STUDIES ON DRAG REDUCTION IN PIPE FLOW OF HEAVY OIL BY USING POLYMER ADDITIVES

A thesis submitted in partial fulfillment of the requirements
for the award of the degree of

DOCTOR OF PHILOSOPHY

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THESIS CERTIFICATE

This is to certify that the thesis entitled **Studies on drag reduction in pipe flow of heavy oil by using polymer additives** submitted by **Mr. Kamaljit Singh,** in the partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in the Department of Chemical Engineering, **Thapar Institute of Engineering and Technology, Patiala, Punjab, INDIA** is a bonafide record of research work carried out by him under my supervision and guidance. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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DECLARATION

I, Kamaljit Singh, hereby declare that the thesis entitled **Studies on drag reduction in pipe flow of heavy oil by using polymer additives** submitted to **Thapar Institute of Engineering and Technology, Patiala (INDIA)** in the partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in the Department of Chemical Engineering is record of original and independent research work done by me during the period 2014-2019, under the supervision and guidance of Dr. D. Gangacharyulu, Professor, Department of Chemical Engineering, Thapar Institute of Engineering and Technology, Patiala.

The research work of the thesis has not been submitted to meet the requirements for any degree or diploma at this or any higher education institute.

22/05/19

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ABSTRACT

Some authors have observed that when a minute amount of high molecular weight polymer injected in the pipe flow, a significant amount of drag has been decreased. This phenomenon is known as drag reduction phenomenon. Although, the drag reduction by using polymer additives is quite effective still the design of the experimental set-ups and injection system is more complex.

In this study, instead of using synthetic polymers, biopolymers like guar gum and gum Arabic were investigated in the one-phase and two-phase flows. Although some authors were able to produce the drag reduction percentage almost 80% with synthetic polymers using premixed solution. In this study, the biopolymers were tested in the turbulent flow and heterogeneous injection of the polymers was used. With heterogeneous injections using biopolymer additives almost 70% drag reduction was observed. Moreover, guar gum and gum arabic are easily available and quite cost effect than synthetic polymers. These both biopolymers are environment friendly because of non-toxic in nature and easily bio-degradable. The other favorable properties of guar gum and gum arabic are gel and film forming ability, higher viscosity and high ability for chemical modification and cross linking.

In the earlier experimentation, the experimental set-up was designed for the injection of the polymer solutions near the boundary layer. By performing some pilot experiments three polymers were selected. One was oil-soluble polymer known as polydimethylsiloxane and the other two polymers were water-soluble polymers i.e. guar gum and gum Arabic. Guar gum is easily soluble in water to produce highly viscous solution, while on the other side gum arabic is also readily soluble in water but do not form too viscous solution like guar gum. However, if allow hydration overnight, the solubility is enhanced. Rheological characterization of the selected polymers was done. The effect of the polymer concentration and the shear rate on viscosity was observed. It was observed that with the addition of the polymers there was an increase in the viscosity of the solvent. The increase in the viscosity of the solution was more rapid in the case of guar gum as compared to gum Arabic and polydimethylsiloxane. Even at the low concentration guar gum was able to increase the viscosity of the solvent 500 times with 3000 ppm of the concentration.

The effect of the shear rate was observed on the viscosity of the polymer solutions. It was found that with an increase in rate there was a decrease in the viscosity of the guar gum and gum arabic solutions. For guar gum, the behavior of the solution for all the concentrations was shear thinning behavior. For gum arabic, the behavior of the solution for higher concentrations was found to be shear thinning, but for lower concentrations, there was Newtonian behavior was observed. For the polydimethylsiloxane, the Newtonian behavior was observed in case of all the concentrations. In rheological characterization, the effect of the temperature was observed from 25 ^{o}C to 45 ^{o}C on polymer solution viscosity and density. It was found that with an increase in the temperature, the viscosity of the solution decreases and the same was observed in the case of density for selected polymers. The density of the water was not affected by the addition of the polymer concentration but increased with the addition of the KCl salt concentration. For polydimethylsiloxane, there was an increase in the viscosity of the polymer solution with an increase in concentration and the density of the solution decrease considerably with increase in temperature.

After rheological characterization, the selected polymers were tested in the one-phase flow. The effect of the Reynolds number and concentration of the polymer was investigated on drag reduction percentage. It was observed that the 71.4% drag reduction was observed with guar gum solution and 62.1% maximum drag reduction was observed with gum Arabic solution. The degradation of the polymer solutions was studied under the high shear conditions and the effect was continuously observed with a number of passes in a closed system. The shear stability of both water-soluble polymers was improved with the addition of the KCl salt and optimum concentration was selected. Then polydimethylsiloxane, an oil-soluble polymer was tested in the turbulent condition to investigate the effect of the concentration on the drag reduction percentage. The maximum drag reduction with the oil-soluble polymer was observed to be 23.9%. since the viscosity of the oil was high so it was not easy to maintain the high Reynolds number. Also, the effect of the slot injection was studied with and without perforated end. It was found that the perforated end was able to produce more drag reduction effect than the injection end without perforation.

The selected polymers were also tested in the two-phase flow system. Since the water-soluble polymer was quite effective in one phase flow then a further study has been done by using similar water-soluble polymers in two-phase flow systems. Water and oil flow simultaneously in the pipe and the water-soluble polymer was injected in the water flow. The mixing of the water and oil was done by using’ the Y’ junction at the entrance. Both the polymers also produced a positive effect in the two-phase flow system. The effect of the polymer concentration, mixture velocity and oil fraction on the drag reduction was observed. The effect of the polymer was maximum at 0.1 oil fraction, and then considerable drag reduction effect was observed up to 0.3, thereafter, a decrease in the drag reduction percentage was observed up to 0.5 fraction. The minimum drag reduction effect was observed at 0.7 fraction of oil which eliminates with further increase in the fractions of oil. Simultaneously, the study of the flow patterns was also observed in two-phase flow systems and the effect of the polymer concentration on the flow patterns was recorded in the form of photographs. It was found that there was an increase in the stratification of the flow with the addition of the polymer in the water/oil flow systems.

A problem was found with the master polymer solutions, that there was a decrease in the effectiveness of the polymers after 3 number of days. So, the stability study was done to maximize the stability and to observed the effect of the polymer concentration on the stability of the master solution. The polymers were added in the different concentration and the stability was checked with number of days. It was found that the guar gum solution was more stable than the gum arabic solution. If the guar gum solution can be changed to a hydrogel, the solution can be stable up to 15 days with negligible degradation.

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NOMENCLATURE

Symbol	Description	Unit
D_h	Hydraulic diameter	mm
L	Length of pipe	mm
Δp	Pressure drop	Pa
τ_w	Wall shear stress	Pa
f	Friction factor	Dimensionless
ρ	Density	(kg/m^3)
μ	Dynamic viscosity	Pa.s
v	Mean velocity	m/s
Re	Reynolds number	Dimensionless
f_s	Friction factor of solvent	Dimensionless
f_p	Friction factor with polymer	Dimensionless
Mw	Molecular weight	g/mol
U_m	Velocity of mixture	m/s
Q_T	Total volumetric flow rate	L/h
Q_W	Volumetric flow rate of water	L/h
Q_o	Volumetric flow rate of oil	L/h
Φ_o	Fraction of oil	
Φ_w	Fraction of water	
H_o	Height of oil layer	mm
H_T	Height of total emulsion	mm
t	Temperature	^{0}C

Notation	Description
ppm	Parts per million
cP	centipoise
Pa.s	Pascal second
1/s	Shear rate

Abbreviation	**Description**
GG	Guar gum
GA	Gum arabic
PDMS	Polydimethylsiloxane
XG	Xanthan gum
MDRA	Maximum drag reduction asymptote
DRA	Drag reduction additive
DR	Drag reduction
PEO	Polyethylene oxide
PAAM	Polyacrylamide
KCl	Potassium chloride
N_p	Number of passes
ST	Stratified flow
DC	Dual continuous flow
Dw/o	Dispersed water in oil
Do/w	Dispersed oil in water

CHAPTER-1

INTRODUCTION

Fluid flow through the pipelines is very common these days in many industries like petrochemical, food processing, district heating/cooling, agriculture, textile and oil well drilling, etc. Flow through the pipes and conduits can be classified into three types namely laminar, transition, and turbulent flows. In the laminar flow, the velocity at the center of the pipe is maximum and almost negligible at the internal surface of the pipe or almost assumed to be zero. Laminar flow is also known as the streamline flow. The transition flow is the flow beyond the laminar zone in which some disturbance in the relative layers of the flowing fluid can be observed. Some authors and books assumed it as the start of the turbulence in the flow. Turbulent flow is the flow with full of randomness in which the particular behavior of the fluid motion cannot be easily understand.

