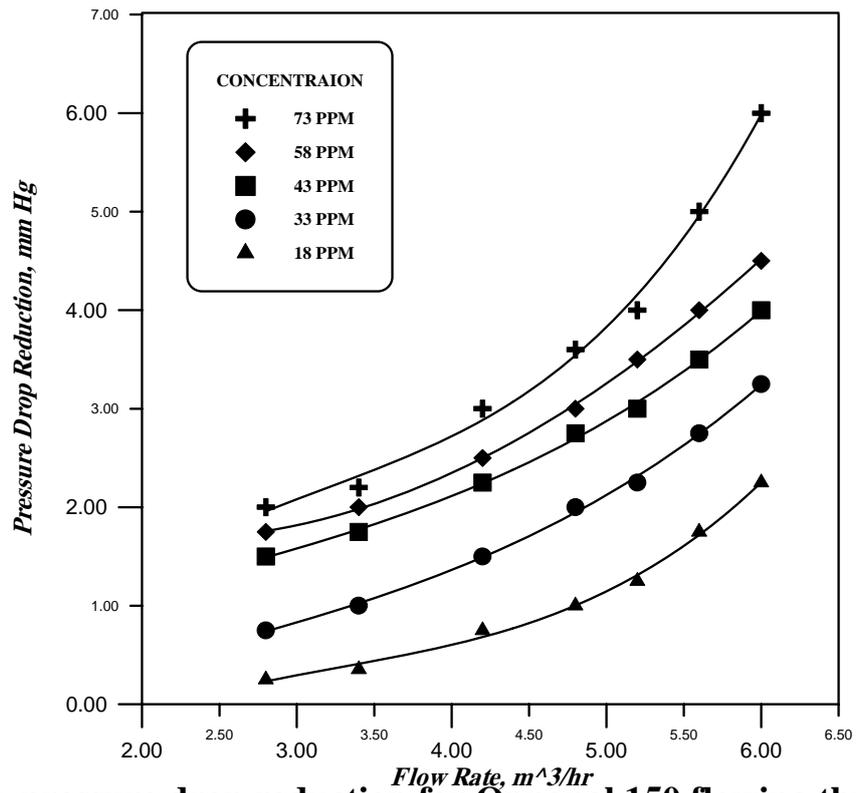


Fig. 4.2, pressure drop reduction for Oppanol 150 flowing through 1 inch I.D pipe

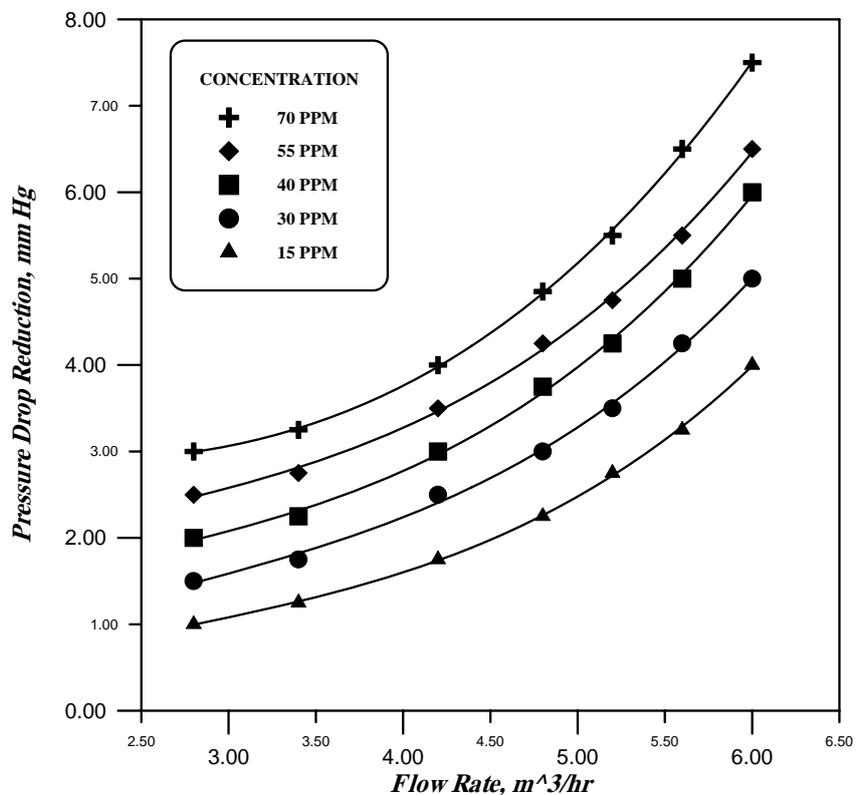


Fig. 4.3, pressure drop reduction for Oppanol 200 flowing through 1 inch I.D pipe

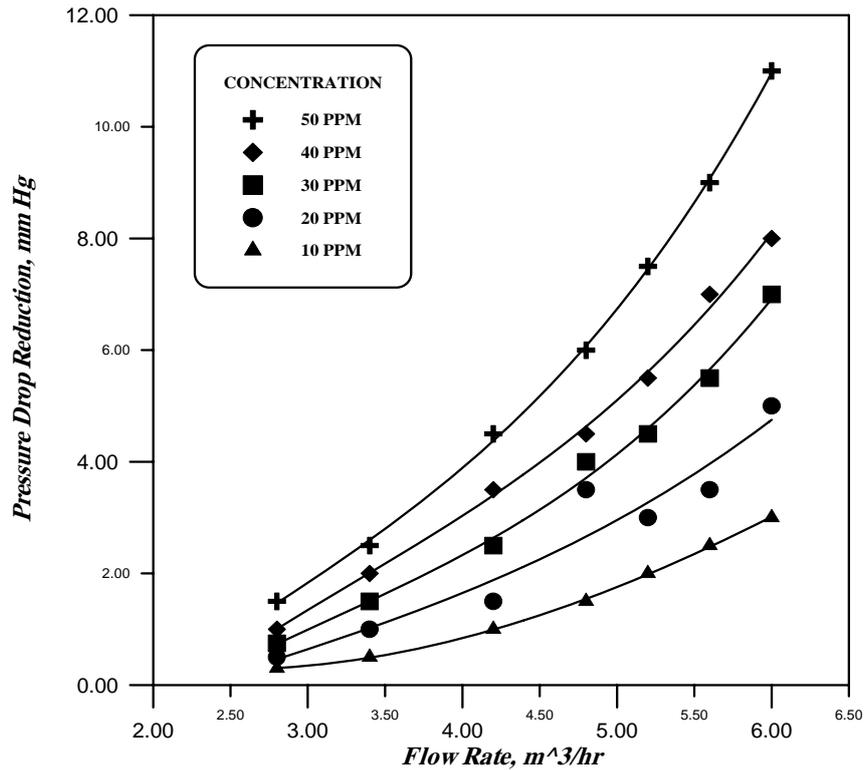


Fig. 4.4, pressure drop reduction for Oppanol 250 flowing through 1 inch I.D pipe

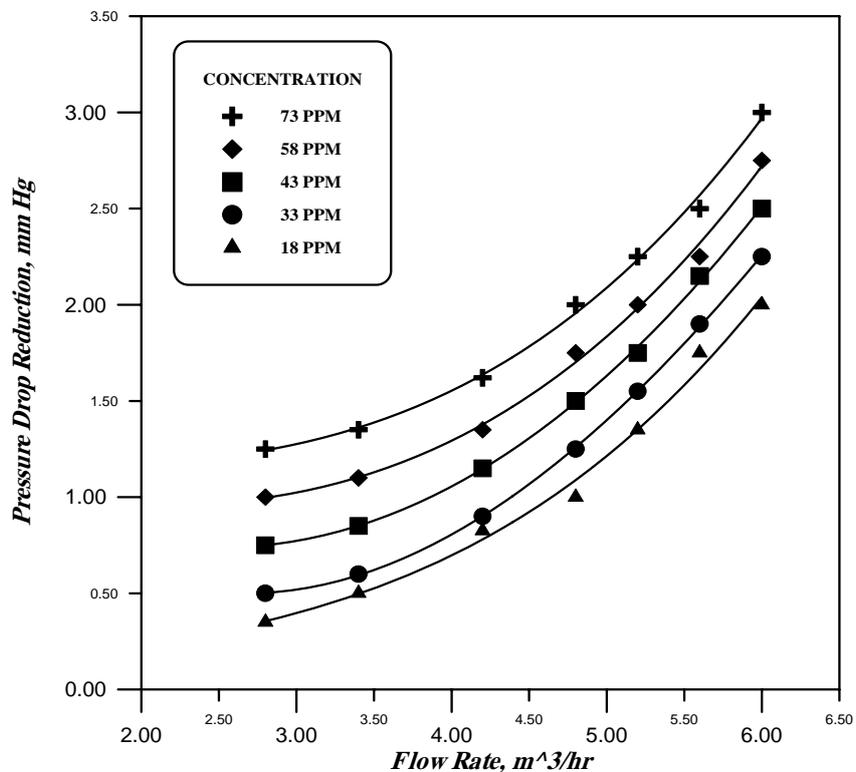


Fig. 4.5, pressure drop reduction for Oppanol 150 flowing through 1.25 inch I.D pipe

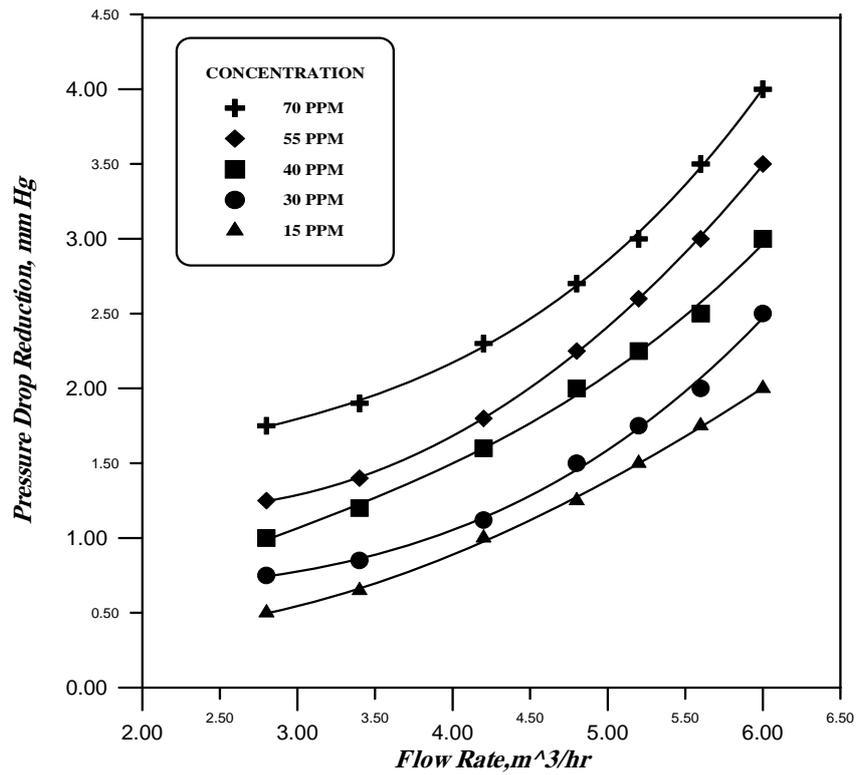


Fig. 4.6, pressure drop reduction for Oppanol 200 flowing through 1.25 inch I.D pipe

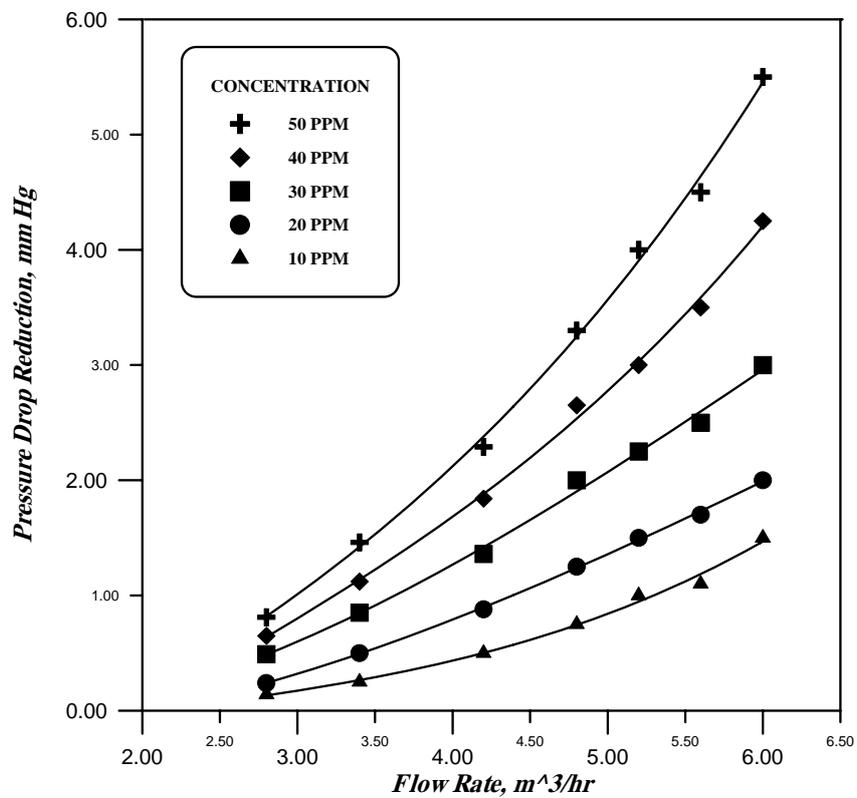


Fig. 4.7, pressure drop reduction for Oppanol 250 flowing through 1.25 inch I.D pipe

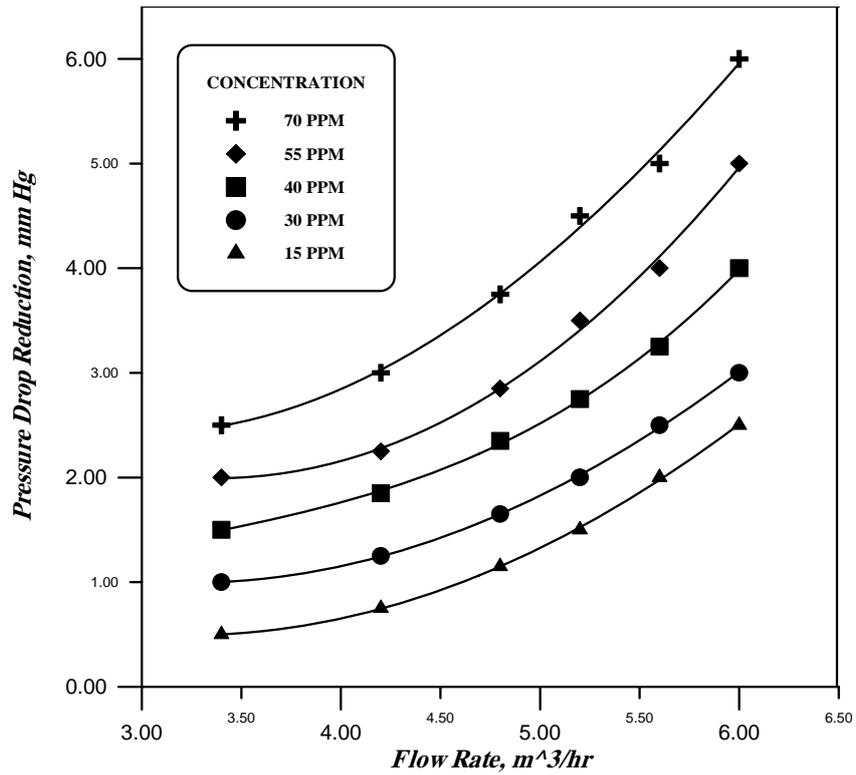


Fig. 4.8, pressure drop reduction for Oppanol 150 flowing through 2 inch I.D pipe

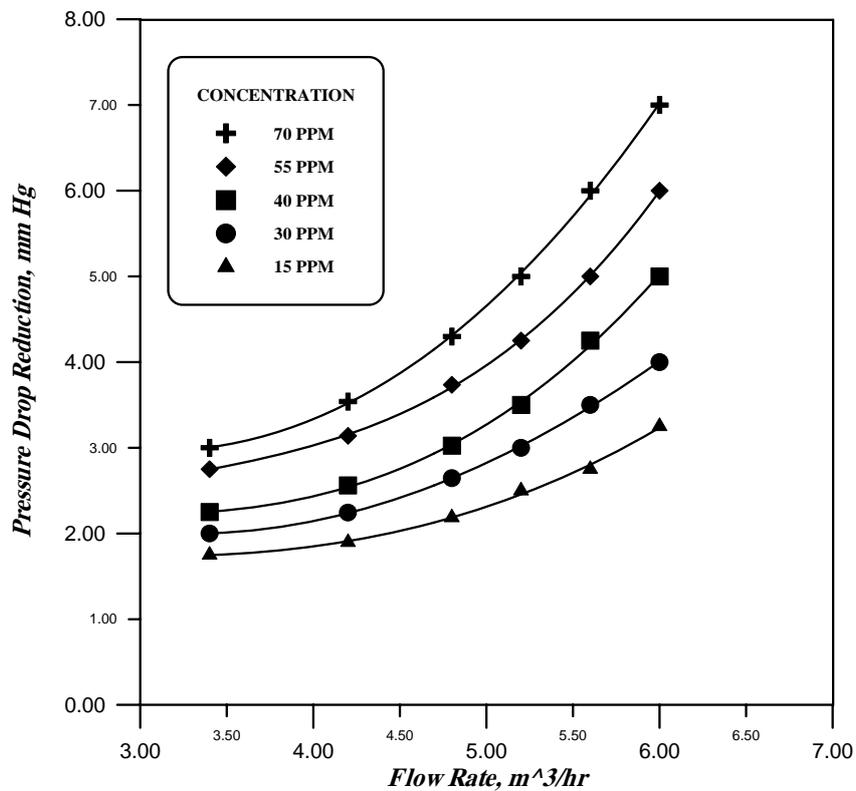


Fig. 4.9, pressure drop reduction for Oppanol 200 flowing through 2 inch I.D pipe