In present days most of the industries are working in the turbulent flow regime to meet the flow rate requirements. In industries like chemical, petroleum and food processing industries, the Reynolds number of the fluids are quite high [1]. Due to the high Reynolds number, a significant amount of energy has been lost in the form of the pressure drop. Pressure drop leads to a decrease in the flow rate and in turn, more pumping power input is required to obtain the desired flow rate.

1.1 Drag

When a fluid flow in a closed channel or pipe, a friction force experienced near the surface of the pipe or channel. This is due to the viscosity of the fluid and in order to maintain the constant flow rate power is applied in the form of pumping by some external means. After analysing the force balance of passage fluid, the relationship between the shear stress and the pressure difference can be derived [2]. The wall shear stress is defined as

$$\tau_w = \frac{D}{4L} \times \Delta p \qquad (1.1)$$

Where ‘D’ is the hydraulic diameter (mm) of the flow passage, ‘L’ is the specified distance (mm) and $'\Delta p'$ is the pressure difference across the length L. The above equation applies for both pipe and channel flow [1]. When the higher flow rate is needed, fluid deformation is higher and shear stresses increase, Therefore more pressure must be applied to maintain the flow at the same average velocity [3].

After measuring the shear stress of the flow, the frictional resistance coefficient of the wall flow can be calculated. The Fanning friction factor is often used and defined as follows:

$$f = \frac{\tau_w}{\frac{1}{2}\rho v^2} \tag{1.2}$$

Where ‘v’ is the mean velocity (m/s) in the pipe, ′ρ′ is the fluid density [4]. The formulae used to evaluate the friction factor in laminar and turbulent flow are given by equations (1.3) and (1.4), respectively.

$$f = 16/\mathrm{Re} \tag{1.3}$$

$$\frac{1}{\sqrt{f}} = 4\log_{10}\left(\mathrm{Re}\sqrt{f}\right) - 0.4 \tag{1.4}$$

The Reynolds number (Re) and friction factor (*f*) were calculated based on the properties of the bulk solution and the flow rate of the bulk solution was adjusted accordingly to maintain a constant Reynolds number during the experiments. Equation (1.5) gives the expression for Virk’s MDRA (maximum drag reduction asymptote) at which friction factor approaches to an asymptotic value.

$$\frac{1}{\sqrt{f}} = 19.0\log_{10}\left(\mathrm{Re}\sqrt{f}\right) - 32.4 \tag{1.5}$$

The percentage of drag reduction can be calculated by measuring the corresponding pressure drop and friction factor ‘*f*’ using equation (1.6).

$$\text{Drag reduction, DR (\%)} = \left[\frac{f_s - f_p}{f_s}\right]_{\mathrm{Re}=const} \times 100 \tag{1.6}$$

where ‘ f_s ’ is the friction factor for solvent (water) and ‘ f_p ’ is the friction factor observed after injection of polymer solution [5].

1.2 Phenomenon of drag reduction

Toms (1948) discovered that if a small number of long-chain polymer molecules are added in the turbulent flow in a pipe, then it could reduce the pressure losses in the turbulent flow and reported that minute amounts (5-10 ppm by weight) of polymers could have a dramatic effect on drag reduction of water. In other words, the drag reducing effect became a promising candidate for a partial solution to the problem of energy savings [6]. When drag reduction additives are dissolved in fluid, the polymer molecules start uncoil when interact with turbulent eddies as shown in Figure 1.1. The interaction is quite complex because the polymer molecules near the pipe wall acts as a buffer to dampen the continuous formation of eddies. This suppression effect reduces the loss of pressure which leads the decrease in energy consumption or an increasing flow [1].

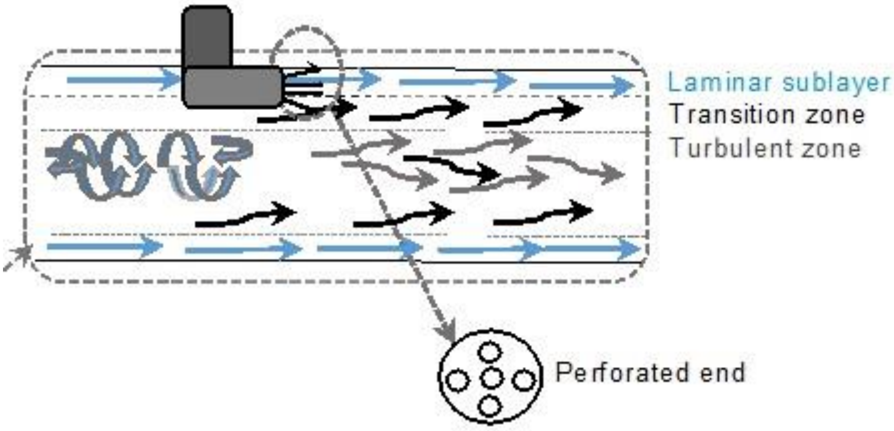


Figure 1.1: The possible effect of the drag reduction additives in a turbulent flow.

Some of the suggested theories by some authors are like Lumely theory [7], who described the phenomenon as 'Molecular Extension'. He proposed that randomly coiled polymer chains stretched due to high shear rate of strong turbulence, outside the viscous sub layer. Due to this effective viscosity increases in the turbulent regime, but the viscosity in the viscous sublayer remains less. This high viscosity increases the thickness of the viscous sublayer and thus reduces the drag. Another theory was proposed by Hinch [8], who studied the extended state of the randomly coiled macro-molecules. In 'Elastic ellipsoidal model', he interpreted the dependence of polymer chain stretching due to strong turbulence on the distortion. With increase in distortions the frictional intensity of the flow increases. Large distortions in the strong flows grow until they are limited by finite extensibility of the polymer chains. He considered the effect of hydro-dynamic stretching and inextensibility of flexible polymer threads. A two scale model was implemented by Landahl [9] to understand the mechanism of drag reduction. This model was proposed to study the effect of local turbulence on large scale. This small-scale motion is produced by the secondary inflectional instabilities, which is considered as the driving mechanism for the large scale with generation of local Reynolds stresses.

1.3 Applications of drag reduction

As the development of the phenomenon of the drag reduction and continuous improvement in the effectiveness of the drag reduction additives by researchers over the year, areas of the applications of the drag reduction also widening day by day. The most commercial application of the drag reducing additives is in the Trans-Alaska pipeline system, where initially the drag reducing set-up was installed temporary due to delay in the pumping power stations. But, after comparing the effect and the cost of the drag reducing additives were compared with the pumping power, the idea of the installation of the pumping stations was dropped and the desired flow was obtained by using drag reducing additive. With further development in the area of the long chain polymers it was found that with higher molecular weight polymer, even 10 ppm of the injection of the polymer in the boundary layer of the pipe flow was able to produce 25% drag reduction in heavy oil flow. After this commercialization of the polymer [10], drag reducing additives were used by many other countries in the oil pipeline system to maintain the flow rate and reduce the pressure drop. The most of the additives used so far as drag reduction additives were soluble in oil or water instead of using any nano-particles, which can be extracted easily or during refining. Moreover, the amount used of additives was in ppm which was quite less and have no effect observed on the properties of procured oil.

Drag reducing additives are also used in every airport of the world for filling of the fuel in the planes for a reduction in time. If drag reducing additives are not used to fuel up the tank of the planes, it will take almost twice of the present time taken. A natural example of drag reduction is the blood flow in human veins. Despite these applications, drag reducing additives are also used in good drilling, firefighting, hydro-transport, and marines, etc. In cold areas of many countries drag reducing additives are used in district heating and cooling purpose to maintain the temperature in the hot water flow [2]. In India, the drag reducing additives are used in many areas in the sewer flow. Because of the increase in the population, the flow in the sewer is also increased with years. So, there is a need to increase the network of the sewer pipe and their diameters. But it is not possible to dig all the municipal sewer system in one day and replace with the larger ones, so until the time of the replacement the old one sewer systems are using drag reducing additives to increase the flow rate as a temporary solution [11].

1.4 Summary

Energy consumption in the pipe in the form of pumping power is a problem from decades. This problem becomes more severe when the viscosity of the fluid is more. To overcome this problem a few years back researchers found an effective way to reduce the pressure drop in flow fluid. It was found that some drag reduction additives can lead to a decrease in the pressure drop significantly and can maintain the flow rate without aiding any external force. This observation produced a new innovation in the flowing fluid which is nowadays known as drag reduction. In this chapter the basic phenomenon of the drag reduction was discussed and the application of this phenomenon in various fields.

The thesis is organized in the following chapters.

Chapter - 1 includes the introduction of the drag and the drag reduction phenomenon. Some fundamentals and the applications of the drag reduction in the various fields were discussed.

Chapter - 2 covers the detailed literature review in the field of drag reduction. The effect of the various parameters like molecular weight, Reynolds number and concentration were discussed. The research outcomes of the various research publications were discussed.

Chapter - 3 include the rheological characterization of the selected polymers. the effect of the polymer concentration on the viscosity was studied. The effect of the shear rate on the behaviour of the viscosity of the solution was discussed. The effect of the temperature, salt concentration on the viscosity as well as density was discussed.

Chapter - 4 includes the drag reduction phenomenon in the single-phase flow. Two biopolymers guar gum and gum arabic and one oil-soluble polymer polydimethylsiloxane were selected. the effect of the polymer concentration and the Reynolds number was investigated. The effect of the injection position on the drag reduction percentage was discussed.

Chapter - 5 includes the drag reduction phenomenon the two-phase flow systems. The water and oil flow simultaneously in the pipe and the effect of the concentration of the polymer and the mixture velocity as well as fraction of the oil was investigated on the maximum drag reduction percentage. The effect of the polymer addition on the flow patterns was also investigated.

Chapter - 6 includes the study of stability and aging of the polymer solution with a number of days. Effect of the concentration of the polymer on stability or aging of the polymer solution and morphology were discussed. The effect of the polymer concentration on the droplet diameter and effect of aging on the drag reduction was also discussed.

Chapter - 7 covers the conclusions of the results derived from the various results outcome in the chapters of this thesis and the future scope of the work.

CHAPTER -2

LITERATURE REVIEW

In today’s industrial revolution the turbulent flow is very common in all the industries like petrochemical, food, heating and cooling devices, sewer systems, etc. in all these industries turbulent flow is the primary requirement to meet the daily output. But as there is continuous increase in the turbulent flow in a closed pipe or duct, a considerable amount of energy lost in the form of pressure drop. to overcome the loss of the energy, pumping power applied to maintain the desired flow rate. Increase in pumping power to maintain the desired flow rate is not a favorable method every time, because, it involved a significant running cost as well as installation cost. A few decades ago, some researchers observe that when a small amount of polymer with the high molecular weight used in transport media like water, there was a considerable amount of decrease in pressure drop. Later, a series of experimentation has been started by different authors to prove the phenomenon. This phenomenon was later known as “drag reduction’. It was observed that instead of using pumping aid, when drag reduction additives were added in the turbulent flow, there was an increase in flow rate.

Drag reduction is a boundary layer phenomenon. As we know that when the flow in the closed conduit and pipes is laminar, the maximum velocity is at the center of the pipe and negligible at the internal pipe surface. In the case of turbulent flow, randomness in the fluid is quite high due to the continuous formation of the eddies from the turbulent core. Generally, this was considered that there are “eddies in the eddies in the eddies” in a turbulent flow. Continuous formation of these eddies leads to loss of energy of the fluid in the form of pressure drop. Drag reduction additives suppressed the eddies. Up to the present year, hundreds of research articles published in the area of the drag reduction, where the authors used a number of different polymers or other additives for drag reduction. Drag reduction additives are generally divided into three categories:

a) Drag reduction by using fibers,
b) Drag reduction by surfactants, and
c) Drag reduction by polymers

2.1 Drag reduction by using fibers

Drag reduction by using fibers was firstly observed by Toms (1948), when he was working in the wood pulp fibers [12]. During his work, he noticed that when the wood fibers were present in the flow there was an increase in the flow velocity of the water. After that, some authors used this additive to develop this phenomenon more widely. It was supposed that the mechanism behind the drag reducing using fibers is an extensional mechanism in the inter-vortex region. Fibers get aligned in the y-z direction and generate large normal and shear stresses [12–15]. These stresses create a force opposite to the Newtonian accelerations in the direction of wall stresses and spanwise, which weakens the near wall vortex and leads to reduce the drag. It was found that the significant effect of the concentration and aspect ratio on drag reduction effectiveness and the negative effect of the elasticity of the fibers. Reduction in the aspect ratio modifies the dynamic behavior of the fibers and fiber extra stress. But a decrease in the aspect ratio increases the viscosity and negative effect on drag reduction effectiveness. Work of some authors is shown in the Table 2.1. Nylon, Rayon, glass fiber and cotton fibers are investigated in turbulent flow by different authors. Flow with suspended fibers is very common in many industries like paper and pulp flow. Mostly three types of flow regimes were observed during the fiber flow like plug flow, mixed flow, and turbulent flow. When the velocity of the flowing liquid was less there was no relative velocity of the fibers in between so the fibers move forward in the core of the pipe and known as plug flow. This plug was surrounded by the water near the pipe wall. But when the velocity of the flow increased, mixed flow observed and with more velocity turbulent flow was observed [16]. Still, there are some problems associated with the flow of fibers in pipe s and converging section such as,

a) Fiber flocculation,
b) Flow regime, and
c) Velocity profiles,

Table 2.1: Work done by various authors using a different type of fibers

Sr. No.	Author(s)	Outcome	Type of fiber used	Base fluid	Drag reduction (%)
1.	Vaseleski and Metzner [13]	1. Observed the change in the velocity profile and loss of pressure in turbulent flow with fiber suspensions, different size of tubes, concentrations of fiber, and geometries. 2. It was observed that turbulent core region was involved during the drag reduction using fiber suspensions, which is not in the case of polymer. 3. Drag reduction is independent of the scale system	Nylon fiber	water	15% at 100 ppm 17% at 800 ppm 8% at 10,000 ppm
2.	Andric et al. [14]	Studied the influence of straight and curved shapes of fibers on the behavior of fiber suspension in turbulent flow.	Straight, curved and rigid fibers	Water	N.A.
3.	Kazi et al. [15]	1. Data is obtained for a number of flow rates and temperatures to calculate pressure drop and heat transfer in pipelines. 2. With fiber suspension heat transfer coefficient decreases and further decrease with an increase in flexibility of fiber	Wood pulp fiber suspension	Water	3.5-19.5%
4.	Cui & Grace [16]	A brief review of pulp fibers and suspended particles in the multiphase flow.	N.A.	N.A.	N.A.

5.	Xu and Aidun [17]	1. Studied the effect of the parameters like Reynolds number and concentration of fiber on the velocity profile. 2. Presence of fibers reduces the turbulence intensity. 3. The velocity profile becomes sharper with decreasing the flow rate and/or increasing the fiber concentration. 4. With further decrease in flow rate and/or increase in fiber concentration, the velocity profile becomes blunt again.	Natural flexible cellulose wood fiber	Water	10-20%
6.	Lin et al. [18]	Rheological behavior of fiber suspension in the fluid at different Reynolds number.	Nylon	Water	N.A.
7.	Yang et al. [19]	Used two different methods for modeling the interaction of flexible fibers with moving viscous fluids.	Straight and U-shaped	Viscous fluid	N.A.
8.	Waskito et al. [20]	Used coconut fibers in a circular pipe with 25000 Reynolds number to observe the effect of concentration of the fiber and Reynolds number on drag reduction percentage.	Fine straight fibers with 1mm length	Water	7.6%

2.2 Drag reduction using surfactants

Drag reduction using various surfactants had come into light in 1980s as there was not much literature available earlier. But some authors like Mysels and co-authors started work using aluminum disoap in gasoline flow. During which they found a reduction in the pressure drop for the same flow with gasoline only. In earlier days, aluminum disoap was the only surfactant used for the drag reduction research, but the problem associated with this additive was that when it comes under the high shear or elongation like in pump circulation it gets degraded and lose its drag reduction effectiveness property. It takes a number of days to recover its properties [21].