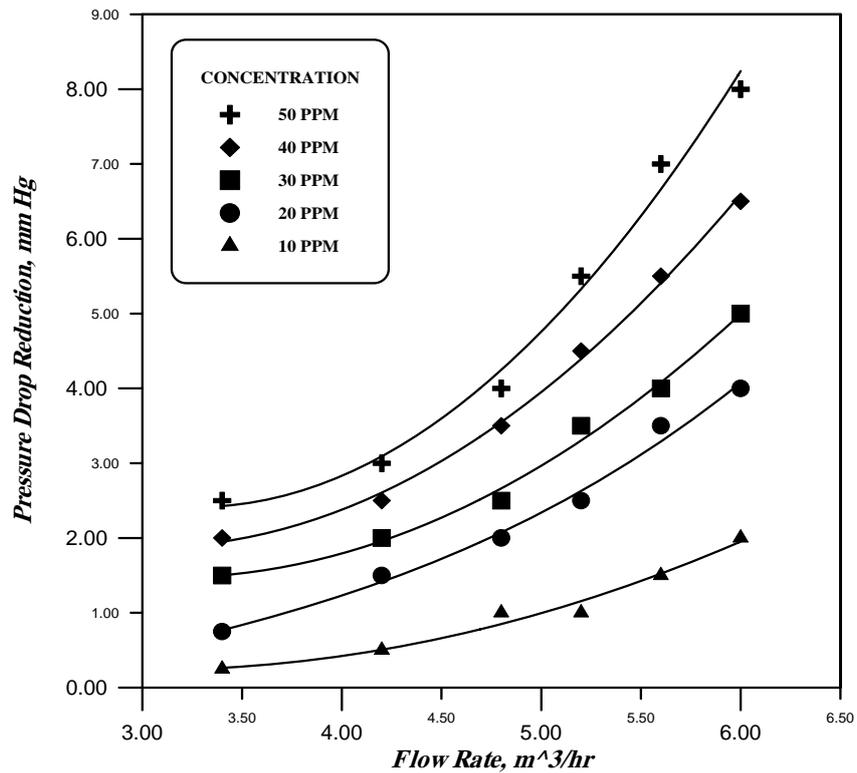


Fig. 4.10, pressure drop reduction for Oppanol 250 flowing through 2 inch I.D pipe

4.3 Concentration Effect

The results of the effect of additive concentrations up to 50 ppm by weight, on drag reduction rate are illustrated in figures 4.11 through 4.19 for flow rates. The figures show that drag reduction increases as polymer concentration increases for three pipe sizes. This phenomenon can be explained by the elastic-sublayer model theory of Virk⁽⁵⁶⁾. This sublayer starts to grow with increasing additive concentration.

The effect of polymeric concentration on drag- reduction is noticeable for concentrations above 40 wppm. Further increase above 70 wppm was not considered due to economical aspects.

Furthermore, figures 4.11-4.19 indicate that the molecular weight of additive is predominate in achieved percentage drag reduction. Thus, about 19% drag reduction was obtained by using 50 wppm Oppanol B 250 (MW=5.9 *10⁶ g/mol), while the values for lower molecular weight polymers, B 200 (4.1*10⁶ /mol) and B 150 (2.5*10⁶ /mol) were about 11.5 and 9 % respectively at the same operating conditions (1.25 inch I.D. pipe, 6 m³/hr flow rate and 50 w ppm concentration).

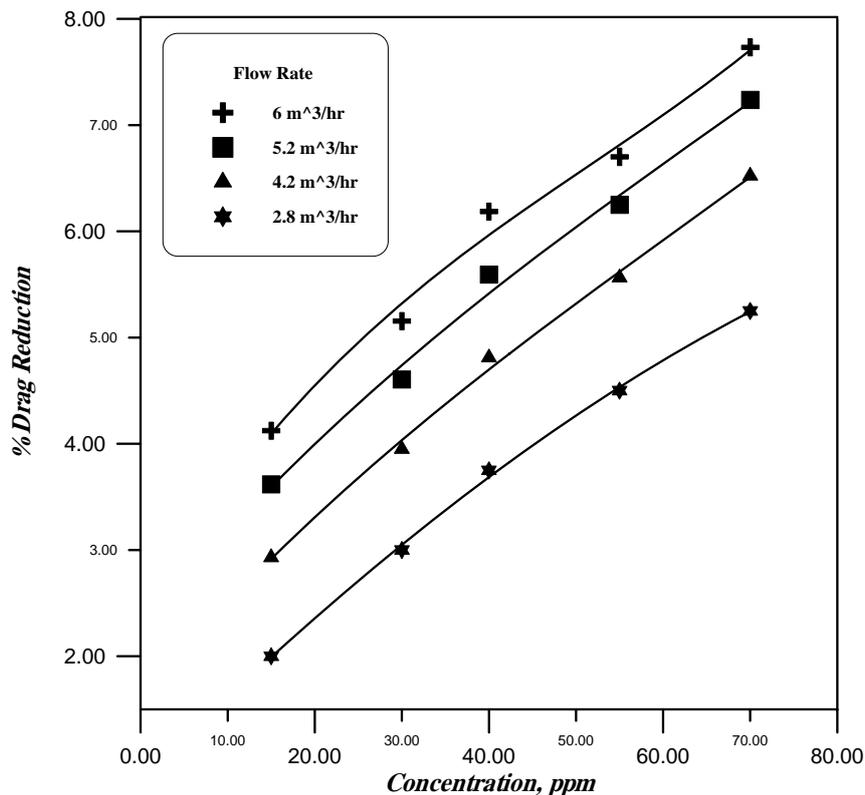


Fig. 4.11, Effect of concentration on percentage drag reduction for Oppanol 150 through 1 inch I.D pipe

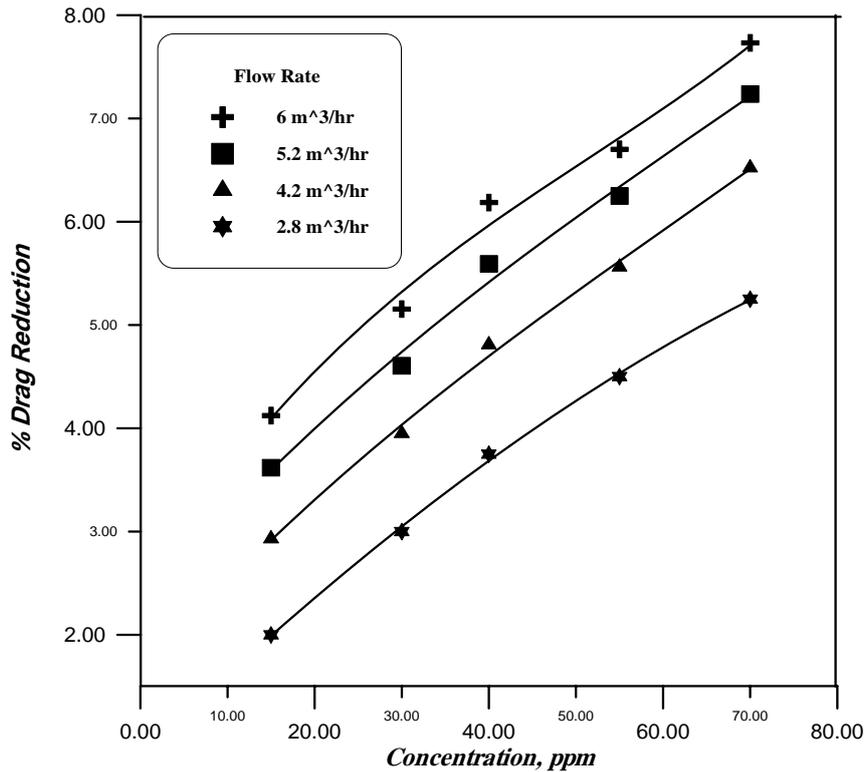


Fig. 4.12, Effect of concentration on percentage drag reduction for Oppanol 200 through 1 inch I.D pipe

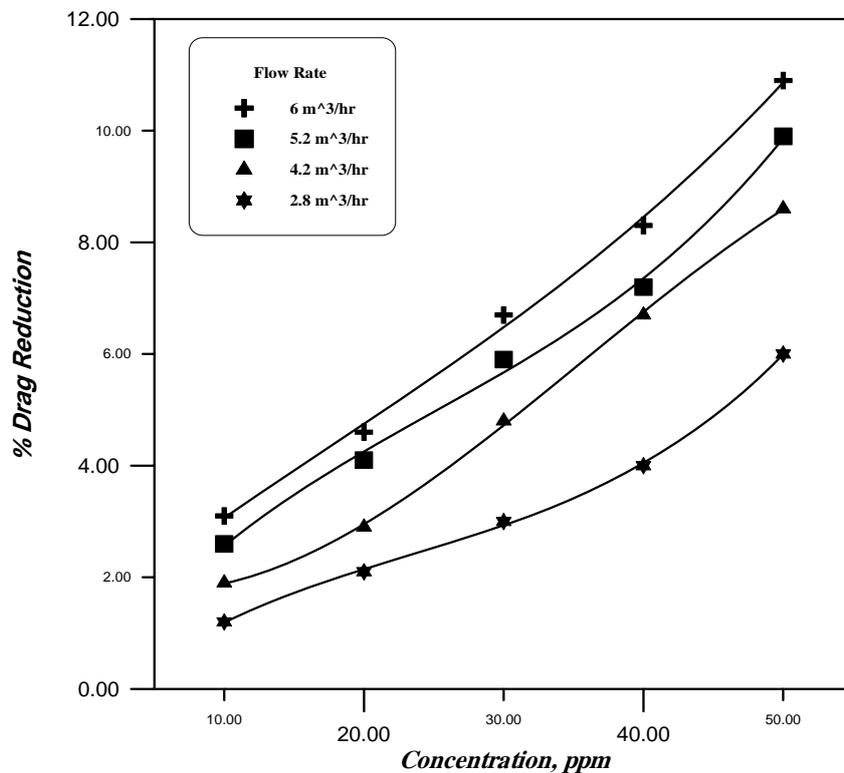


Fig. 4.13, Effect of concentration on percentage drag reduction for Oppanol 250 through 1 inch I.D pipe

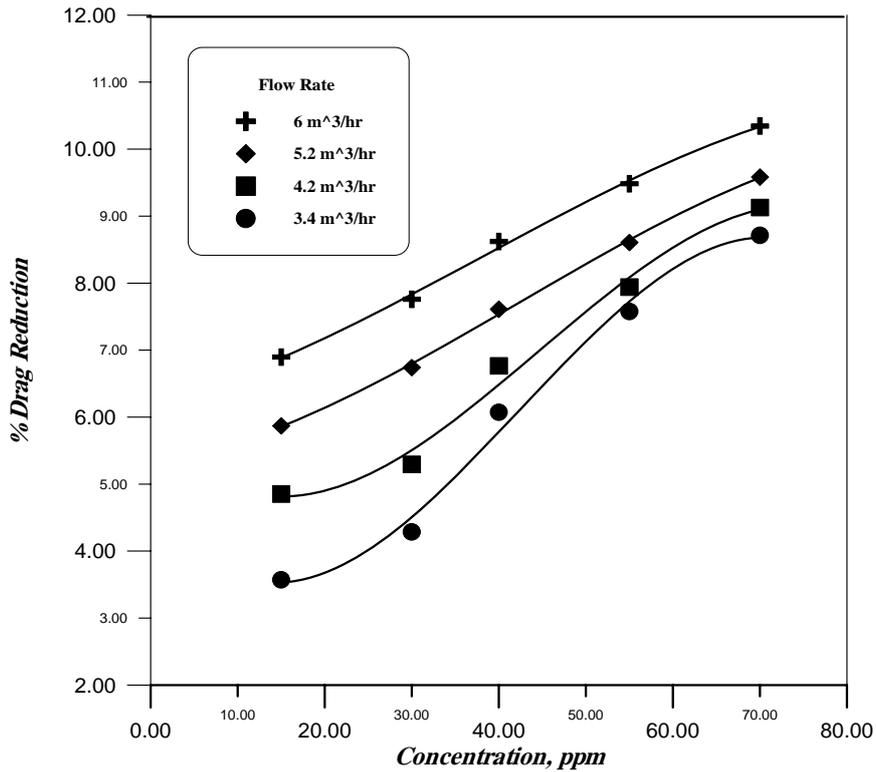


Fig. 4.14, Effect of concentration on percentage drag reduction for Oppanol 150 through 1.25 inch I.D pipe

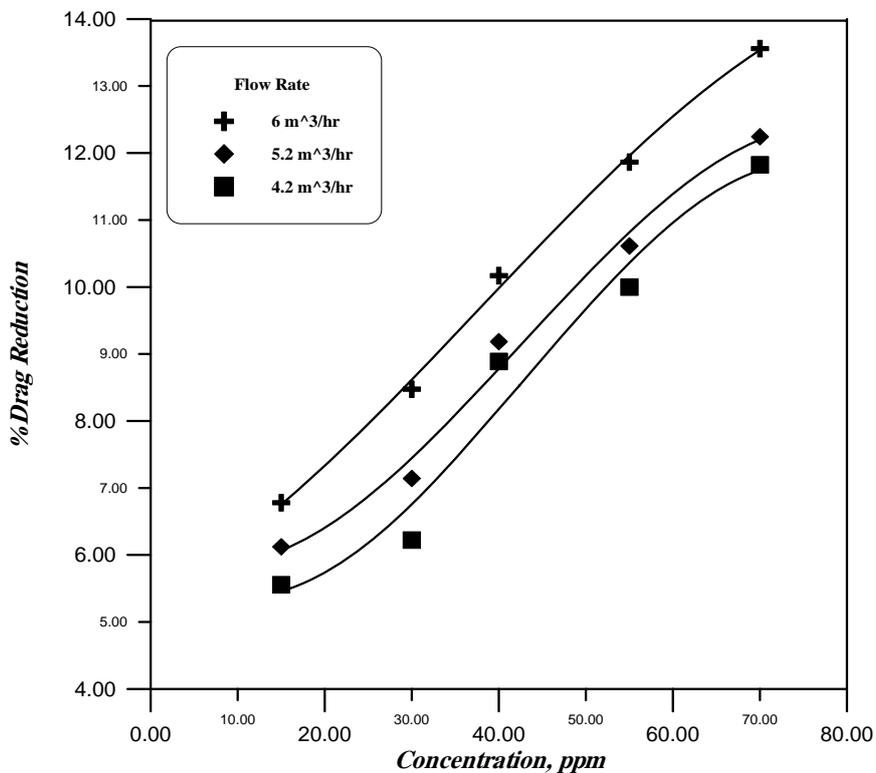


Fig. 4.15, Effect of concentration on percentage drag reduction for Oppanol 200 through 1.25 inch I.D pipe

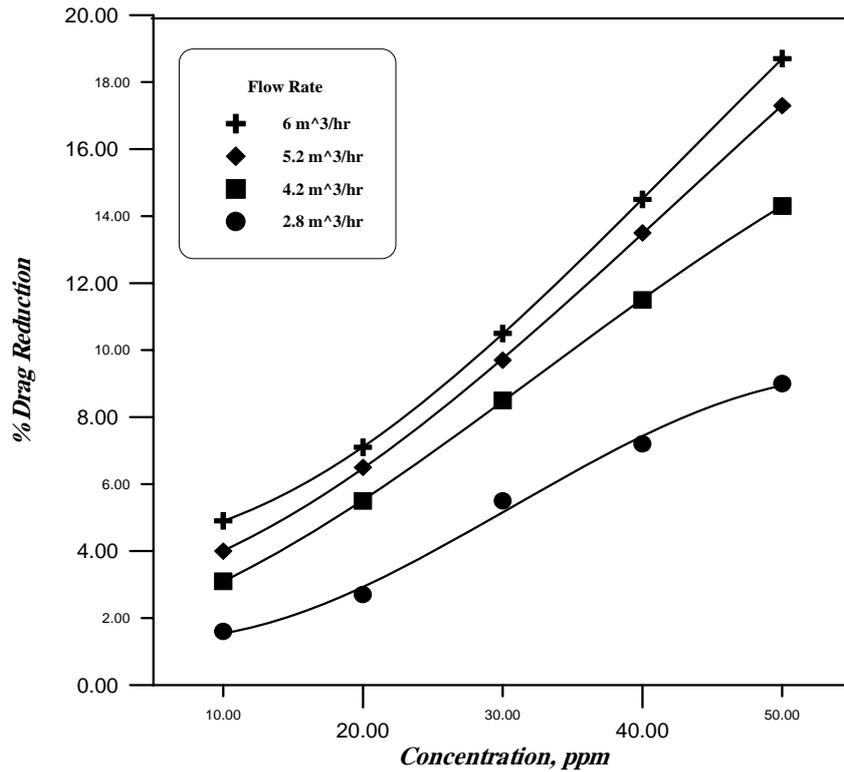


Fig. 4.16, Effect of concentration on percentage drag reduction for Oppanol 250 through 1.25 inch I.D pipe