Surfactants are categorized into four types like anionic, cationic, non-ionic and zwitterionic [22]. Cationic is the most investigated surfactant so far due to its ability to reduce the drag up to 80% [18, 19, 20]. But non-ionic surfactant is a less toxic, environmental friendly and biodegradable than a cationic surfactant. Surfactants are low molecular chemical compounds which consist of the water-soluble (hydrophilic) and water-insoluble (hydrophobic) part [2]. Depending upon this part classification of the surfactants are done. More than the critical concentrations, the molecules start to form aggregates, which is known as micelles. On the basis of the geometrical types, micelles can be divided into three types i.e. spheres, rod-like, and discs. Many authors have used different surfactants to investigated the different parameters affecting drag reduction in turbulent flow. The surfactant is not only limited to increase the drag reduction percentage of the turbulent fluid flow but is very well known to overcome the problem in the field of the shear or mechanical degradation. Even the use of the surfactants to enhance the shear resistance of the polymer molecules were widely used in case of flexible polymers. The relevant research work is given in the tabular form in Table 2.2.

Table 2.2: Work done by various authors with different types of surfactants

Sr. No.	Author(s)	Parameters investigated and outcomes	Type of surfactant used	Base fluid	Drag reduction (%)
1.	Warholic et al. [25]	Measurements were made for four different Reynolds number, (13300, 19100, 32000 and 49100) based on bulk viscosity *Remarks*: The rod-shaped micelles were able to produce more drag reduction effect than the classical method of micelle formation.	Ethoquad T/13-15 and sodium salicylate	Water	48-76%
2.	Roanski [26]	Investigate the effect of k/D factor on drag reduction for five different pipes and k/D ratio varies from 0.012 to 0.056 *Remarks*: The drag reduction effect was more in rough pipes as compared to smooth pipes.	Hexadecyltrimethylammoniumchloride (CTAC) solutions with addition of sodium salicylate (NaSal)	Water	56-73.5%
3.	Al-Sadat et al. [27]	Effect of temperature, pH, shear conditions and methanol additives on the rheological properties of surfactant. *Remarks:* The solution was showing shear thinning behaviour up to 150 ^{o}C and has strong influence of pH on elastic properties of solution.	zwitterionic erucy- lamidopropyl carboxybetaine	Water	N.A.
4.	Cai and Higuchi [28]	APG solution has high drag reduction capability at 3000 ppm *Remarks:* The maximum drag reduction was observed at 20 ^{o}C and solution was not showing any viscoelastic properties during viscosity measurements even at higher concentrations.	Non-ionic Alkyl Polyglucoside	Water	70%

5.	Matras and Kopiczak [29]	Three zones were identified and Increase in the pipe diameter leads to an extension of the transition zone *Remarks:* The increase in the intensification of the drag reduction was observed when polymer was used as a mixture of surfactant solution.	Polymer - PEO, Cationic surfactant – cetyl trimethyl ammonium bromide	Water	60% with PEO & 75% CTAB
6.	Jing et al. [30]	Aqueous foam solution prepared to investigate the effect of foam on drag reduction of crude oil in pipeline flow. *Remarks*: The wet foam was able to produce more drag reduction effect than dray foam.	Sodium dodecyl sulphate Sodium benzenesulfonate Cetyl trimethylammonium bromide	Heavy crude oil	53%
7.	Tamano et al. [22]	The drag reduction and degradation of non-ionic surfactant solutions i.e. nontoxic and bio- degradable were studied in closed loop flow with recirculation. *Remarks:* Homogeneous and heterogeneous injection was compared and injection of polymer solution was found to be more effective than premixed solution.	oleyldimethylamine oxide (ODMAO)	Water	75%
8.	Adwani et al. [31]	Rheological characterization has been done for Kuwaiti crude oil with 5 different surfactants and compared with polyacrylamide. *Remarks:* The decrease in viscosity of the crude oil with 70 ppm of polymer was less as compared to the surfactant addition.	poly(sodium 4-styrenesulfonate) (PSSS), sodium dodecyl sulfate (SDS), cetyltrimethylammonium bromide (CTAB), hexadecylphosphocholine (HTPC), and CHP & Polyacrylamide	Crude oil	N.A.

A literature study of the fibers, as well as a surfactant, as mentioned above, was kept limited because the work is done in this thesis with the use of polymers. The above survey of the literature has been done to know the research background of the drag reduction phenomenon and the simultaneous development in the area of the surfactants. Since the surfactants in some cases are able to produce more drag reduction than the polymers with high molecular weight, but the toxicity and the effect of the surfactants on the environment cannot be neglected nowadays days.

1.3 Drag reduction using polymer additives

Drag reduction using polymer was discovered a few decades before, which leads to a series of experimentation to develop this phenomenon in various fields and with different additives. Fundamentals of this work were developed by Virk [32], who done a lot of experiments with a number of solvents and additives to find out the maximum possible drag reduction, which was later known as Virk's maximum drag reduction asymptote. A proper explanation about this phenomenon is still unknown, but a number of authors have made enormous efforts to understand the basic idea behind the process. On the basis of the boundary layer theory, the drag reduction phenomenon is categorized into three zones: the viscous sublayer, the elastic sublayer, and the Newtonian plug.

According to Virk’s hypothesis, the axial intensity in elastic sublayer region is more than the radial intensity and turbulent shear stress. Further explanation of this phenomenon was given by Lumley [33] based on the observation that increase in concentration of polymer results in thickening of buffer layer due to which, the formation of eddies get dampened. The dampening of eddies causes a reduction in Reynolds stresses and results in drag reduction. Various authors have explained the mechanism through different numerical simulations and models [34–37]. To observe the phenomenon more deeply, some authors performed direct numerical simulations to verify the phenomenon by using the FENE-P dumbbells model [35, 36]. They observed that the rate of strain in Newtonian flow is maximum at the top of the buffer layer due to the large stretching rate of polymers, which damps the wall-normal fluctuations.

The percentage of drag reduction is generally affected by various parameters. Several studies have been done so far to explain the influence of various parameters on the reduction of friction factor or skin friction [37, 38]. Effect and interaction of the parameters like Reynolds number, polymer concentration and mixing on turbulence in channel flow were observed by Warholic et al. [25]. These authors conducted rheological studies to observe the effect of polyethylene oxide concentration on the viscosity of water. They found that shear thinning behavior increased as the concentration was increased. They observed drag reduction even at very low concentration of polymer (0.29 ppm), which was affected significantly by the degree of mixing and Reynolds number. Choi et al. [43] used double-stranded DNA (mixed with a buffer solution containing HCl, NaCl, and EDTA) for drag reduction of water in a rotating disk apparatus. They showed that up to 20% drag reduction can be achieved even with very low concentrations (1.7–2.7 ppm) of DNA because the length of the DNA molecule is comparable with the microscales of turbulence. Some properties of polymers like the type of polymer, molecular weight, shear stability, and temperature also have a significant influence on skin frictional drag reduction.

Drag reduction by using polymers is not limited to use of only synthetic polymer but investigation is being carried out to find the effect of bio-polymers on drag reduction in turbulent flows. The following literature was divided into two groups:

(i) Effect of Reynolds number, concentration, mixing, and molecular weight
(ii) Effect of degradation or shear on the effectiveness of the polymer

The literature in relation to above mentioned parameters are explained as follows:

1.3.1 Effect of the Reynolds number, concentration, mixing, and molecular weight

The above-mentioned parameters considerably affect the performance of the polymers in the turbulent flow. A good number of research articles are published by a number of researchers to find the effect of the various parameters on the possible drag reduction.

Virk et al. [6] performed experiments with the use of polyethylene oxide with a molecular weight from 80,000 to 60,000,00. Polymer concentration, as well as pipe diameter, was varied to investigate Tom's phenomenon. Authors found that there was a significant effect of the polymer concentration, flow rate as well as molecular weight on the drag reduction percentage. If the drag reduction is limited by maximum drag reduction asymptote then there was no effect of the polymer and diameter of the pipe. With the addition of the polymer in the turbulent flow, due to the high wall stress the fluctuation strain causes the polymer molecules to expand [33]. Expansion of the molecules leads to increase the effective viscosity, which damps the eddies. But this expansion viscosity does not affect the viscous sublayer. As the intensity of the eddies decreased, the reduced Reynolds stress at the buffer layer delays the reduction of the mean profile slope by thickening the sublayer. Virk[32] proposed the elastic sublayer model based on the large number of experimentation in pipe flow. In this model it was proposed that there is formation of the elastic layer between laminar and turbulent core. The change in the velocity gradient is large in this layer. As shown in Figure 2.1, this formation of the layer leads to increase in the velocity by increasing the flow rate which is due to the drag reduction.

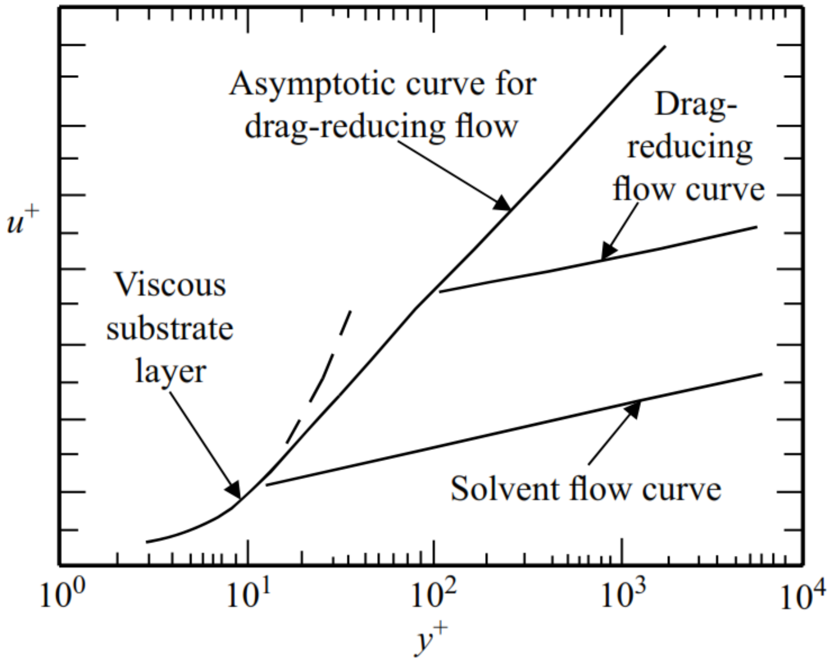


Figure 2.1: Model of elastic sublayer [32].

Burger et al. [11] studied the bulk velocity. Solvent viscosity and pipe diameter on the effect of drag reduction additive. This is one of the first commercial application of the drag reduction. In the Trans-Alaska pipeline, a high molecular weight polymer was used to overcome the requirement of the pumping station. Laboratory scale experiments were performed on 1-inch and 2-inch diameter pipe and then scale up the same for 19- and 48-inch pipe diameter. Initially, this replacement of the drag reduction additives was temporary but as the successful running of the additive to increase the flow rate the same was done permanently. The concentration of the polymer was varied from 5-25 ppm and the maximum drag reduction was obtained to be more than 25%. The effect of the heterogenous injection of the polyacrylamide near the pipe wall and observed the effect of the injection position and concentration on the drag reduction [44]. A test section of 13 m was used to found the effect of the injection of the polymer and compared with the results with a premixed solution or homogeneous injection. The author observed that the heterogeneous injection of the polymer solution near the wall is more effective than the premixed solution. For heterogeneous injection author used simple and perforated injector as shown in Figure 2.2.

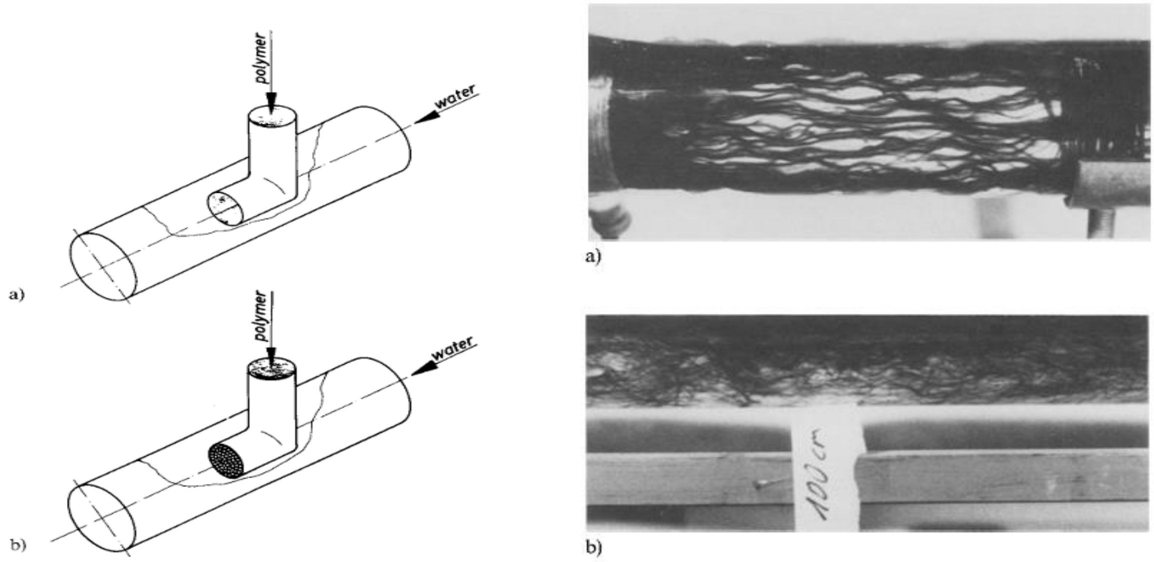


Figure 2.2: Centreline injector (a) with a single thread (b) perforated threads with 52 holes [44].

Diamond et al. [45] reviewed the drag reduction phenomenology and developed the polymer-hydrodynamics turbulence theory model to explain the drag reduction. A set of the macroscopic continuum equations were derived to explain the dynamics of the polymer extensional field and the velocity field. The continuum model is similar to the magnetohydrodynamics model. Hoyt et al. [46] investigated the effect of the polymer polyacrylamide concentration of the scaling of the drag reduction effect. The author compared the drag reduction of 26 mm diameter pipe with 53 mm in diameter. An excellent agreement was obtained between the experimental and prediction. Successful scaling of the drag reduction effect was done using this method. It was observed that the pipes having a diameter less than 10mm, gives poor prediction while scaling up. But more than the 10 mm gives quite accurate predictions and easy to scale-up. Ranade and Mashelkar [47] investigated the effect of the dilute polymer solution on the macromixing and micromixing behavior in turbulent pipe flow. A polymer-turbulence model was developed to evaluate the reduction in friction factor and then used to analyze the mixing in one-dimensional turbulent flow with only one adjustable parameter. Sreenivasan and White [48] published an article to better understand the mechanism of drag reduction. For this, the authors have considered two theories namely elastic theory and maximum drag reduction asymptote.

Li et al. [49] performed a direct numerical simulation for a channel flow based on the FENE-P and Oldroyd-B models to know the dynamics of the drag reduction. The simulations were performed within the limits of the maximum drag reduction asymptote. The effect of the rheological parameters like maximum chain extension and relaxation time was observed. Kim et al. [50] performed the direct numerical simulations to observe the effect of the polymer additives on the structure of the eddies near the wall turbulence. The effect of the polymer force velocity and vorticity was found out by using two-point spatial correlation and linear stochastic estimation. Matras et al. [51] investigated the addition of the polymer (PEO) and surfactant (CTAB) simultaneously. It was found that the addition of the polymer and surfactant, the polymer forms a layer around the micelles. These micelles with the polymer layer get stretched when comes in contact with the turbulent eddies and breakdown. The breakdown molecules are partially reformed due to which these are able to produce drag reduction effect for a longer time.

Gillissen [52] used DNS simulation to investigate the effect of the flexibility of the polymers on the turbulent channel flow drag reduction. The rigid and elastic polymers induced in the flow. It was observed that drag reduction depends on the polymer volume concentration and polymer aspect ratio. Shetty and Solomon [53] used the dynamic light scattering method to study the aggregate flow properties of the dilute polymer solution by PEO. The effect of the inorganic salt on the drag reduction aggregates was studied. It was found that the addition of the salt disaggregates the high molar mass of the PEO, which in result decreases the drag reduction effectiveness of the polymer in a turbulent flow. Yang and Dou [54] investigation of the presence of the polymer in the turbulent flow was studied by using eddy diffusivity model in rough pipes. It was found that the ratio of the effective viscosity to the kinematic viscosity is proportional to the Reynolds number. A formula for flow resistance was derived, which was tested with the results of the Virk’s Newtonian as well as non-Newtonian observations. The prediction using the formula for rough and smooth pipes was satisfactory. It was observed that the drag reduction for the rough pipes comparison to smooth pipes was less if the same polymer solution is used on the same Reynolds numbers. Dean and Bhushan [55] published a critical review on the drag reduction in turbulent flow using shark skin surfaces. Various riblet shapes like saw-toothed, scalloped and blade riblets effect were studied. The idea about the shapes comes from the scale patterns of the fast swimming sharks Shown in Figure 2.3. a review on the riblet studies was studied and optimal designs were selected. Due to the mucus present in the skin of the shark, it acts as a hydrophobic surface and reduces a significant amount of drag to increase the speed of the shark.