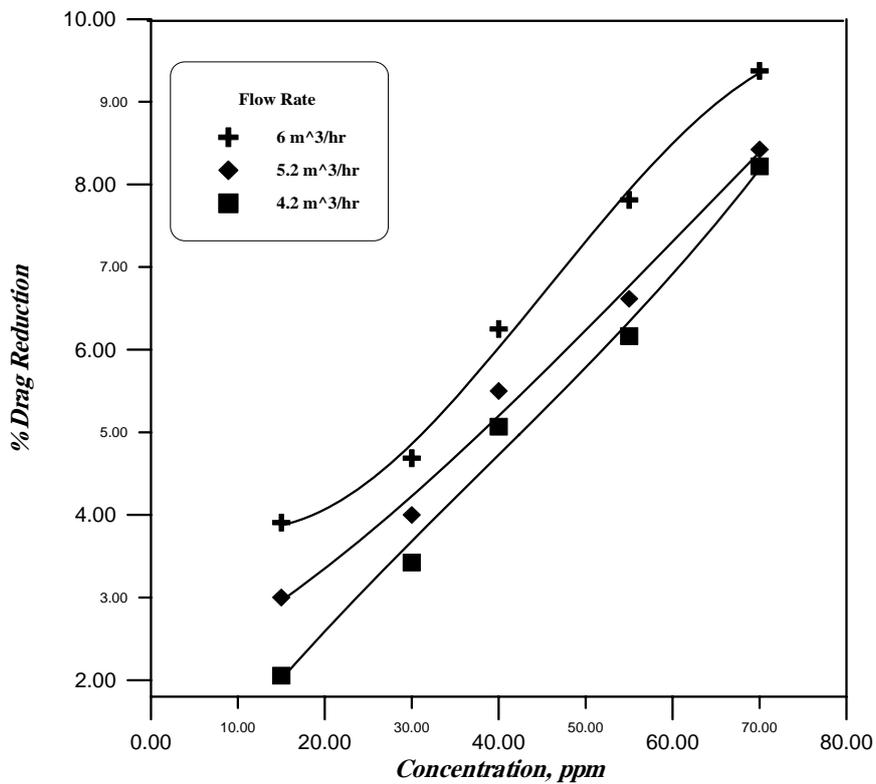


Fig. 4.17, Effect of concentration on percentage drag reduction for Oppanol 150 through 2 inch I.D pipe

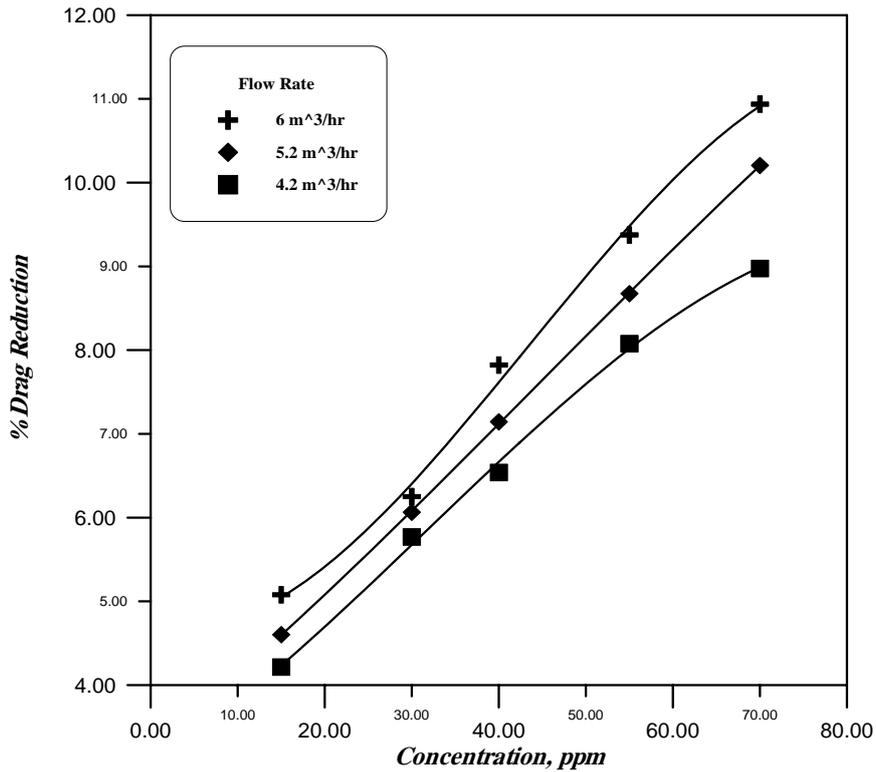


Fig. 4.18, Effect of concentration on percentage drag reduction for Oppanol 200 through 2 inch I.D pipe

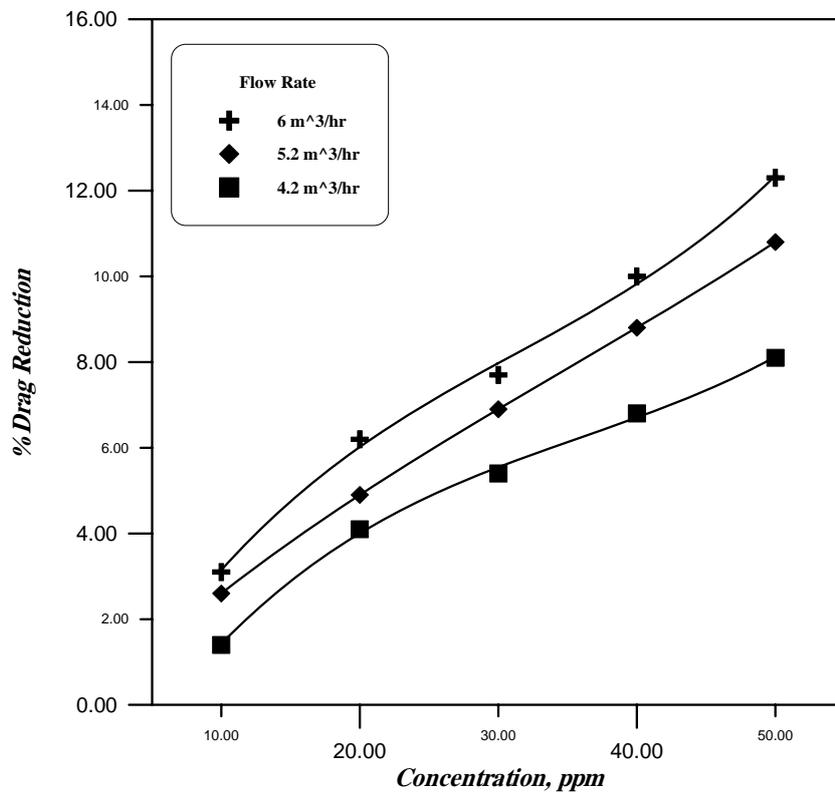


Fig. 4.19, Effect of concentration on percentage drag reduction for Oppanol 250 through 2 inch I.D pipe

The phenomenon of turbulent drag reduction by additives find applications in higher throughput in oil pipelines. Its importance lies in the capability of maximizing flow rate of pumping fluids inside pipes or minimizing the pumping costs.

The effect of additive concentration on through put increase had been studied. The results are illustrated in figure 4.20 for the three molecular weights polymers at selected flow rate 6 m³/hr and pipe diameter, 1.25 inch. This shows clear, that the addition of Oppanol polymers improves the throughput of the flowing gas oil. A linear increase of percentage throughput with concentration increase was observed. The molecular weight of additive has a predominate effect on the throughput increase. The maximum values were 5.8%, 7.3% and 12.2% for Oppanols 150, 200 and 250 respectively, which are ordered according their molecular weight values.

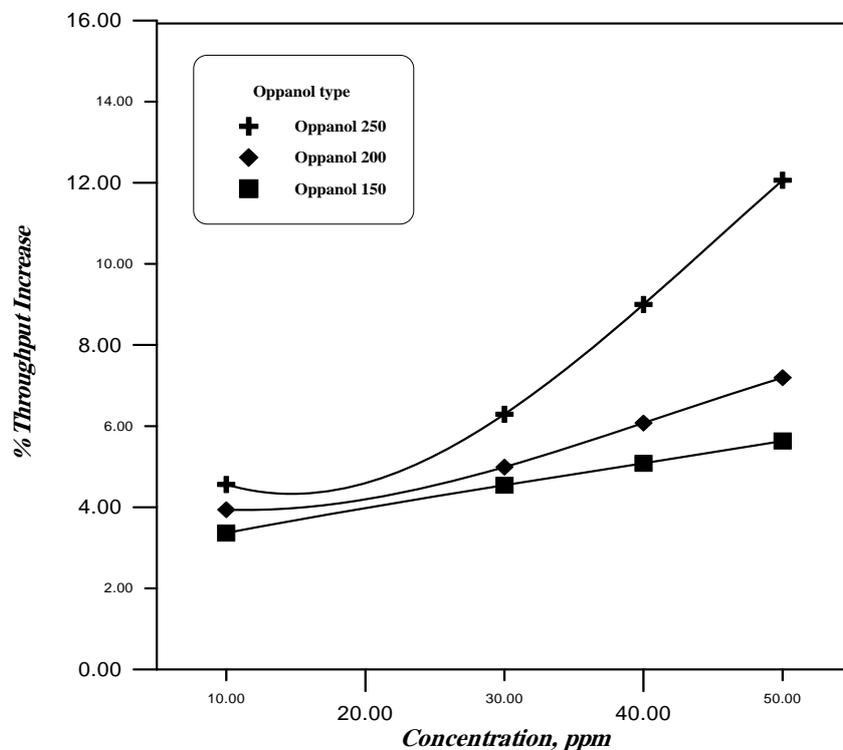


Fig. 4.20, throughput increase at different concentrations, flow rate=6 m³/hr, diameter=1.25 inch

4.4 Flow Rate Effect

It is well known, that drag-reduction by additives occurs only in turbulent flow. The degree of turbulence has a predominate effect on its effectiveness. Therefore its worthy to study the effect of flow rate through the pipe on performance of drag reduction rate.

Figures 4.21 through 4.29 show the variation of percentage drag-reduction with Reynolds number for gas oil flowing into the three different pipes considered in this investigation for various polymer concentration and molecular weights.

It is observed from figures 4.21 to 4.29, that the drag reduction rate increases with flow rate (Reynolds number) for fixed pipe diameter. Increasing the fluid velocity means increasing the degree of turbulence inside the pipe, this will provide a better media to the drag reducer to be more effective. This behavior agrees with Berman and his workers ^{(91), (92)} in which reported that 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 diameter when no other limits are present.

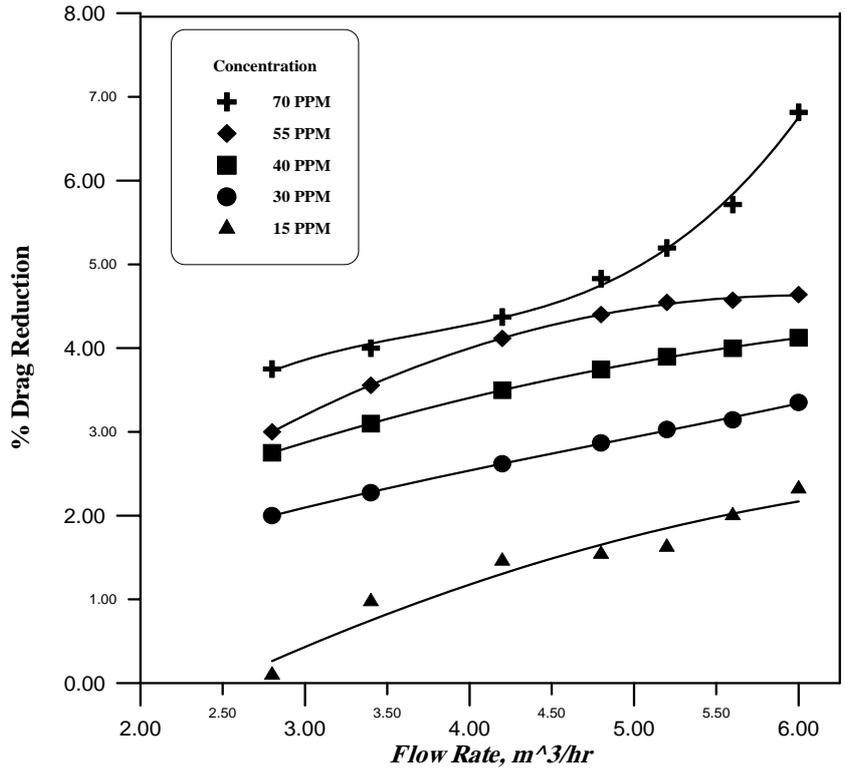


Fig. 4.21, Effect of flow rate on percentage drag reduction for Oppanol 150 through 1 inch I.D pipe

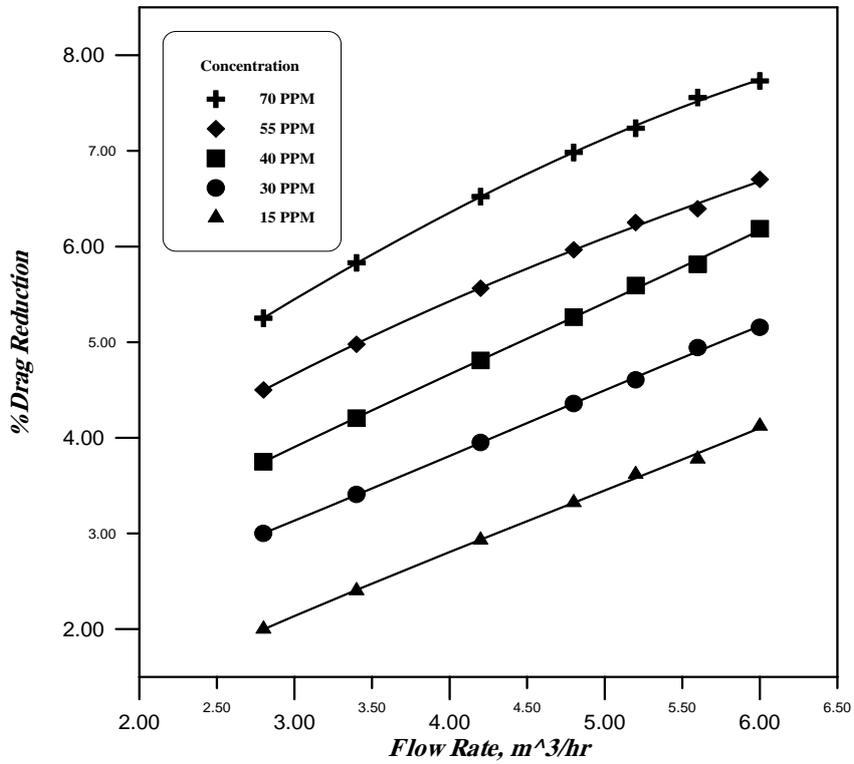


Fig. 4.22, Effect of flow rate on percentage drag reduction for Oppanol 200 through 1 inch I.D pipe

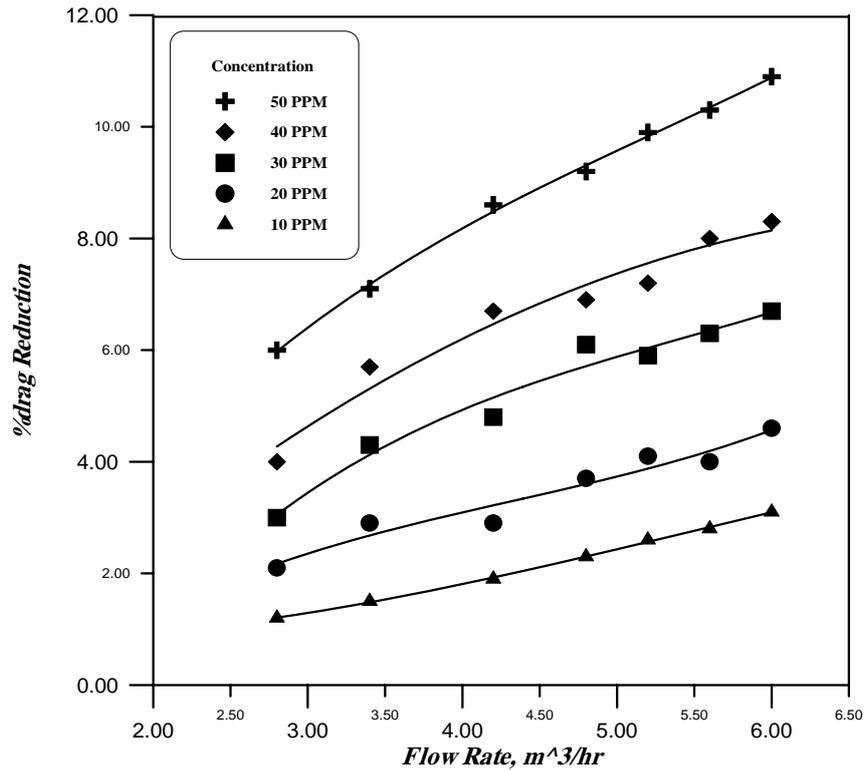


Fig. 4.23, Effect of flow rate on percentage drag reduction for Oppanol 250 through 1 inch I.D pipe

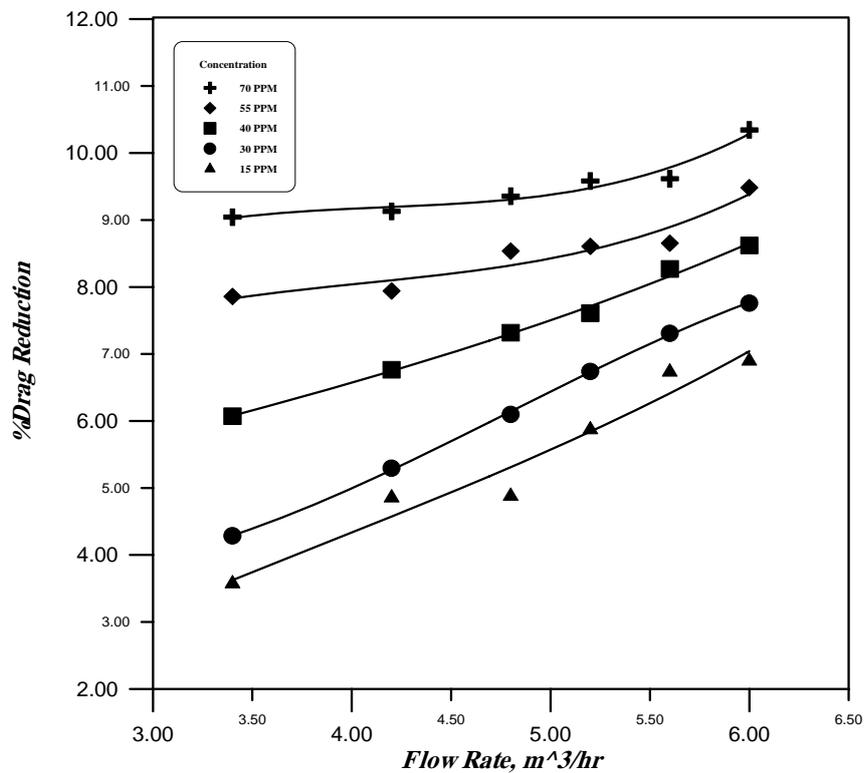


Fig. 4.24, Effect of flow rate on percentage drag reduction for Oppanol 150 through 1.25 inch I.D pipe