Iaccarino et al. [56] used an eddy viscosity model for the prediction of the drag reducing parameter in a turbulent flow. Mean velocity and turbulent fluctuations were predicted with good accuracy with the user of this single transport equation. The computational cost involved in these simulations was quite less. Jang et al. [57] investigated the effect of the pH, rotation speed, surfactant, concentration on the polymer was studied. It was found that polymer chains are very sensitive to pH, the maximum effect of the drag reduction seemed to be observed in the range from 7 to 11. The mixture of the polymer-surfactant was found to be more effective than polymer alone. Hassanean et al. [58] studied the drag reduction effect of the poly alpha olefin in the crude oil. The effect of the rheological properties of the additive and the concentration was observed. It was found that the additive stability was unaffected up to the 26.6 ^{o}C temperature. With the help of this polymer, the author was able to achieve a 36% reduction in the drag with crude oil flow. Hidema et al. [59] used a visual technique, particle image velocimetry to investigate the relation between extensional properties of the polymer solution and the deformation of the vortex in a turbulent flow. Polyethylene oxide was used as a drag reducing additive. Zhu et al. [60] performed DNS simulations for turbulent channel flow. Authors focused on the region of low to high extent drag reduction. It was found that the Reynolds stress was not suppressed not only in the buffer zone but also surrounded the whole channel except viscous sublayer. As the suppression of the Reynolds stresses the shear stress increases but in LDR region the changes occur in buffer zone only.

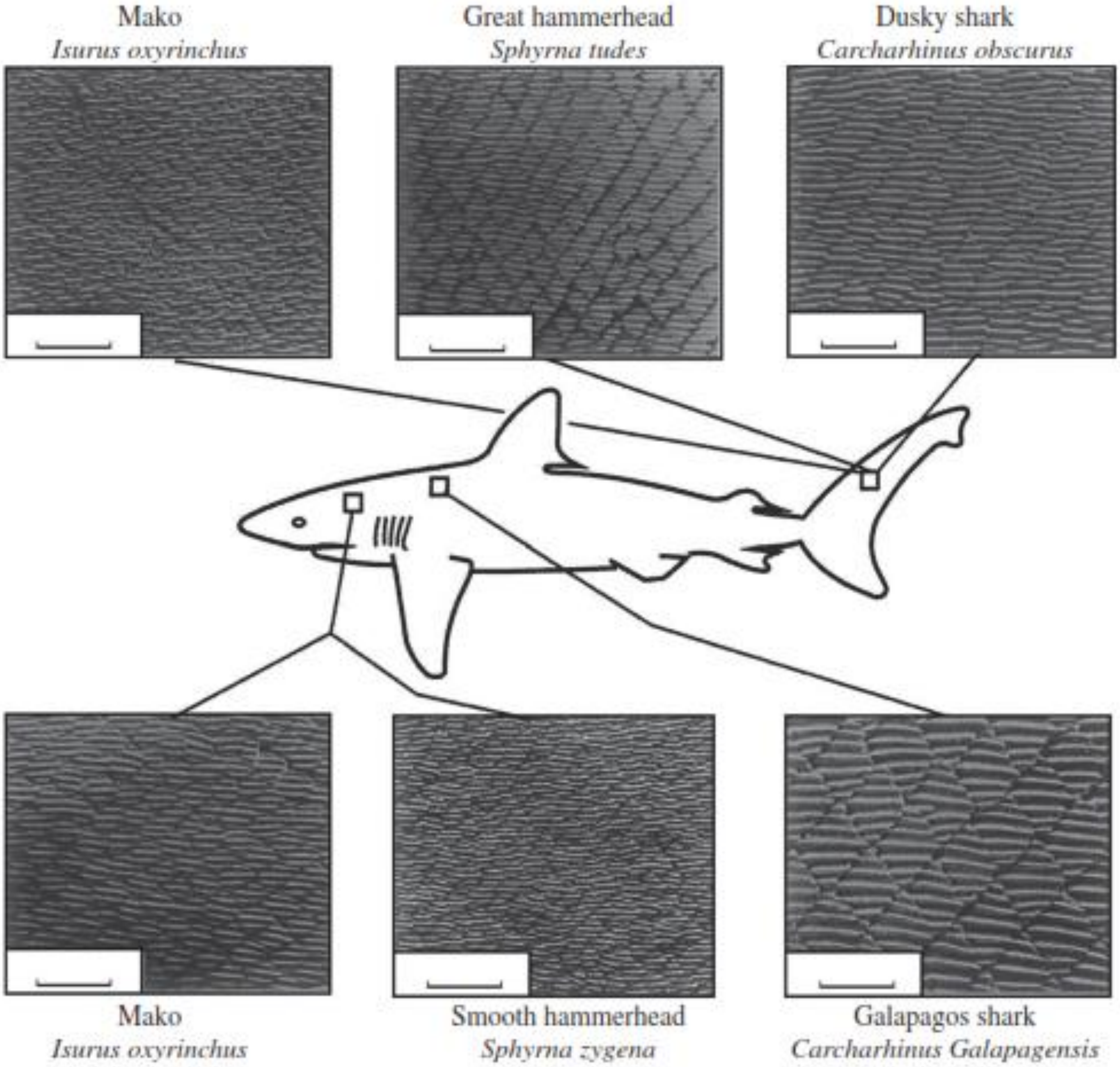


Figure 2.3: Patterns of scale on fast swimming shark's body ([55], [61]).

Soares et al. [62] used biopolymer aloe-vera instead of the use of any synthetic polymer to observe its effect as a drag reducing agent. Effect of the aging of the polymer was also studied. It was found that the fresh sample acts as a good drag reducer because in the fresh sample the acid content was less as compared to the old ones.

Drag reduction by using long-chain polymer additives is not only limited up to single-phase flow or water only. From last 10 years a fair number of research articles published in the heavy oil flow using polymer additives. The transportation of heavy oils in pipeline systems has been a topic of research interest due to the complexities involved in various stages from designing to operation. One of the major problems associated with this is pumping power needed to maintain the flow of heavy and extra heavy oils in pipeline systems. Various researchers suggested a number of ways to decrease the power required as well as improvements in the design systems. Some methods like viscosity reduction, upgrading of oil, and use of drag reduction additives, etc. have become popular so far [63].

Many authors used water-oil flow with water-soluble polymers to reduce the drag experienced by the heavy oil. [63]. The most successful commercial use of drag reduction additives was in the Trans-Alaska oil pipeline transportation system. Due to the delay in installation of two pumping stations, some drag reducing additives were used on a temporary basis, which became so successful that the idea of installation of the pumping stations was dropped [64]. Another example was the experimental investigation of the effect of various parameters on the drag reduction in Prudhoe Bay crude oil pipeline system, which was a quite successful experiment applied commercially, wherein, an α-monomer was injected near the boundary layer with Reynolds numbers ranging from 4,000 to 300,000 [11].

Recently, the transportation of heavy oils as a two-phase mixture (like water-in-oil or oil-in-water dispersed flow) became an alternate way. The immiscible flow of two liquids commonly occurs in many industries like petroleum, geothermal, chemical and nuclear industries [4, 5 – 8]. The flow of heavy oil using water as a second phase became an alternate, but there are a lot of difficulties associated with the flow of two immiscible liquids such as understanding of flow patterns, optimization of design systems, etc. Adequate knowledge of the flow patterns in multiphase flow is very beneficial in the selection of the suitable method of transport, prediction of the pressure drop, and the flow behaviour in the pipeline during the transportation [70]. There have been several studies conducted to understand the dynamics of the oil-water flow through different materials with different parameters. Some researchers also studied the effect of water/oil fraction on hold up, slip velocity, interfacial tension in horizontal as well as inclined pipes.

Addition of the drag reducing additives (DRA) in the single-phase flow is very popular as small amounts (in ppm) of long-chain polymers are able to reduce a significant amount of frictional losses in the flow system [39, 68–70]. The use of DRAs in two-phase flow has been studied to a lesser extent in recent years [73]. However, in the case of two immiscible fluids like water and oil, the drag reduction additives were found effective in single-phase only [1, 67]. The smaller the difference in the densities of water and oil, better will be the reduction in the pressure drop of oil, when transported with water as a mixed flow. However, the addition of a drag reduction polymer to further reduce the drag in the mixed flow as an energy saving measure is quite a useful approach making it more cost-effective. Drag faced by oil is much higher as compared to water due to the low mobility of oil. Hence, the use of water as a second phase during the transportation of oil is the best option due to the ease of separation and improved flow properties [69].

A fair number of studies have been done to understand the hydrodynamics of gas-liquid and water-oil transition characteristics, flow behaviour, and phase inversion phenomenon [1, 63, 65, 72, 74, 78 & 79]. Most of the investigations were made in stirred vessels rather than transportation through pipes. A fair number of literatures are available for gas-liquid flow on the models to predict their behaviour in low viscosity fluids. However, there are very limited studies that investigated the flow characteristics in pipe flow for the two-phase flow of water-oil emulsions. It was found that drag reducing additives not only affect the pressure drop but also affect the flow patterns of the two-phase flow systems. Some of the work done in the field of drag reduction in water/oil flow listed in Table 2.3.

1.3.2 Effect of degradation and shear on the effectiveness of the polymer

As the polymers gained popularity during the past 30 years due to the applications of the drag reduction in the many areas. Initially, a flexible, soluble, high molecular weight and long chain linear polymer were used as favorable drag reducing additives. But the problem associated with the linear chain polymers was to observed the degradation under the shear effect.

When the polymers introduced into the high shear rate, there was continuous degradation of the polymer chain and loss in the effectiveness of their drag reducing capabilities. It led to the use of the polymers in closed loop systems of recirculating systems because in most of the fluid systems the circulation or the discharge is increased with the use of the centrifugal pumps. But due to the impeller speed as well as the rotation of the fluid in the casing of the centrifugal pump, high shear is induced in the pump. This high shear causes the continuous break down of the polymer molecules into smaller chains and after a plateau value, the effectiveness of the polymer almost becomes negligible.

Table 2.3: Water-oil studies using drag reducing additives

Author	**Pipe material**	**Mixture velocity (m/s)**	**Oil/water fraction**	**Type of polymer**	**Oil viscosity (cP)**	**Type of oil**
Al-Yaari et al. [75]	Acrylic	0.5–3.5	0.2–0.8	Polyethylene oxide, Magnafloc 1011	1.57	SAFRA D60
Edomwonyi-Otu et al. [78]	Acrylic	0.74–1.14	0.2–0.8	Magnafloc 1011	5.5	Exxsol D140
Abubaker et al. [77]	Acrylic	0.4–1.6	0.1–0.9	AN 105-SH	24	Shell Tellus S2 V15
Al-Yaari et al. [79]	Acrylic	–	0.3, 0.7	Magnafloc 1011, Polyethylene oxide, Polyisobutylene	1.57	SAFRA D60
Abubaker et al. [80]	Acrylic	0.4–1.6	0.05–0.9	AN 1.5-SH	24	Shell Tellus S2 V15
Eshrati et al. [81]	Acrylic	0.1–1.6	0.1–0.5	AN 125, AN 125-SH, AN 125-VLM	24	Shell Tellus S2 V15

To overcome this problem researchers have found a number of solutions and modification in the design and additives. Literature survey in the field of the decay of the polymers under the shear and modifications in the polymers are given below.

Fisher and Rodriguez [82] used two different polymers polyethylene oxide (PO) and polyacrylamide (PAAM) to observe the degradation as a friction reduction effectiveness under the turbulent flow in the pipe. The Reynolds number of water was kept from range 8600 to 12,000. It was found that the rate of the degradation of the PO was more rapid as compared to the PAAM polymer. The concentration of the PO was varied from 2.5 to 75 ppm and the concentration of the PAAM was varied from 17.5 to 38 ppm.

Bristow [83] used data from the findings of the different researchers and developed a statistical mechanical model for the chain conformations of the polymers. A relation between mechanical degradation and the flow time was derived. It was proposed that the mechanical degradation of the polymer is directly proportional to the molecular weight of the polymer instead of solvent type. The loss of the drag reduction during time ‘t’ through mechanical degradation can be calculated to a first approximation, described by equation (2.1)

$$D/D_0 = e^{-Rt} \qquad (2.1)$$

where, ‘R’ is a parameter not a true constant

Deshmukh et al. [84] investigated the effect of the grafted polymers Xanthan gum and polyacrylamide on drag reduction as well as the shear degradation. Authors investigated that the polymers which were grafted showed a drag reduction effect more time or for the number of passed than non-grafted polymers. The polymers were tested for a fixed 100 number of passes. The degradation for 100 ppm was found to be more than 400 ppm of the polymer concentrations. Ungeheuer et al. [85] used the Xanthan gum and polyacrylamide and grafted polymer of polyacrylamide into Xanthan gum to compare the drag reduction effect and shear stability of the polymers. Authors observed that the shear stability of the Xanthan gum (XG) more than 300 ppm was almost equal to the grafted polymer. It was observed that the polyacrylamide (PAAM) and a mixture of Xanthan and PAAM showed poor stability as compared to Xanthan gum. A particular Reynolds number was selected with a number of passes to continuous observe the behavior of the polymer molecules or reduction in the effectiveness of the polymer. Degradation of the polymer molecules in PAAM and mixture of PAAM and XG was more rapid than grafted polymers.

Muller [86] used an elongation technique to investigate the chain scission of the macromolecules in solution. A cross jet flow setup was prepared to find out the effect of the strain rate on the breakage of the polymer molecules in the semi-dilute and higher concentration region. Polymer atactic Polystyrene with molecular weight 5.8×10^6 was used with different concentration. It was observed that for a dilute solution the scission of the polymer molecules was almost near the center which disappears as the concentration was increased to the semi-dilute region. With the increase in the concentration, the scission becomes randomized due to increase in entanglements per chain.

Choi et al. [87] used a rotating disk apparatus to measure the effect of the polyisobutylene as a drag reducing additive in two different solvents cyclohexane and xylene. Polyisobutylene with four different molecular weights (0.99×10^6, 1.2×10^6, 1.6×10^6, 2.1×10^6 g/mol) was used with different concentrations. Authors observed that the drag reduction effectiveness of any additive with different molecular weight is strongly dependent on solubility and interaction of the polymer with the solvent.

Choi et al. [88] investigated the drag reducing properties of polyethylene oxide (PEO) with molecular weight ranges from $4.0\times l0^5$ to 5.0×10^6 and a natural polymer xanthan gum. The validity of the exponential decay model was investigated. It was found that the exponential model was best fitted for the shear resistant polymers, but deviation from the experimental results was quite large for flexible polymers like PEO.

Sohn et al. [89] used Xanthan gum with different molecular weights to find out the effect of the concentration and molecular weight on the maximum possible drag reduction. An ultrasonic method was used to obtain the different molecular weights of the polymer. Experiments were performed by using a rotational disk apparatus. It was found that the maximum drag reduction depends on the concentration, ionic strength, temperature and molecular weight of the polymer. The concentration required for maximum drag reduction decreases with increase in molecular weight of the polymer. The degradation of the polymer chain depends on the turbulent intensity of the flow.

Buchholz et al. [90] used the polydisperse polymers (MW > $2:5\times10^6$ g/mol; PDI 1.4) in a pressure-induced apparatus using fused silica capillaries with internal diameter 250 µm as shown in the Figure 2.4. the degradation of the polymers was observed with a decrease in the polydispersity index of polymers with a number of passes. It was found that the degradation of the polymers in elongation was purely physical in nature not chemical. The polydispersity index of the polymers was reduced up to 1.12 after degradation. A novel mathematical model was developed by the authors to better understand the characteristics of the chain scission of the polymer molecules which best fit into the experimental results obtained by authors.