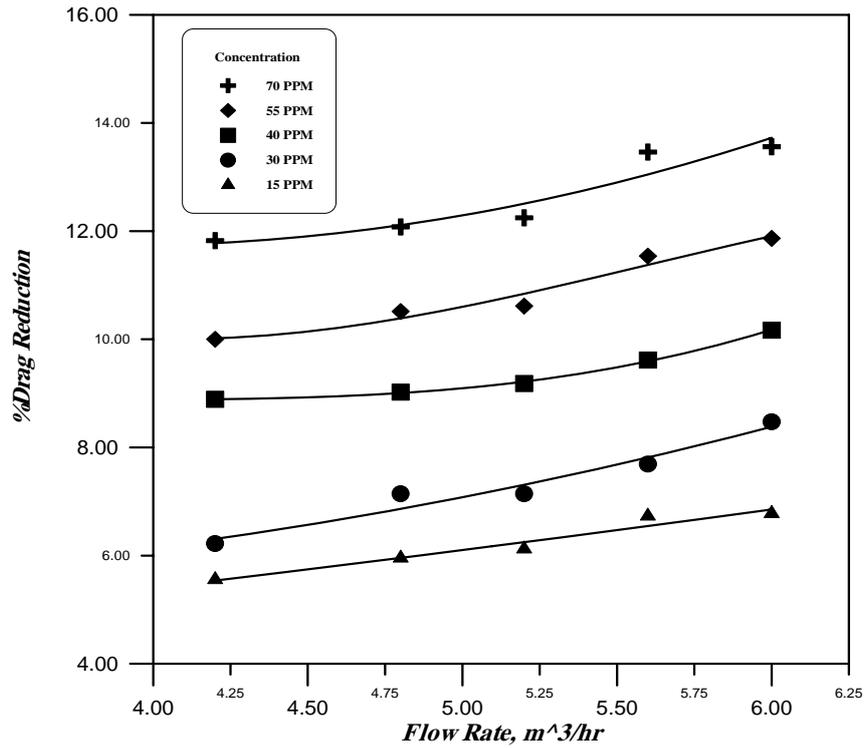


Fig. 4.25, Effect of flow rate on percentage drag reduction for Oppanol 200 through 1.25 inch I.D pipe

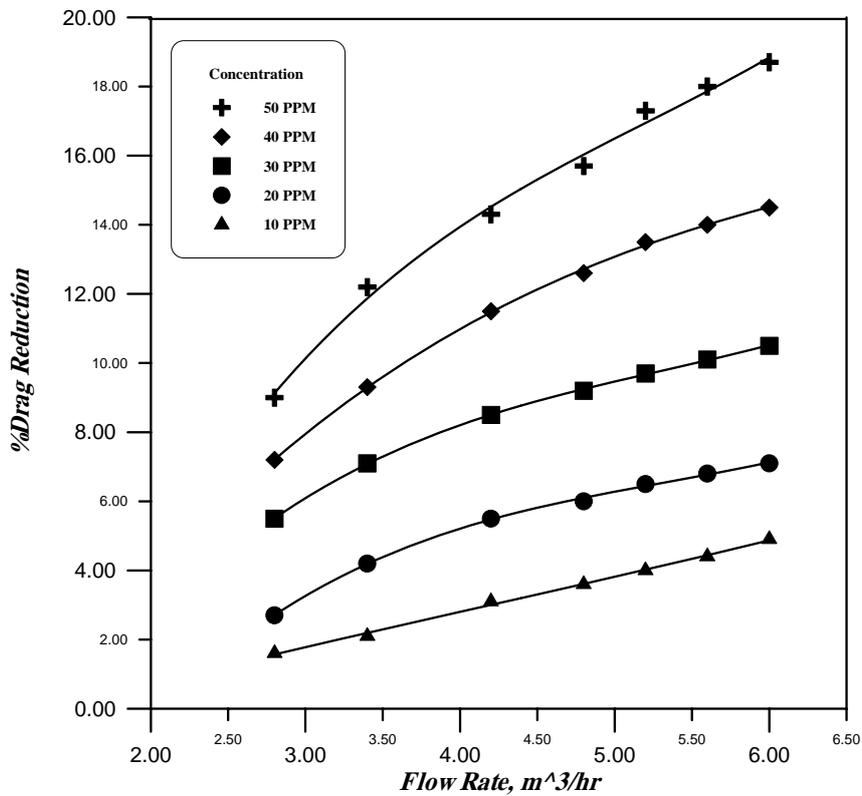


Fig. 4.26, Effect of flow rate on percentage drag reduction for Oppanol 250 through 1.25 inch I.D pipe

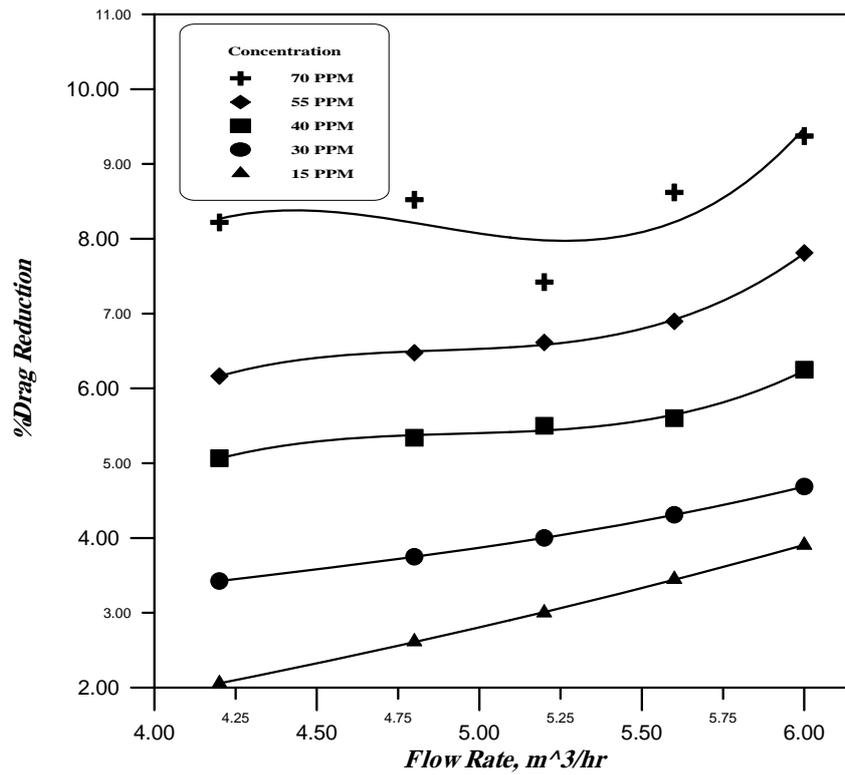


Fig. 4.27, Effect of flow rate on percentage drag reduction for Oppanol 150 through 2 inch I.D pipe

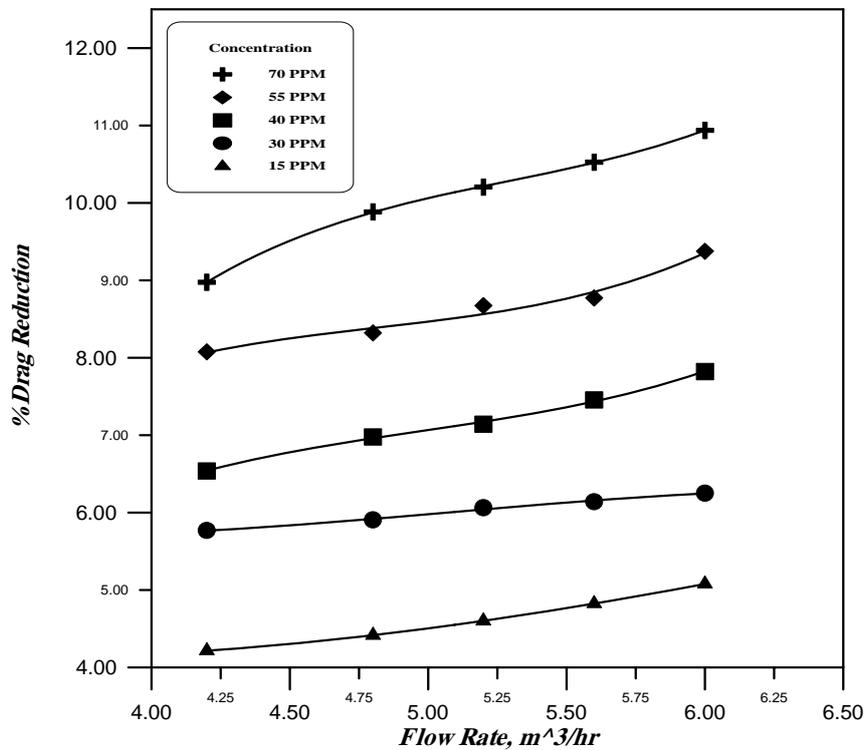


Fig. 4.28, Effect of flow rate on percentage drag reduction for Oppanol 200 through 2 inch I.D pipe

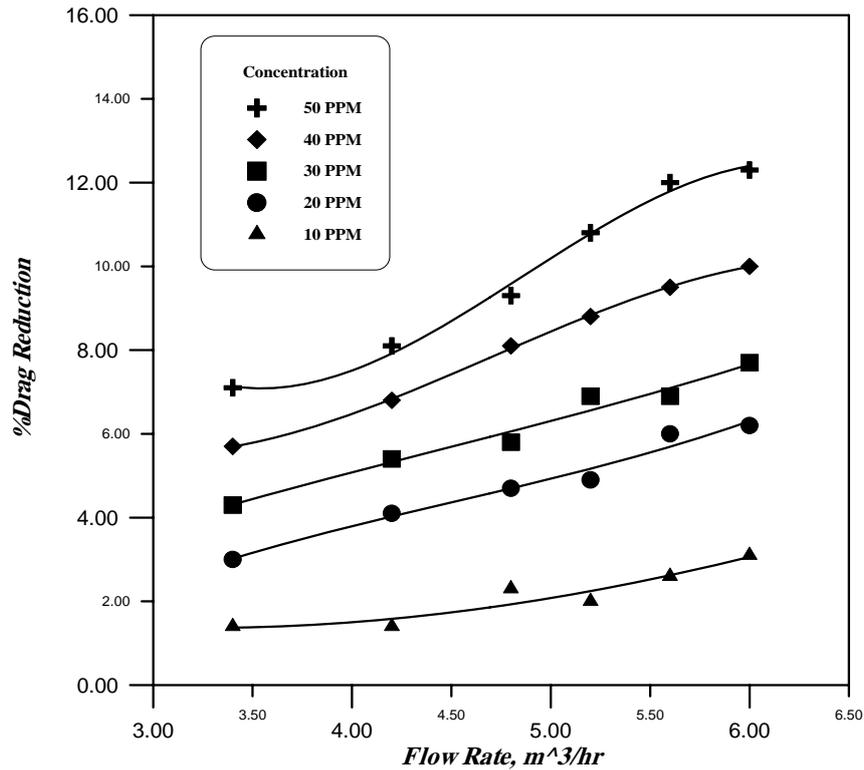


Fig. 4.29, Effect of flow rate on percentage drag reduction for Oppanol 250 through 2 inch I.D pipe

Figure 4.30 shows the effect of fluid turbulence on throughput increase (FI) for different polyisobutylene molecular weights (B 150, B 200 and B 250) added in gas oil flowing in 2 inch pipe at a selected concentration of 40 wppm. The figure shows that the pumpability of gas oil increases by increasing the flow rate at the same behavior mentioned because it is a direct function of percentage drag reduction. The observed results indicate that the use of drag-reduction phenomenon could be economic for increasing flow rate capacity of the working pipelines, in particular for high molecular weight additive and high turbulence.

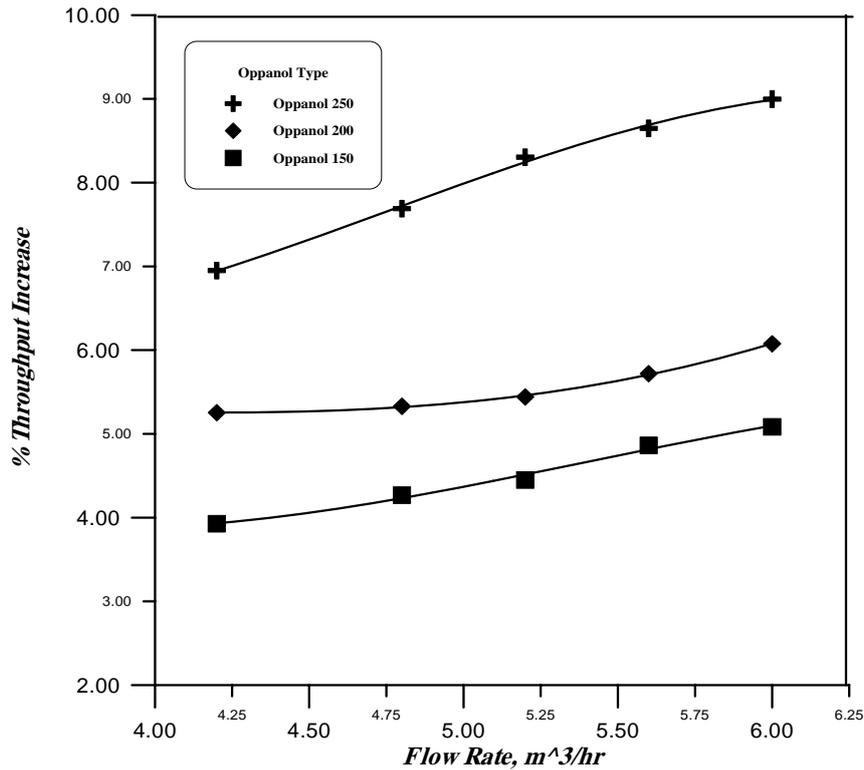


Fig. 4.30, Effect of flow rate on percentage throughput increase, concentration=40 ppm, diameter=1.25 inch

4.5 Molecular Weight Effect

It is well known that drag-reduction will be occur by high molecular weight polymeric additives. The current objective of present investigation was to study the effect of molecular weight of polyisobutylenes on reducing the drag and increasing the flow capacity during pipelining of gas oil. The considered values of molecular weights were, 2.5, 4.1 and 5.9 millions g/mol, which are high to occur remarkable drag reduction.

The effect of molecular weight of additives on the flow performance of gas oil are summarized in tables 4.1, 4.2 and 4.3 for different concentrations, flow rates and pipe diameters respectively.

Tables 4.1 combined effect of polymer molecular weight and concentration on %DR and %TI, 1.25 inch pipe diameter, 6.0 m³/hr flow rate

Polymer conc., wppm	Oppanol B 150		Oppanol B 200		Oppanol B 250	
	% DR	% TI	% DR	% TI	% DR	% TI
15	6.9	3.0	7.0	3.1	7.0	3.5
30	7.8	4.5	8.5	6.1	10.5	6.3
50	9.5	5.6	11.9	7.2	18.7	12.1

Tables 4.2 combined effect of polymer molecular weight and flow rate on %DR and %TI, 1.25 inch pipe diameter, 50 wppm

Flow rate, m ³ /hr	Oppanol B 150		Oppanol B 200		Oppanol B 250	
	% DR	% TI	% DR	% TI	% DR	% TI
4.2	8	4.7	10	6.0	14.3	8.9
5.2	8.6	5.1	10.6	6.4	17.3	11.0
6	9.5	5.6	11.9	7.2	18.7	12.1

Tables 4.3 combined effect of polymer molecular weight and pipe diameter on %DR and %TI, 1.25 inch pipe diameter and 50 wppm concentration

Flow rate, m ³ /hr	Oppanol B 150		Oppanol B 200		Oppanol B 250	
	% DR	% TI	% DR	% TI	% DR	% TI
1.0	4.6	2.6	6.7	3.9	10.9	6.6
1.25	9.5	5.6	11.7	7.2	18.7	12.1
2.0	7.8	4.6	9.4	5.6	12.3	7.5

Another representation to the effect of all variables used in this investigation can be seen using friction factor, which was calculated from equation 3.7

Selected samples of the experimental results for friction factor are illustrated in figures 4.31 to 4.34, these figures showing the effect of polymer molecular weight on friction factor. Friction factor decreases by increasing the polymer molecular weight, which resulted in an increase of drag-reduction.

It can be noticed that, with low polymer molecular weight is 2.5×10^6 (Oppanol 150), most of the experimental data points, are located at or close Blasius asymptote, which give an indication that the starting points of the operation are close to that of the standard operation conditions suggested in the literatures. At high molecular weight and high flow rates, the experimental data points are positioned in the direction of lowering friction towards Virk asymptote that represent maximum limits of drag reduction. This give the idea that, to reach such an asymptote, higher molecular weight and Re are needed for each pipe diameter. But, it must be considered that higher concentrations should not affect solvent properties, also by considering the economical costs of raw material of drag reducing agents, therefore it was difficult to reach Virk asymptote without affecting the investigated solvent properties.

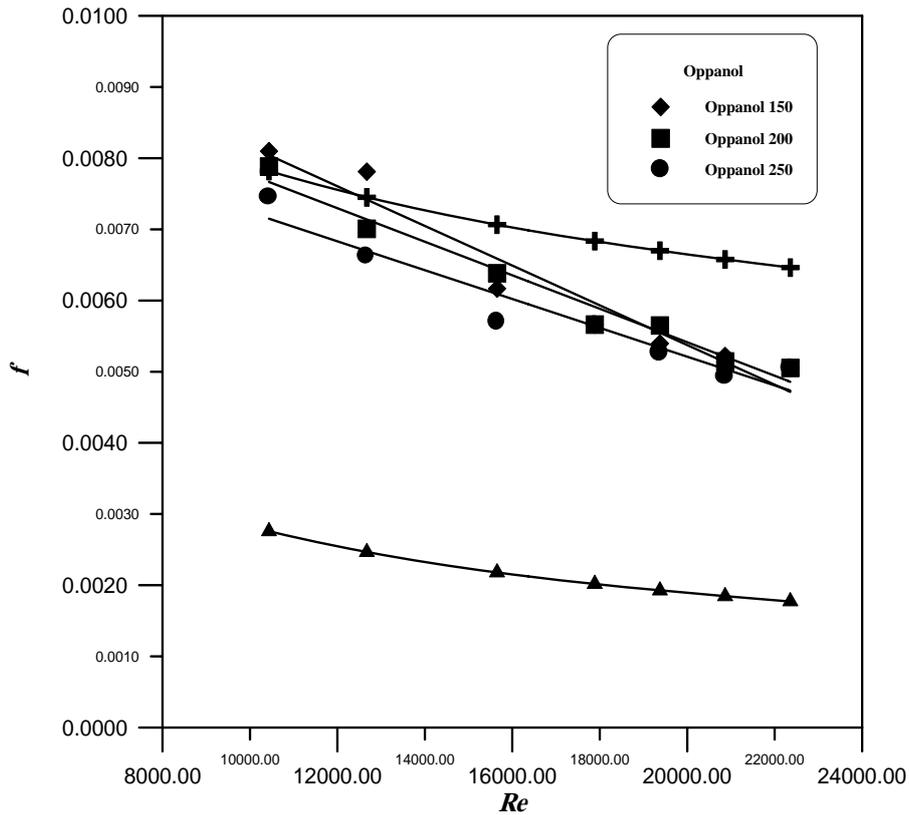


Fig. 4.31, friction factor versus Reynolds number at different polymer molecular weight, at 30 wppm through 1.25 inch I.D pipe.

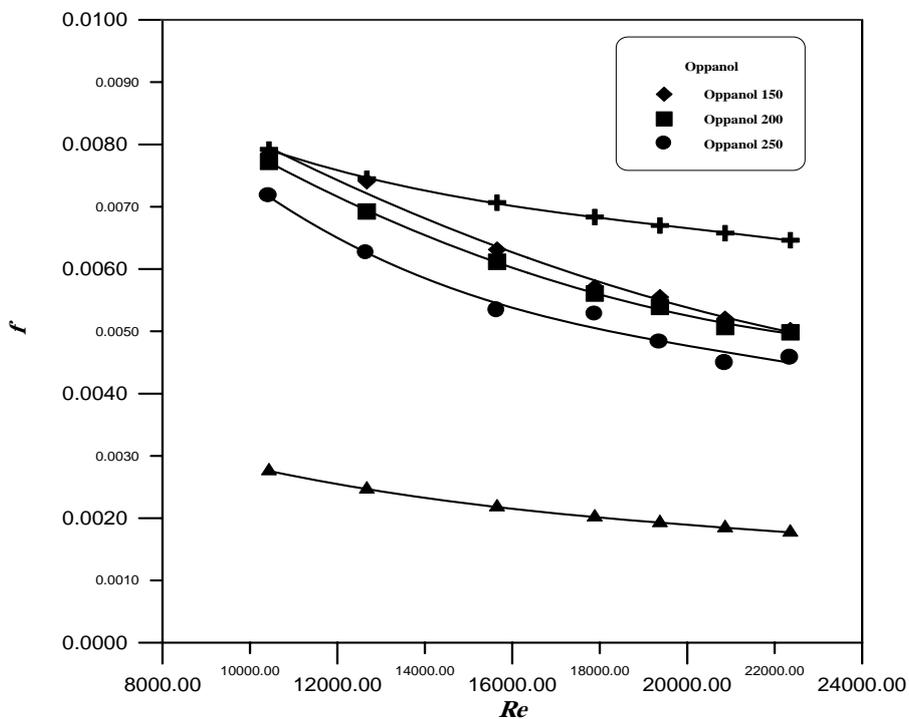


Fig. 4.32, friction factor versus Reynolds number at different polymer molecular weight, at 50 wppm concentration through 1.25 inch I.D pipe.

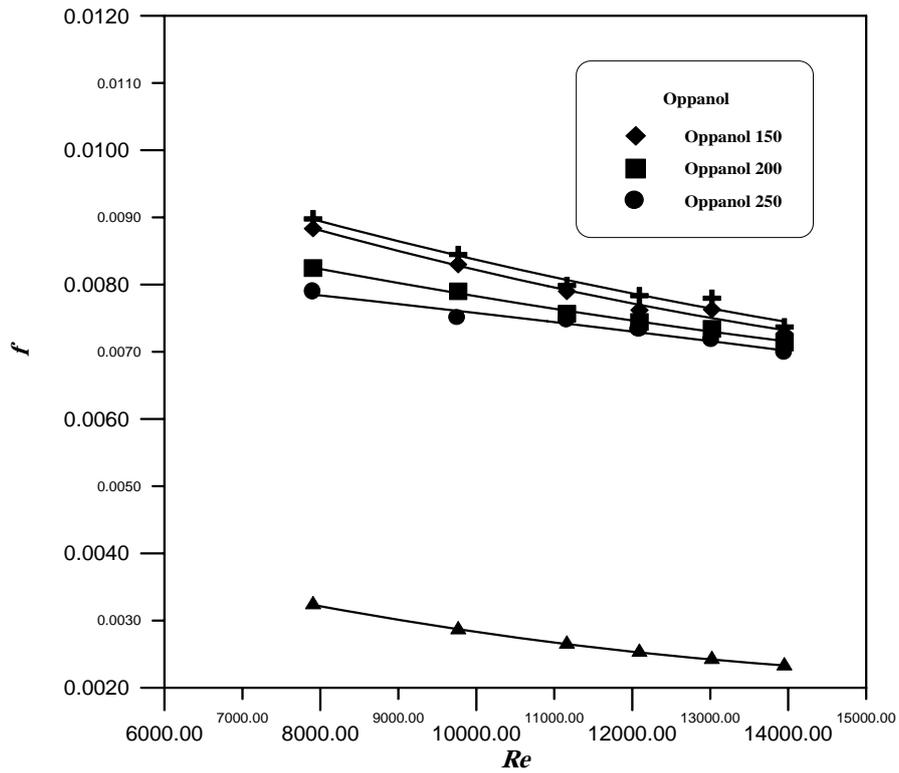


Fig. 4.33, friction factor versus Reynolds number at different polymer molecular weight, at 50 w ppm concentration through 2 inch I.D pipe.

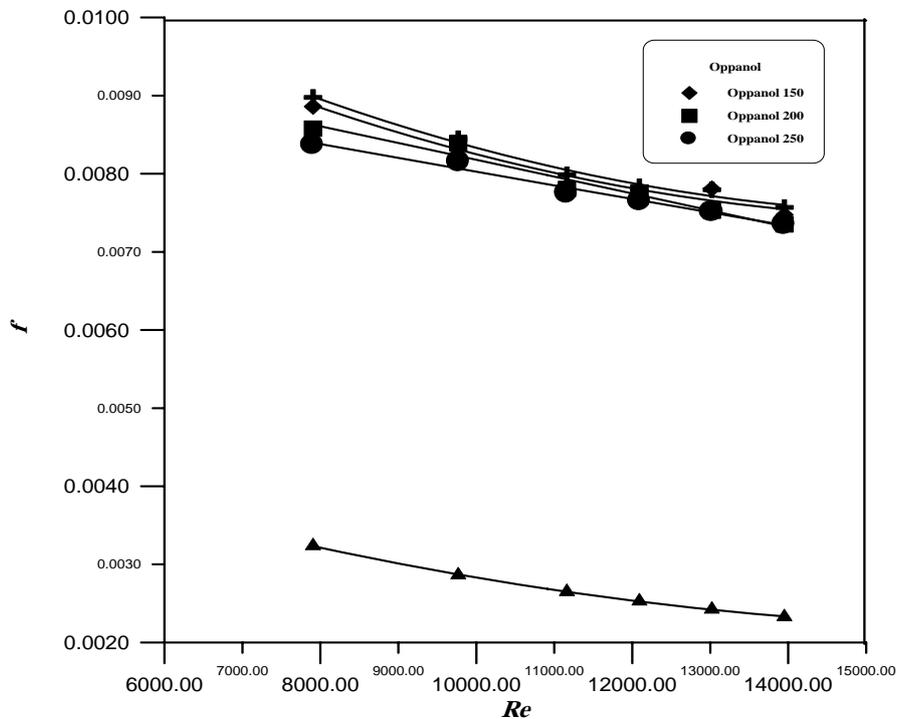


Fig. 4.34, friction factor versus Reynolds number at different polymer molecular weight, at 30 ppm concentration through 2 inch I.D pipe.

4.6 Effect of pipe diameter

Figures 4.35 to 4.37 Show that drag reduction percentage increase as pipe diameter increases for different flow rate. Therefore a maximum drag reduction percentage is obtained in the 1.25 inch pipe. This amount of drag reduction seems to be promising for practical applications.

These results agree with the works of Breman ⁽⁹²⁾, who found that in a larger pipe, compared with a smaller pipe size.

This phenomenon can be interpreted by turbulent or molecular interactions as follows: DR can be increased when pipe diameter is increased when pipe diameter is increased if the persistence time of larger eddies that is proportional to D/u is important. This persistence time 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 molecule ⁽⁹¹⁾.

Since the polymer turbulent drag-reduction is induced by the viscoelastic behavior concentrations from the individual polymer molecules, the increment of polymer concentration increases the drag reduction efficiency.

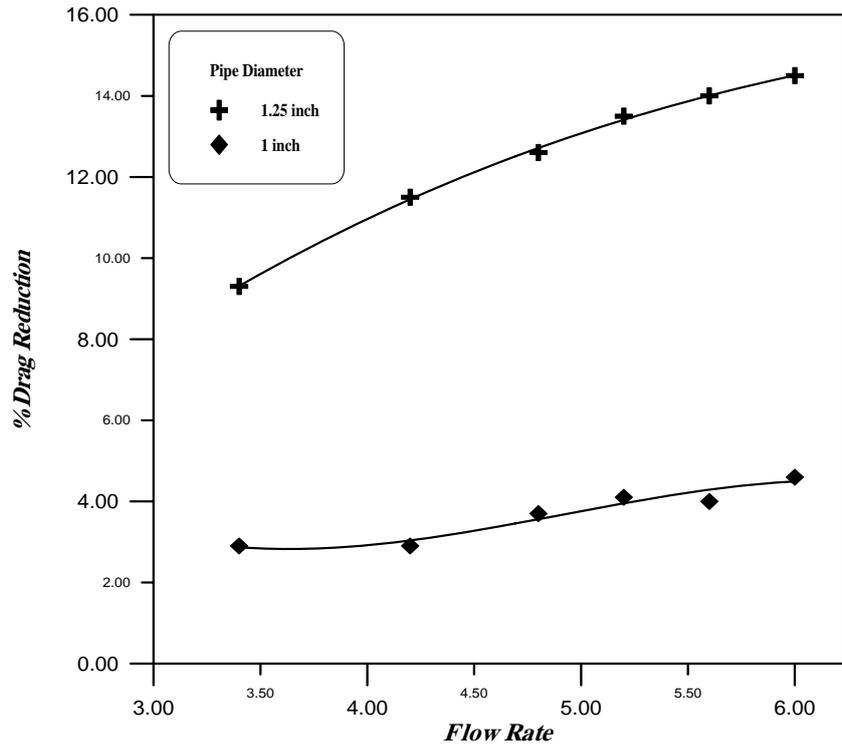


Fig. 4.35, Effect of pipe diameter on percentage drag reduction for Oppanol 250 and 40 ppm polymer concentration

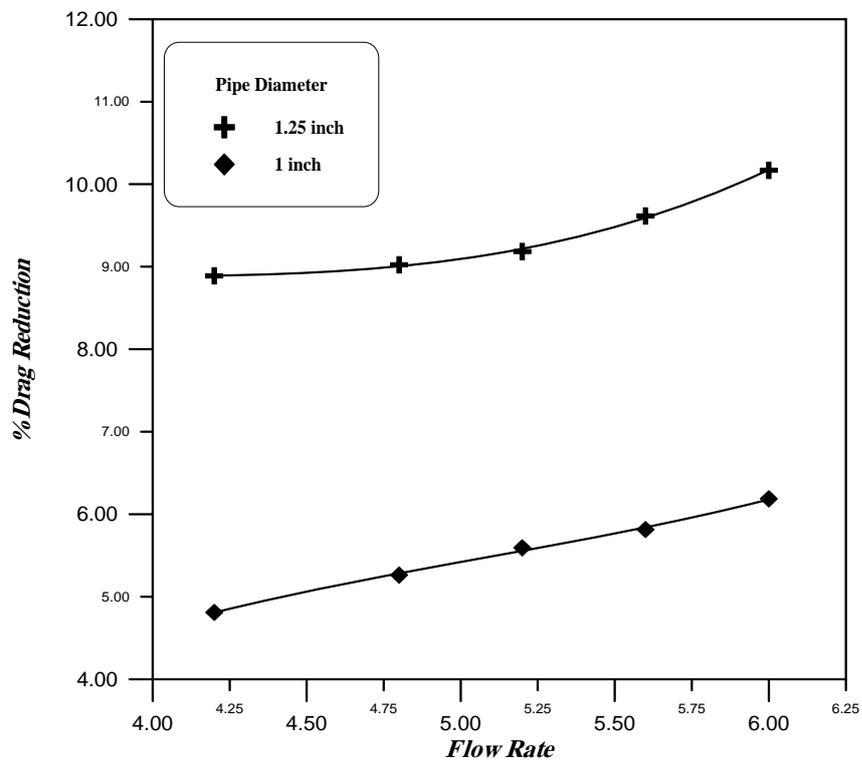


Fig. 4.36, Effect of pipe diameter on percentage drag reduction for Oppanol 200 and 40 ppm polymer concentration

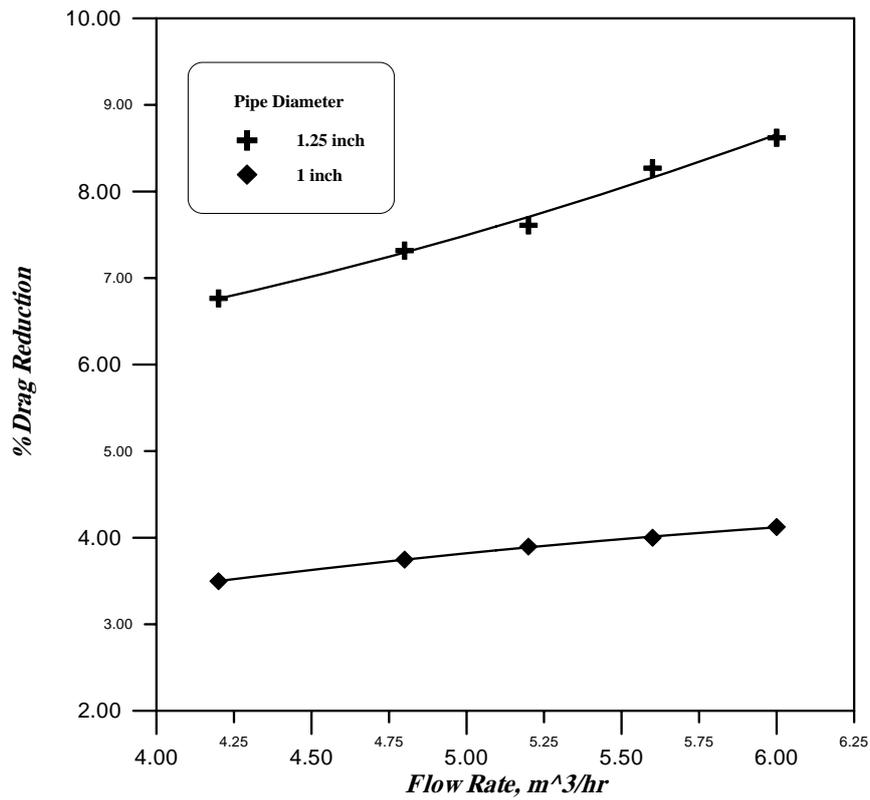


Fig. 4.37, Effect of pipe diameter on percentage drag reduction for Oppanol 150 and 40 ppm polymer concentration

4.7 Correlations

The experimental results show, that the drag-reduction efficiency is to be a function of polymer molecular weight, polymer concentration and the degree of turbulence (flow rate), while pipe diameter has an inverse effect. The primary end use of drag reducers is usually to increase the flow rate (throughput increase) without exceeding the safe pressure limits within the flow system.

The evaluation of drag-reduction rate was done experimentally by measurement of pressure drop in a test section of the fully developed flow. It was useful to find correlations to predict the pressure drop values based on flow conditions such as polymeric molecular weight, concentration, flow rate and pipe diameter.

The dependence of pressure drop reduction (PDR) with polymer concentration and flow rate, is fitted as follows

$$\text{PDR} = b_1 + b_2 * f * (c)^{b_3} + b_4 * f^{(b_5)} * (c)^{b_6} \quad \dots(4.2)$$

Where:

c = concentration in ppm

f = flow rate in m³/hr

A computer program was used to find the values of the constants b₁, b₂, b₃, b₄, b₅ and b₆ that give the best fitting of the experimental data. The coefficients for each system i.e., for each polymer molecular weight (B250, B200 and B150) and each pipe diameter's (1.25 inch and 2 inch) are tabulated in table 4.4.

Figures 4.38 to 4.40 show the relation between the observed values of pressure drop reducing taken from experimental data and the predicted values from the correlation. It can be noticed that most points lie at or close to the straight line, which means a good agreement between theoretical and experimental data, with correlation coefficient values ranging between 0.97313 to 0.99528.

Table 4.4, Values of the correlations coefficients for each system

Pipe diameter	Poly mer	B1	B2	B3	B4	B5	B6	Variance	Correlation coefficient
2 inch	B 250	-0.338912	-5.26066	-21.0261	0.05384	0.826786	0.296694	0.9364	0.96768
1.25 inch	B 250	0.990665	-0.286292	0.519698	0.09570	1.411511	0.683722	.99058	0.99528
1.25 inch	B 200	546.6498	.963143	.143152	-	0.07846	0.000151	0.96456	0.98212
1.25 inch	B 150	12.43224	1.803605	0.054726	-	0.344664	-0.000084	0.96962	0.98469
2 inch	B 150	0.088752	-0.114093	0.208706	0.06562	1.196205	.290549	.94698	.97313
2 inch	B 200	0.105573	0.4493	-13.7962	0.00001	3.193634	0.980813	.98161	0.99076

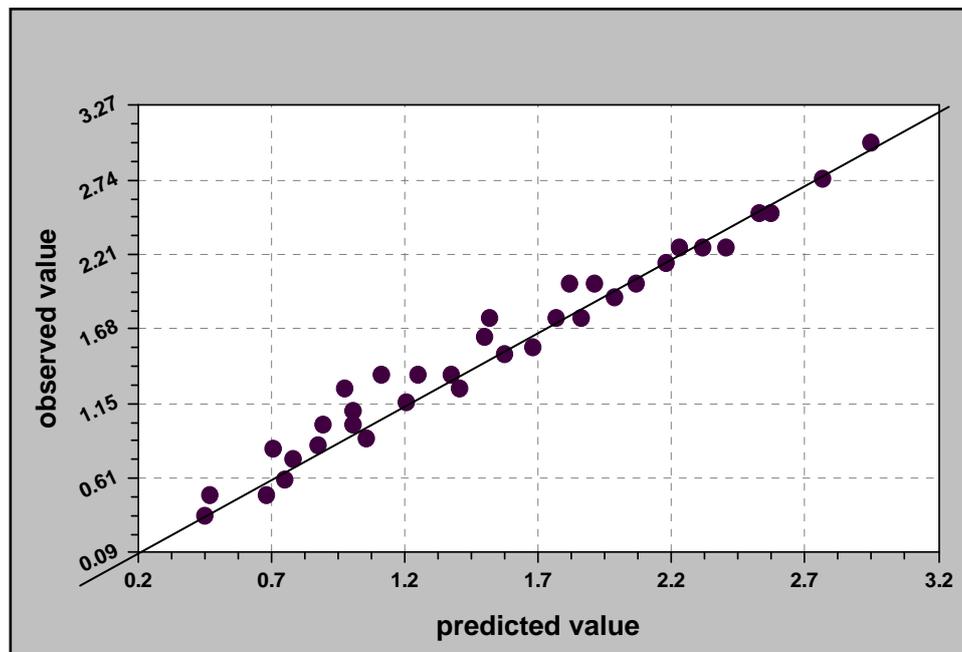


Fig.4.38, predicted versus observed values of pressure drop reducing for 1.25 inch pipe, Oppanol 150

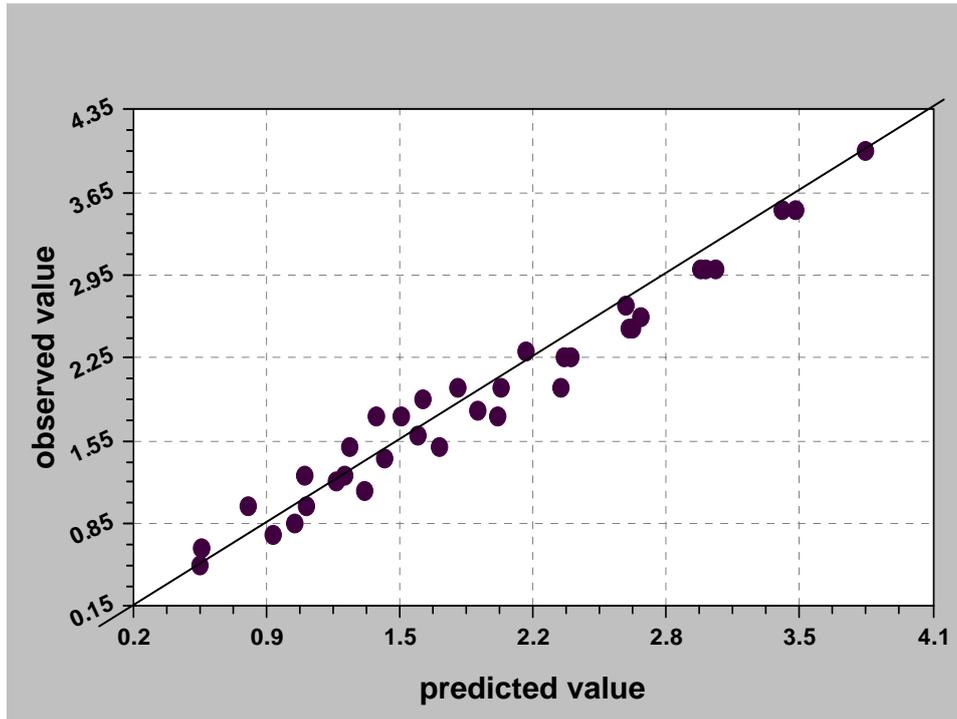


Fig.4.39, predicted versus observed values of pressure drop reducing for 1.25 inch pipe, Oppanol 200

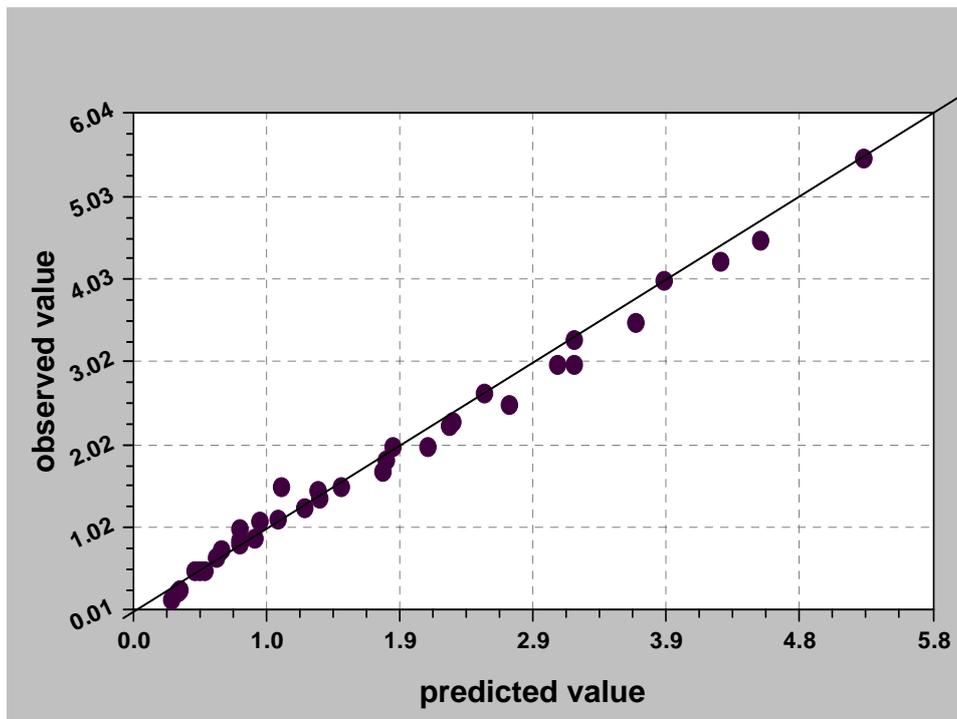


Fig.4.40, predicted versus observed values of pressure drop reducing for 1.25 inch pipe, Oppanol 250

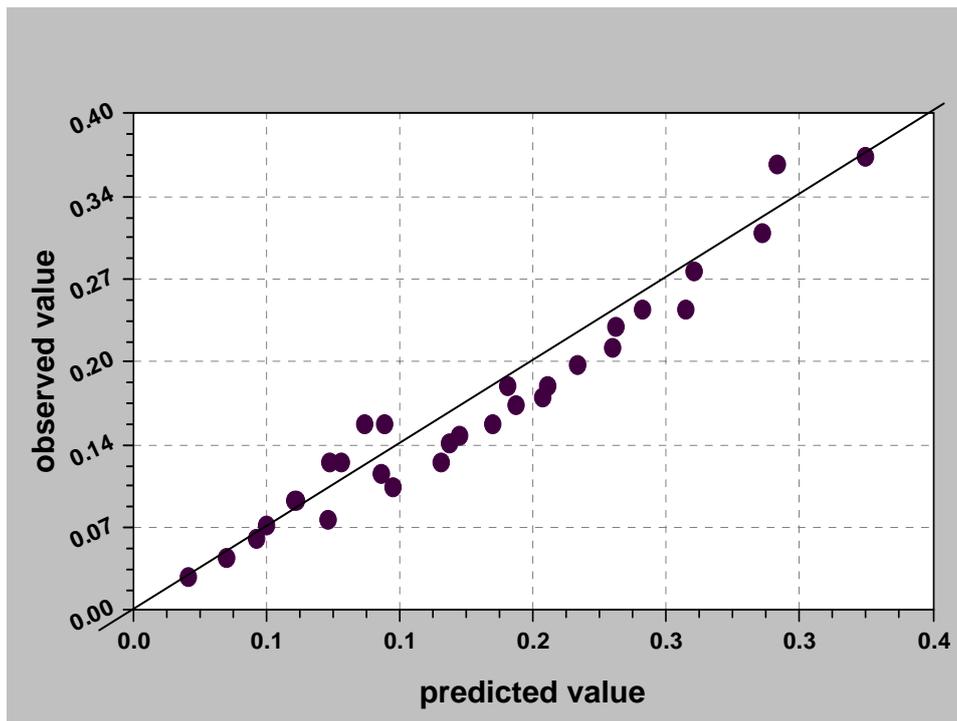


Fig.4.41, predicted versus observed values of pressure drop reducing for 2 inch pipe, Oppanol 150

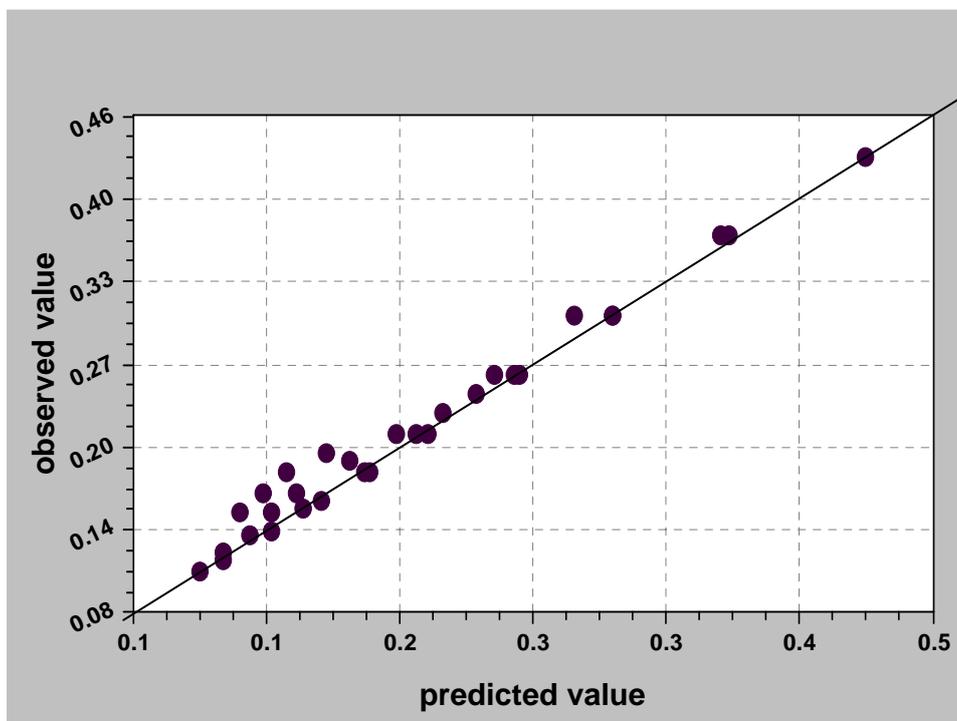


Fig.4.42, predicted versus observed values of pressure drop reducing for 2 inch pipe, Oppanol 200

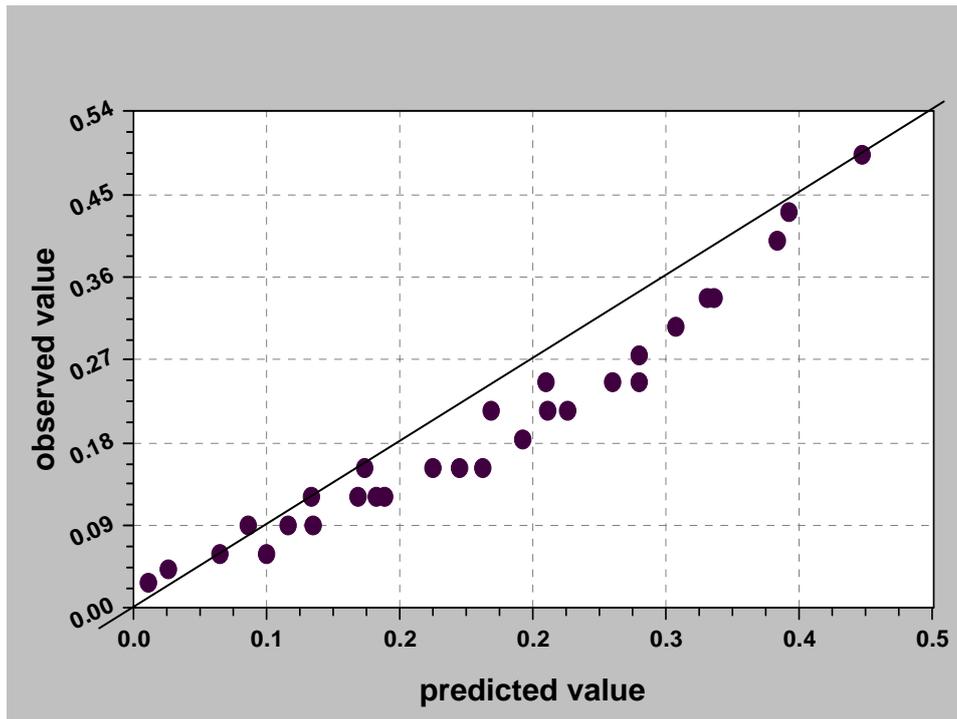


Fig.4.43, predicted versus observed values of pressure drop reducing for 2 inch pipe, Oppanol 250

Equation 4.3 was used to include the effect of molecular weight in addition to polymer concentration and flow rate of pumping fluid

$$PDR = b_1 + b_2 * M * f^{b_3} + b_4 * f^{b_5} * (c)^{b_6} * (M)^{b_7} \quad \dots(4.3)$$

Where:

M = molecular weight in g/mole

The values of the constants b_1 , b_2 , b_3 , b_4 , b_5 , b_6 and b_7 where give the best fitting of the experimental data for each pipe diameter, were computed by Statica program

Figures 4.41 to 4.42 show the relation between the observed values of pressure drop reducing taken from experimental data and the predicted values from mathematical correlation. It can be noticed that most points lie at or close to the straight line, which means a good agreement between theoretical and experimental data, with correlation coefficient values ranging between 0.96699 to 0.97268.

Table 4.5, Values of the correlations coefficients for each system

Pipe diameter	B1	B2	B3	B4	B5	B6	B7	Variance	Correlation coefficient
2 inch	0.0394	.4126	.4611	-0.4439	0.9492	0.4461	1.0175	0.93508	0.96699
1.25 inch	1.830913	0.093519	0.394692	-0.397183	.564216	.233129	.867464	0.94611	.97268

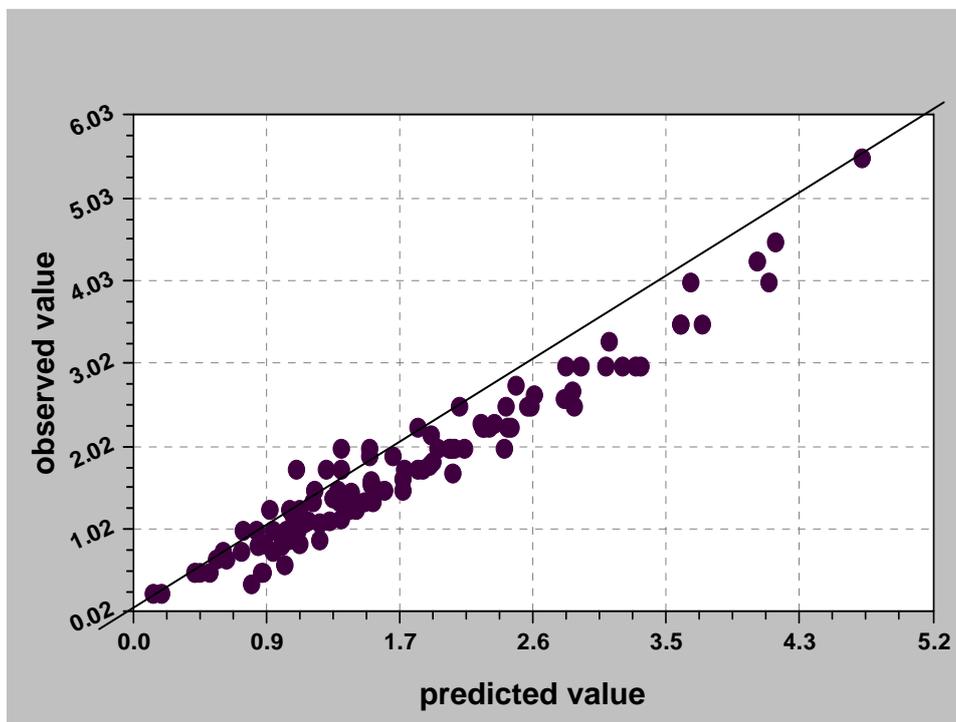


Fig.4.44, predicted versus observed values of pressure drop reducing for 2 inch pipe

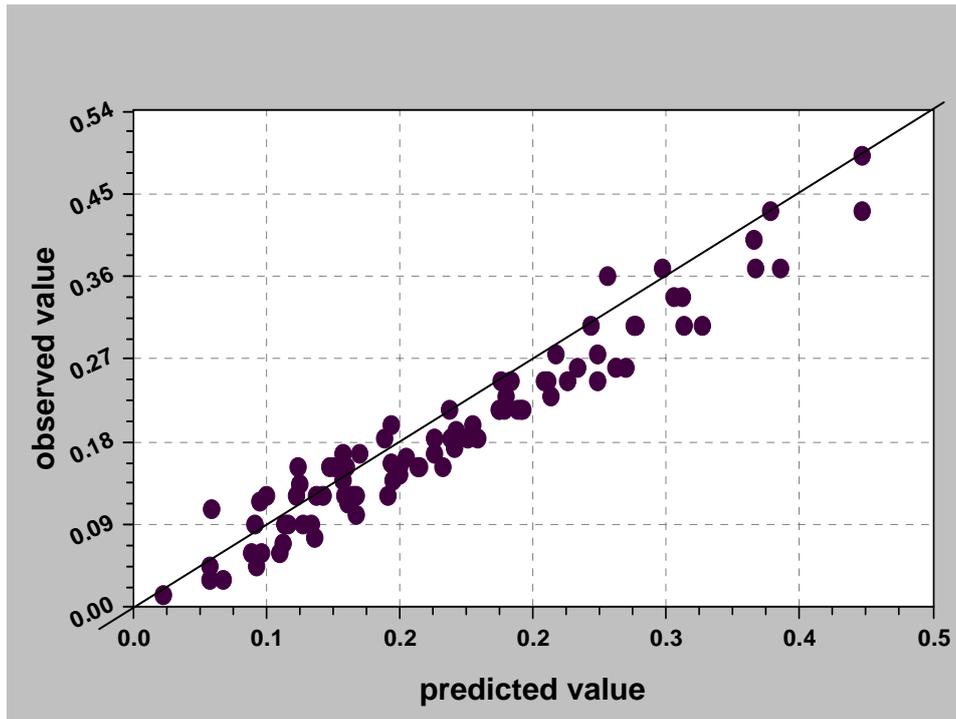


Fig.4.45, predicted versus observed values of pressure drop reducing for 1.25 inch pipe

Furthermore, equation 4.4 was fitted to include pipe diameter in addition to polymer concentration and flow rate for estimation of pressure drop reduction

$$PDR = b_1 + b_2 \cdot (1/D) \cdot f \cdot (c)^{b_3} + b_4 \cdot f^{(b_5)} \cdot (c)^{b_6} \cdot (1/D)^{b_7} \dots (4.4)$$

Where:

D = pipe diameter in inch

The values of the constants b_1 , b_2 , b_3 , b_4 , b_5 , b_6 and b_7 which give the best fitting of the experimental data for each molecular weight, were computed by Statistica program

Figures 4.43 to 4.45 show the relation between the observed values of pressure drop reducing taken from experimental data and the predicted values from mathematical correlation. It can be noticed that most points lie at or close to the straight line, which means a good agreement between theoretical and experimental data, with correlation coefficient values ranging between 0.99181 to 0.99327

Table 4.6, Values of the correlations coefficients for each system

Polymer	B1	B2	B3	B4	B5	B6	B7	Variance	Correlation coefficient
B 250	1.9817	4.7574	.5293	-5.3214	0.9595	0.5113	0.9422	0.98658	0.99327
B 200	.206015	-0.084086	0.310145	0.10001	1.43193	.491987	3.200766	.98612	.99304
B 100	0.030959	0.000031	1.928576	.237661	1.95493	.207741	9.278361	.98368	.99181

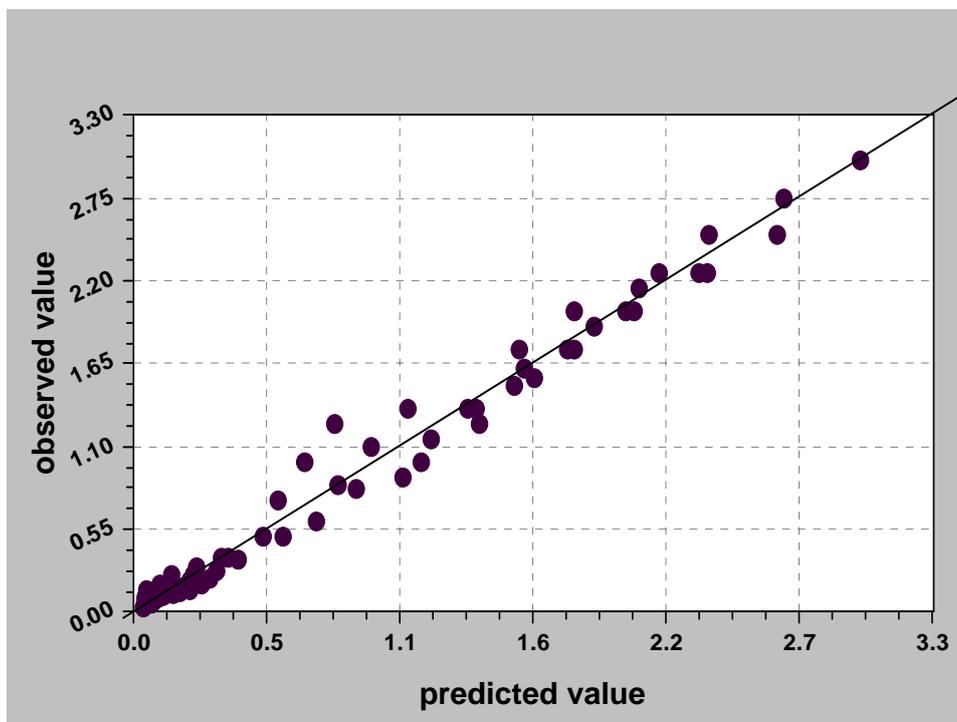


Fig.4.46, predicted versus observed values of pressure drop reducing for Oppanol 150

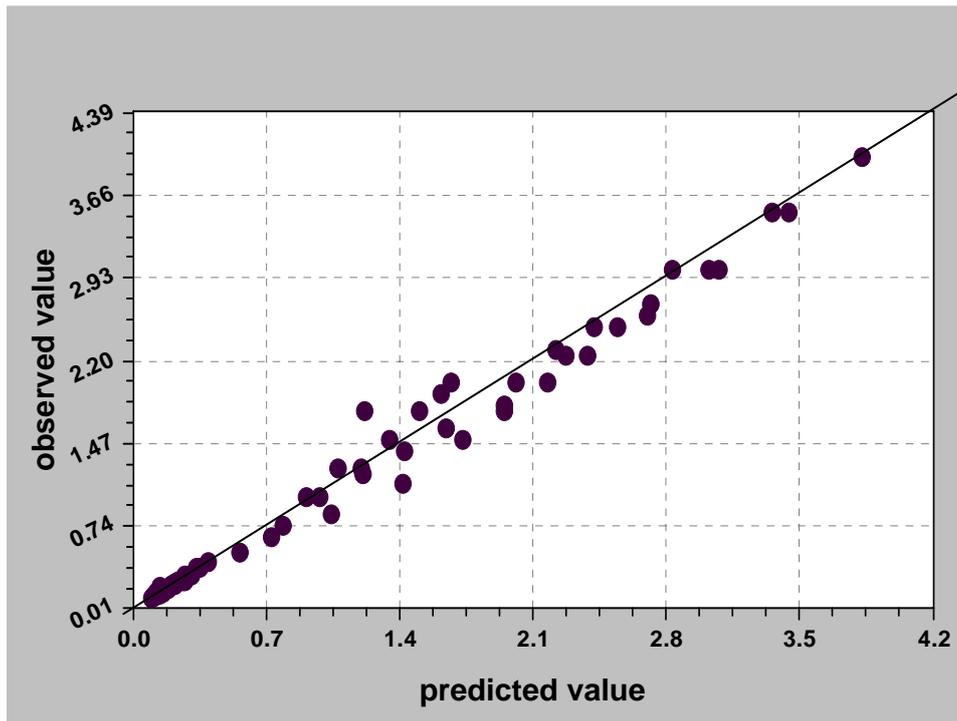


Fig.4.47, predicted versus observed values of pressure drop reducing for Oppanol 200

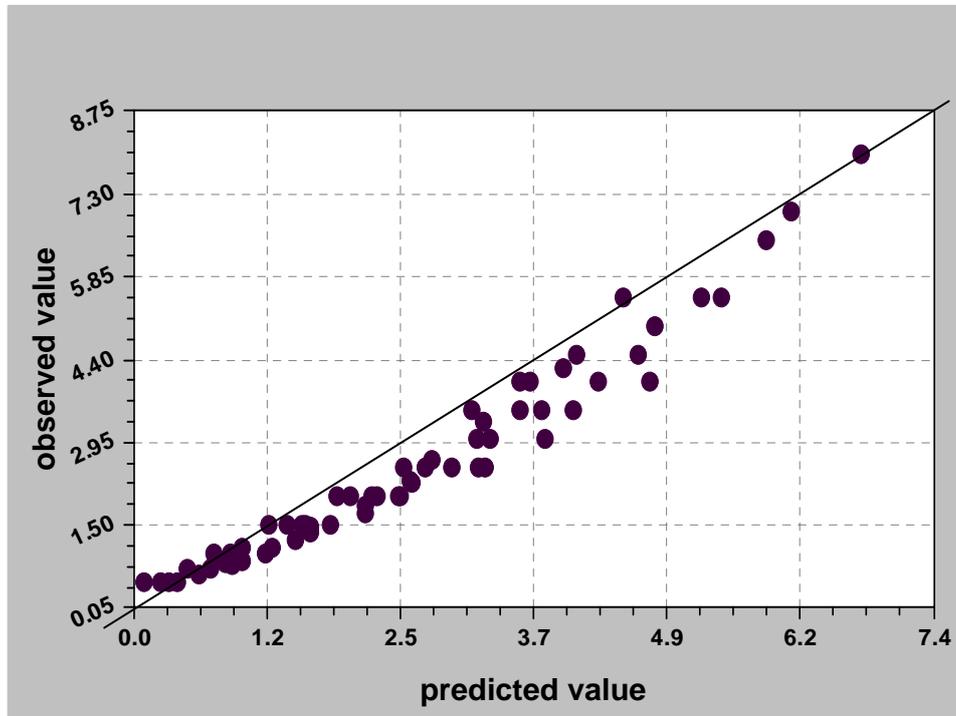


Fig.4.48, predicted versus observed values of pressure drop reducing for Oppanol 250

Equation 4.5 was modified by enter the effect of pipe diameter and molecular weight of polymer used as follows:

$$PDR=b_1+b_2*((M/D)^{b_3})*(f^{b_4})*(c^{b_5})+b_6*(f^{b_7})*(c^{b_8})*((M/D)^{b_9})*(M^{b_{10}}) \quad \dots(4.5)$$

The coefficients of equation 4.5 were found by using a computer program, statistica as listed in table 4.7.

Figure 4.46 show the relation between the observed values of pressure drop reducing taken from experimental data and the predicted values from mathematical correlation. It can be noticed that most points lie at or close to the straight line, which means a good agreement between theoretical and experimental data.

Table 4.7, Values of the correlations coefficients for all system

B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	R	V
0.1193	-0.0094	3.175	0.1744	-0.3207	0.0207	1.7477	0.5324	5.5933	-4.75396	0.9853	0.97092

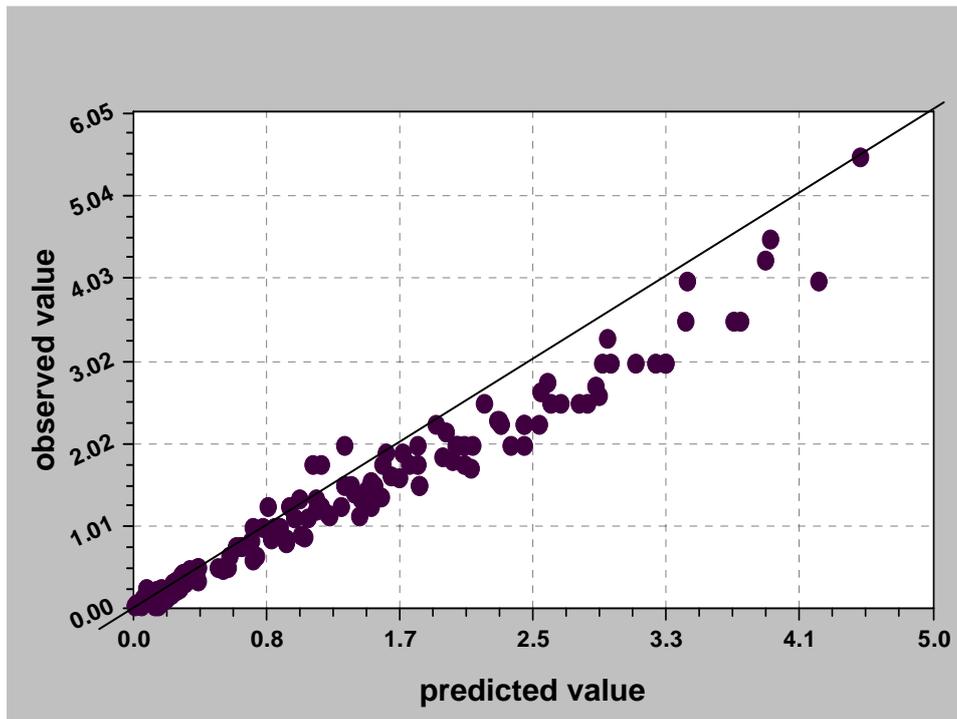


Fig.4.49, predicted versus observed values of pressure drop reducing for all parameters

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. The three types of polyisobutylene of different molecular weights investigated (B250, B200 and B150) were found to be effective drag reducing agent when used in turbulent gas oil pipelining.

For each polymer type, percentage drag reduction was found to increase by increasing the polymer concentration. This was due to the increase of turbulence spectrum that is under the drag reducer effect.

2. Percentage drag reduction, or percentage flow increase are found to increase progressively by increasing the solution velocity (represented by Reynolds number).

For all polymers investigated and at constant flow rate, high values of percentage drag reduction were obtained for smaller pipe diameters. That was due to the increase of turbulence which will provide better media to the additives investigated to be more effective.

3. Maximum %Dr of 18.7% was reported using 50ppm B250 polymer of highest molecular weight dissolved in gas oil flowing at a rate of 6.0 m³/h through 1.25 inch I.D pipe.

4. The highest molecular weight polyisobutylene B250 treated gas oil show the greatest degree of flow capacity increase, approaching the maximum drag-reduction asymptote of Virk.

5. Correlation equations were fitted to represent the experimental data using a computer program (statistica). These correlations show the pressure drop reducing (PDR) as a function of Reynolds number (Re), additive concentration (C), pipe diameter (D) and polymer molecular weight (M). The results showed good agreement between the observed and the predicted values of friction factor with high values of variance and correlation coefficients.

5.2 Recommendations

1. Further work can be carried out to prepare solutions of other types of drag-reducer, with difference molecular weights such as polyethylene oxide and polyacrylamide as water-soluble polymer and studying their drag-reducing effectiveness.
2. An extended study concerning the effect of temperature on the stability of different drag-reducers additives and there efficiency.
3. Performance of a full-scale tests of drag reducing additives in the field before selecting the final additive is an important step for an accurate simulation of the whole process of drag reduction.
4. Investigation the effect of mechanical stresses and time on the effectiveness of high molecular polymers as drag- reducer under turbulent flow.
5. Using advanced high technical equipment (Laser dipolar, thermal streak measurements) in the measurements of some macro-scale behavior of the fluid inside pipes, to have a clear and very close picture

about the real behavior of fluid masses, eddies and vortexes, which will make it possible to a closer idea about the real mechanism that controls the system.

6. Using advanced technique to measure some of the important properties of the drag reducing solutions such as the viscoelasticity and the extensional viscosity to have a better understanding of the phenomena.

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Appendices

Appendix (A) Pressure Drop Data for All Oppanol Types and Pipes Diameter

Table (A-1) Pressure Drop in mm Hg for Oppanol 250 in Pipe 1 Inch for 3m

Flow rate m ³ /hr	50 ppm	40 ppm	30 ppm	20 ppm	10 ppm	Pure
6	11	8	7	5	3	97
5.6	9	7	5.5	3.5	2.5	87
5.2	7.5	5.5	4.5	3	2	76
4.8	6	4.5	4	2.5	1.5	65.5
4.2	4.5	3.5	2.5	1.5	1	52
3.4	2.5	2	1.5	1	0.5	35
2.8	1.5	1	0.75	0.5	0.3	25

Table (A-2) Pressure Drop in mm Hg for Oppanol 200 in Pipe 1 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm	Pure
6	7.5	6.5	6	5	4	97
5.6	6.5	5.5	5	4.25	3.25	86
5.2	5.5	4.75	4.25	3.5	2.75	76
4.8	4.85	4.25	3.75	3	2.25	65.5
4.2	4	3.5	3	2.5	1.75	51.5
3.4	3.25	2.75	2.25	1.75	1.25	35
2.8	3	2.5	2	1.5	1	25

Table (A-3) Pressure Drop in mm Hg for Oppanol 150 in Pipe 1 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm	Pure
6	6	4.5	4	3.25	2.25	97
5.6	5	4	3.5	2.75	1.75	87.5
5.2	4	3.5	3	2.25	1.25	77
4.8	3.6	3	2.75	2	1	65
4.2	3	2.5	2.25	1.5	0.75	51.5
3.4	2.2	2	1.75	1	0.35	36
2.8	2	1.75	1.5	0.75	0.25	26

Table (A-4) Pressure Drop in mm Hg for Oppanol 250 in Pipe 1.25 Inch for 3m

Flow rate m ³ /hr	50 ppm	40 ppm	30 ppm	20 ppm	10 ppm	Pure
6	5.5	4.25	3	2	1.5	29.5
5.6	4.5	3.5	2.5	1.7	1.1	25
5.2	4	3	2.25	1.5	1	23
4.8	3.3	2.65	2	1.25	0.75	21
4.2	2.29	1.84	1.36	0.88	0.5	16
3.4	1.46	1.12	0.85	0.5	0.25	12
2.8	0.81	0.65	0.49	0.24	0.14	9

Table (A-5) Pressure Drop in mm Hg for Oppanol 200 in Pipe 1.25 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm	Pure
6	4	3.5	3	2.5	2	29.5
5.6	3.5	3	2.5	2	1.75	26
5.2	3	2.6	2.25	1.75	1.5	24.5
4.8	2.7	2.25	2	1.5	1.25	21
4.2	2.3	1.8	1.6	1.12	1	18
3.4	1.9	1.4	1.2	0.85	0.65	13
2.8	1.75	1.25	1	0.75	0.5	10

Table (A-6) Pressure Drop in mm Hg for Oppanol 150 in Pipe 1.25 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm	Pure
6	3	2.75	2.5	2.25	2	29
5.6	2.5	2.25	2.15	1.9	1.75	26
5.2	2.25	2	1.75	1.55	1.35	23
4.8	2	1.75	1.5	1.25	1	20.5
4.2	1.62	1.35	1.15	0.9	0.825	17
3.4	1.35	1.1	0.85	0.6	0.5	14
2.8	1.25	1	0.75	0.5	0.35	10

Table (A-7) Pressure Drop in mm Hg for Oppanol 250 in Pipe 2 Inch for 3m

Flow rate m ³ /hr	50 ppm	40 ppm	30 ppm	20 ppm	10 ppm	Pure
6	0.4911	0.399	0.3069	0.2455	0.1227	3.9845
5.6	0.4297	0.3376	0.2455	0.2148	0.092	3.5554
5.2	0.3376	0.2762	0.2148	0.1534	0.0613	3.1263
4.8	0.2455	0.2148	0.1534	0.1227	0.0613	2.6359
4.2	0.1841	0.1534	0.1227	0.092	0.0306	2.2681
3.4	0.1534	0.1227	0.092	0.046	0.0153	1.5325
2.8	0.4911	0.399	0.3069	0.2455	0.1227	3.9845

Table (A-8) Pressure Drop in mm Hg for Oppanol 200 in Pipe 2 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm	Pure
6	0.4297	0.3683	0.3069	0.2455	0.1995	3.9232
5.6	0.3683	0.3069	0.2609	0.2148	0.1688	3.4941
5.2	0.3069	0.2609	0.2148	0.1841	0.1534	3.0037
4.8	0.2609	0.2302	0.1841	0.1627	0.135	2.6359
4.2	0.2148	0.1934	0.1565	0.1381	0.1166	2.3907
3.4	0.1841	0.1688	0.1534	0.1227	0.1074	1.5325
2.8	0.4297	0.3683	0.3069	0.2455	0.1995	3.9232

Table (A-9) Pressure Drop in mm Hg for Oppanol 150 in Pipe 2 Inch for 3m

Flow rate m³/hr	70 ppm	55 ppm	40 ppm	30 ppm	15 ppm	Pure
6	0.3683	0.3069	0.2455	0.1841	0.1534	3.9232
5.6	0.3069	0.2455	0.1995	0.1534	0.1227	3.5554
5.2	0.2762	0.2148	0.1688	0.1227	0.092	3.065
4.8	0.2302	0.1749	0.1442	0.1013	0.0706	2.6972
4.2	0.1841	0.1381	0.1135	0.0767	0.046	2.23745
3.4	0.1534	0.1227	0.092	0.0613	0.0306	1.5325

Appendix (B) Drag Reduction Data for All Oppanol Types and Pipes Diameter

Table (B-1) Percentage Drag Reduction for Oppanol 250 in Pipe 1 Inch for 3m

Flow rate m ³ /hr	50 ppm	40 ppm	30 ppm	20 ppm	10 ppm
6	11.3	8.3	6.7	4.6	3.1
5.6	10.3	8	6.3	4	2.8
5.2	9.9	7.2	5.9	4.1	2.6
4.8	9.2	6.9	6.1	3.7	2.3
4.2	8.6	6.7	4.8	2.9	1.9
3.4	7.1	5.7	4.3	2.9	1.5
2.8	6	4	3	2.1	1.2

Table (B-2) Percentage Drag Reduction for Oppanol 200 in Pipe 1 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm
6	7.732	6.701	6.1856	5.1546	4.1237
5.6	7.5581	6.3953	5.814	4.9419	3.7791
5.2	7.2368	6.25	5.5921	4.6053	3.6184
4.8	6.9822	5.9655	5.26213	4.35752	3.32304
4.2	6.5218	5.56309	4.8098	3.95	2.93073
3.4	5.8286	4.97735	4.2054	3.4066	2.40202
2.8	5.25	4.5	3.75	3	2

Table (B-3) Percentage Drag Reduction for Oppanol 150 in Pipe 1 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm
6	11.3	8.3	6.7	4.6	3.1
5.6	10.3	8	6.3	4	2.8
5.2	9.9	7.2	5.9	4.1	2.6
4.8	9.2	6.9	6.1	3.7	2.3
4.2	8.6	6.7	4.8	2.9	1.9
3.4	7.1	5.7	4.3	2.9	1.5
2.8	6	4	3	2.1	1.2

Table (B-4) Percentage Drag Reduction for Oppanol 250 in Pipe 1.25 Inch for 3m

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

Table (B-5) Percentage Drag Reduction for Oppanol 200 in Pipe 1.25 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm
6	13.559	11.864	10.169	8.4746	6.7797
5.6	13.462	11.538	9.6154	7.6923	6.7308
5.2	12.245	10.612	9.1837	7.1429	6.1224
4.8	12.078	10.514	9.0238	7.1429	5.9524
4.2	11.8234	10	8.8889	6.2222	5.5556

Table (B-6) Percentage Drag Reduction for Oppanol 150 in Pipe 1.25 Inch for 3m

Flow rate m³/hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm
6	10.345	9.4828	8.6207	7.7586	6.8966
5.6	9.6154	8.6538	8.2692	7.3077	6.7308
5.2	9.5826	8.6057	7.6087	6.7391	5.8696
4.8	9.3561	8.5366	7.3171	6.0976	4.878
4.2	9.1294	7.9412	6.7647	5.2941	4.8529
3.4	9.0429	7.8571	6.0714	4.2857	3.5714

Table (B-7) Percentage Drag Reduction for Oppanol 250 in Pipe 2 Inch for 3m

Flow rate m³/hr	50 ppm	40 ppm	30 ppm	20 ppm	10 ppm
6	12.3	10	7.7	6.2	3.1
5.6	12	9.5	6.9	6	2.6
5.2	10.8	8.8	6.9	4.9	2
4.8	9.3	8.1	5.8	4.7	2.3
4.2	8.1	6.8	5.4	4.1	1.4
3.4	7.1	5.7	4.3	4.3	1.4

Table (B-8) Percentage Drag Reduction for Oppanol 200 in Pipe 2 Inch for 3m

Flow rate m³/hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm
6	10.938	9.375	7.8215	6.25	5.0781
5.6	10.526	8.7719	7.4561	6.1404	4.8246
5.2	10.204	8.6735	7.1429	6.0628	4.602
4.8	9.8837	8.3209	6.9767	5.9058	4.4163
4.2	8.9744	8.0769	6.5385	5.7692	4.2156

Table (B-9) Percentage Drag Reduction for Oppanol 150 in Pipe 2 Inch for 3m

Flow rate m³/hr	70 ppm	55 ppm	40 ppm	30 ppm	15 ppm
6	9.375	7.8125	6.25	4.6875	3.9063
5.6	8.6207	6.8966	5.6034	4.3103	3.4483
5.2	7.4216	6.6152	5.5	4	3
4.8	8.5227	6.4773	5.3409	3.75	2.6136
4.2	8.2192	6.1644	5.0685	3.4247	2.0548

Appendix (C) Throughput Increase Data for All Oppanol Types and Pipes Diameter

Table (C-1) Percentage throughput increase for Oppanol 250 in Pipe 1 Inch for 3m

Flow rate m ³ /hr	50 ppm	40 ppm	30 ppm	20 ppm	10 ppm
6	6.553388	4.881011	3.887931	2.623871	1.747073
5.6	6.160794	4.692771	3.643776	2.270604	1.574234
5.2	5.901318	4.195416	3.401231	2.329244	1.459466
4.8	5.451505	4.010618	3.522303	2.095251	1.287999
4.2	5.070208	3.887931	2.742393	1.631755	1.06064
3.4	4.133714	3.280556	2.446809	1.631755	0.834715
2.8	3.461717	2.270604	1.689368	1.17414	0.666201

Table (C-2) Percentage throughput increase for Oppanol 200 in Pipe 1 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm
6	4.525413	3.888543	3.574244	2.953485	2.343156
5.6	4.41722	3.701799	3.349292	2.826719	2.141404
5.2	4.218148	3.61337	3.215617	2.627007	2.047702
4.8	4.061161	3.440838	3.017738	2.480691	1.876111
4.2	3.77896	3.198177	2.748211	2.24132	1.649432
3.4	3.358104	2.847786	2.391153	1.924573	1.346217
2.8	3.010484	2.564755	2.124418	1.689368	1.117345

Table (C-3) Percentage throughput increase for Oppanol 150 in Pipe 1 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm
6	3.574244	2.647071	2.343156	1.89203	1.299176
5.6	3.289171	2.606954	2.270604	1.771856	1.117345
5.2	2.977493	2.591641	2.209778	1.704881	0.904261
4.8	2.759195	2.506501	2.121967	1.61282	0.856398
4.2	2.488518	2.338577	1.976668	1.470354	0.810118
3.4	2.270604	2.011382	1.746004	1.272265	0.538772
2.8	2.124418	1.689368	1.545508	1.117345	0.052922

Table (C-4) Percentage throughput increase for Oppanol 250 in Pipe 1.25 Inch for 3m

Flow rate m ³ /hr	50 ppm	40 ppm	30 ppm	20 ppm	10 ppm
6	12.05989	8.998027	6.291205	4.133714	2.801799
5.6	11.53274	8.64903	6.030832	3.949223	2.505734
5.2	11.01252	8.303163	5.772249	3.765651	2.270604
4.8	9.848678	7.688347	5.451505	3.461717	2.036988
4.2	8.858049	6.950102	5.007036	3.160278	1.747073
3.4	7.418236	5.515435	4.133714	2.387979	1.17414
2.8	5.323973	4.195416	3.160278	1.516804	0.891063

Table (C-5) Percentage throughput increase for Oppanol 200 in Pipe 1.25 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm
6	8.343814	7.192812	6.075618	4.991007	3.936773
5.6	8.277004	6.975367	5.717786	4.500685	3.906798
5.2	7.448528	6.364433	5.441095	4.160171	3.535888
4.8	7.448528	6.147127	5.328302	4.160171	3.432913
4.2	7.329517	5.966019	5.253317	3.596475	3.193676

Table (C-6) Percentage throughput increase for Oppanol 150 in Pipe 1.25 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm
6	6.190097	5.63258	5.083298	4.54199	4.008529
5.6	5.846667	5.104239	4.861641	4.261985	3.906798
5.2	5.825501	5.073812	4.448668	3.911884	3.382862
4.8	5.808408	5.030144	4.2678	3.520848	2.788722
4.2	5.662502	4.655987	3.927575	3.036864	2.773807
3.4	5.60698	4.60344	3.504965	2.43839	2.020342

Table (C-7) Percentage throughput increase for Oppanol 250 in Pipe 2 Inch for 3m

Flow rate m ³ /hr	50 ppm	40 ppm	30 ppm	20 ppm	10 ppm
6	7.485585	5.966019	4.50548	3.582989	1.747073
5.6	7.283894	5.643622	4.010618	3.461717	1.459466
5.2	6.487671	5.196875	4.010618	2.801799	1.117345
4.8	5.515435	4.755412	3.340844	2.683084	1.287999
4.2	4.755412	3.949223	3.100287	2.329244	0.778455
3.4	4.133714	3.280556	2.446809	2.446809	0.778455

Table (C-8) Percentage throughput increase for Oppanol 200 in Pipe 2 Inch for 3m

Flow rate m ³ /hr	70 ppm	50 ppm	40 ppm	30 ppm	15 ppm
6	6.57839	5.563453	4.575603	3.61337	2.907841
5.6	6.308192	5.179052	4.353906	3.546808	2.756998
5.2	6.098356	5.116708	4.160171	3.535888	2.922095
4.8	5.890782	5.146727	4.057777	3.560402	2.930626
4.2	5.307681	4.740932	3.789158	3.322265	2.785037

Table (C-9) Percentage throughput increase for Oppanol 150 in Pipe 2 Inch for 3m

Flow rate m³/hr	70 ppm	55 ppm	40 ppm	30 ppm	15 ppm
6	5.563453	4.575603	3.61337	2.675677	2.215745
5.6	5.083298	4.008529	3.222413	2.452874	1.948782
5.2	5.323973	4.072114	3.160278	2.270604	1.689368
4.8	5.021366	3.751798	3.064879	2.124418	1.467259
4.2	4.830218	3.561373	2.902117	1.935079	1.148457

الخلاصة

تم دراسة تقليل الاعاقة الاضطرابي في منظومة جريان مغلقة لزيت الغاز بوجود ثلاث اوزان جزيئية مختلفة من البولي ايزوبيوتيلين. تم الحصول على الجريان الاضطرابي بواسطة مضخة الازاحة الموجية لتجنب الانحلال الميكانيكي لسلاسل البوليمرية. البوليمرات المستخدمة على شكل محاليل في الريفورميت و تمثل مديات مختلفة للوزن الجزيئي، هي $1.0^6 * 2,9$ ، $1.0^6 * 4,1$ و $1.0^6 * 5,9$ غرام/الوزن الجزيئي، بهدف دراسة تأثير الوزن الجزيئي على تقليل الاعاقة و زيادة طاقة الضخ في انليبب نقل زيت الغاز.

تم اختبار تأثير تركيز البوليمرات المضافة بحدود تصل الى ٧٠ جزء بالمليون وزنا، علاوة على سرعة الجريان المتمثلة بعدد رينولدز بحدود ٨٣٤١ الى ١٧٨٧٤ في انابيب جريان بأقطار ١، ٢،٥ و ٢،٥ أنج. يحص زيادة مستمرة في تقليل الاعاقة بزيادة تركيز البوليمر المضاف، و سرعة الجريان زيت الغاز و انخفاض قطر الانبوب.

تم حساب معامل الاحتكاك من نتائج العملية لتقليل الاعاقة. تقع قيم معامل الاحتكاك لزيت الغاز الغير معامل باتجاه محاذي بلاسيوس. بينما تتجه قيم معامل الاحتكاك نحو محاذي فيرك عند أضافة بوليمرات لتقليل الاعاقة، خاصة للنوع ذي الوزن الجزيئي الاعلى. النتائج العملية تشير بوضوح الى تأثير الوزن الجزيئي العالي على فعالية تقليل الاعاقة.

تم اقتراح معادلات تخمينية لتقدير تأثير معاملات منظومة الجريان، و هي التركيز، سرعة الجريان، قطر الانبوب، و اخيرا الوزن الجزيئي على انخفاض تقليل هبوط الضغط. نتائج المعادلات تؤشر الى توافق كبير بين قيم هبوط الضغط المستحصلة عمليا و المحسوبة من المعادلات التخمينية بنسبة اعلى من ٩٩،٥.

شكر و تقدير

الحمد والشكر لله أولاً على فضله و كرمه في انجاز هذا البحث و جزيل
الشكر و التقدير و الامتنان لاستاذي الفاضل الدكتور جابر شنشول جمالي
على متابعته المستمرة و توجيهاته القيمة و تشجيعي أثناء فترة البحث.

و أود التقدم بالشكر الى السيد رئيس القسم المحترم و كافة منتسبي القسم
ممن كان له الفضل في اتمام هذا البحث.

واشكر عائلتي على ماقدمته لي من دعم و اسناد غير محدود خلال البحث.

واخيرا اشكر زملائي و زميلاتي و أصحابي الاعزاء على دعمهم و
تشجيعهم و كل من كان له الفضل علي في اتمام هذا البحث و الحمد لله
اولا و اخيراً.

تأثير الوزن الجزيئي على تقليل الاعاقة الاضطرابي بواسطة اضافات بوليمر الايزو بيوتيلين

رسالة

مقدمة إلى كلية الهندسة في جامعة النهريين
و هي جزء من متطلبات نيل درجة ماجستير علوم
في الهندسة الكيماوية

من قبل

حيدر موفق توفيق ال قماجي

بكالوريوس علوم في الهندسة الكيماوية

٢٠٠٣

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شوال

تشرين الثاني