Lim et al. [91] observed the effect of the injection of the spermidine in the λ-DNA in a turbulent flow. Authors have compared the effect of the injection of the spermidine (SPD) on drag percentage with 1.37 wppm at a rotational speed of 1157 rpm a Reynolds number of 5,90,000. It was found that when SPD was not injected in the rotational disk apparatus the decrease in the drag reduction efficiency was only 1% after 60 min but when SPD injected in the solution in first 30 sec there was 40% decrease in the drag reduction efficiency, which almost becomes zero after 60 min.

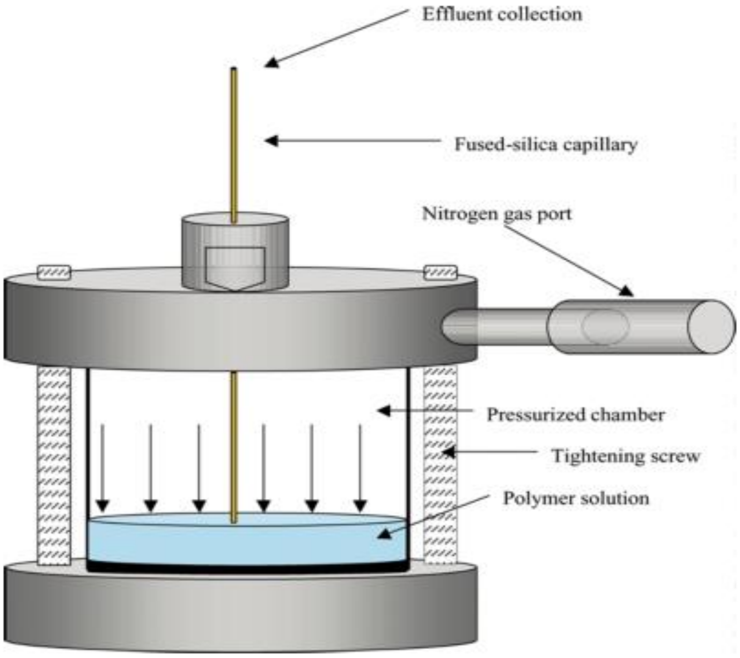


Figure 2.4: A schematic diagram of the custom-built pressure loading device with suspended capillaries [91].

Hong et al. [92] observed the effect of the natural biopolymer guar gum on the drag reduction percentage and its decay rate with the time in a rotational disk apparatus with a number of passes. It was found that the drag reduction was a function of concentration and molecular weight of the polymer while the degradation of a polymer depends upon the turbulent intensity of the flow. The author used two models like a single relaxation process and exponential stretched model to compare the experimental results. Ultra-sonification method was adopted to make the guar gum with different molecular weight. It was observed that the stretched-exponential model describes the degradation behavior better.

Wyatt et al. [93] investigated the effect of the xanthan gum on the drag reduction with and without the presence of the salt in the solvent. Two different methods of dilution were also adapted to compare the effect of the injection method. The maximum drag reduction was observed from 2% to 35% with Xanthan gum and no significant reduction in the effectiveness was observed after 5h in homogeneous solution. But when the salt was introduced, the drag reduction of the stock solution, as well as rheological properties, also change.

Mohsenipour and Pal [94] found the effect of the non-ionic polyethylene oxide and anionic polyacrylamide with different surfactants to observe the effect on the percentage of drag reduction. Various interaction of the surfactants was made to observe the effect on shear degradation. It was found that coiled polymer molecules undergo rapid shear degradation than stretched polymer molecules.

Yang and Ding [95] derived the equations for the velocity distribution and the friction factor in the turbulent drag reduction flows. It was found that the degradation of the polymer chains leads to alteration of the molecular weight. The drag reduction percentage depends on the concentration as well as polymer-solvent interactions.

Sandoval and Soares [96] used three different polymers (PEO, PAAM, and XG) to check their effect on the drag reduction efficiency and on degradation with a number of passes. It was found that the mixture of the flexible polymer PEO with XG was able to produce more drag reduction as compared to the single polymer. Since the polymer structure of the XG is rigid and when added in the flexible polymer, there was a positive increase in the drag reduction percentage as well as their shear resistance becomes better.

Le Brun et al. [97] observed the effect of the pure partially hydrolyzed polyacrylamide and with sodium 2-acrylamide-2-methylpropane sulphonic acid in the area to improve the performance of the hydraulic fracturing fluids. Experiments were performed in a closed loop test section to simultaneously study the shear degradation effect. It was found that the addition of the polymer improves the drag reduction capability but there was no effect on its susceptibility to degrade under the high shear flows.

Karami et al. [98] studied the effect of three polymer PEO, PAAM and XG under the high Reynolds numbers with distilled and tap water as a solvent. It was found that the mechanical degradation of the polymer was more in the case of tap water as compared to the distilled water.

However, this is dependent on the molecular weight of the polymer and rigidity of the molecular backbone.

Motta et al. [99] used FTIR characterization method to understand the mechanism of the mechanical degradation of the polymer under the shear of pumps. A biopolymer guar gum was used as a drag reducing agent and continuous observations were noted to make the mechanism more clearly. It was proposed by the authors that degradation of the guar gum was due to the hydrolysis of bond α (1→6), liberating the galactose.

1.4 Summary

In this chapter, a literature survey has been done from the introduction of the drag reduction phenomenon to the recent progress in this area. From the first observation of the phenomenon to the fundamentals derived for the drag reduction and its applications in the various fields were discussed. Drag reduction by using fibers and surfactants were discussed problem-related to their implementation, the effect on the environment, etc. Use of the polymers in the turbulent drag reduction and types were tried to cover in the literature survey. The effect of the various parameters like Reynolds number, concentrations of the polymer, turbulent intensity, polymer-solvent interactions was explained using the research in this field. A large number of experimental as well as numerical methods were adopted to get the maximum output from the different additives. Polymers which were sensitive to pH, and other parameters such as temperature, molecular conformation were studied.

It was commonly known that the flexible polymer is very prone to degrade in the shear of mechanical stresses. Different types of polymers and their decay rate with time as well as a number of passes was observed. Some authors used surfactant-polymer additives to improve the shear stability of dilute polymer solutions. It was found that some biopolymer has a more rigid chain structure to shear degradation. This research diverts the direction of the use of biopolymers instead of synthetic polymers.

In the past decade use of polymers in the heavy oil, drag reduction fetched the attention of the many researchers. In the transportation of the heavy oil or fluid through the pipelines consumes a significant amount of energy in the form of pumping power. Some parameters like type of drag reducing agent, injection method still a part of research to be explored. Use of the drag reduction additives in water/oil flow is mostly discussed in the transparent as well as smooth pipelines but in case of metal limited literature is available. In case of single phase like water, biopolymers can be a better alternative of the synthetic polymer, as some synthetic polymers are not easily biodegradable.

1.5 The scope of the present work

1. In the present work, two polymers were selected on the basis of the effect on rheological properties.
2. Effect of the different concentration of the polymer on rheological properties like viscosity with respect to shear rate was observed.
3. Biopolymers tested in water flow and their behavior was observed on the basis of the percentage of drag reduction and shear degradation with a number of passes. Biopolymer were soluble in the water phase, so initially, the experimentation was performed to investigate the behaviour of the polymer in water flow.
4. To avoid the degradation in the effectiveness of the polymers with aging or number of days, stability study was done with various concentrations of the polymer.
5. Biopolymers were tested in the heavy oil transportation in water-oil flow to get the maximum output from the selected polymer and their effect on the flow pattern was also studied. Transportation of the heavy oil is one of the most energy consuming process to maintain the desired flow rate. From past few years, instead of single-phase transportation, the oil is being transported with help of water as a second medium to reduce the pressure drop. Moreover, the polymers are more effective in water phase instead of oil, so water soluble polymers are being used to reduce the further drag during transportation of heavy oil.

1.6 Objectives of the work

The specific objective(s) are as follows:

1. Selection of suitable polymer additive(s) by rheological studies.
2. To study the effect of temperature and additive concentration on density and viscosity of heavy oil.
3. To study the effect of Reynolds number on the drag reduction of heavy oil.
4. To study the effect of injection positions on the drag reduction of heavy oil.

CHAPTER-3

RHEOLOGY OF THE POLYMER SOLUTIONS

3.1 General

In the previous chapter, a detailed survey of the literature in the field of drag reduction has been reported. From the introduction of the phenomenon to the development of the process and then the difficulties in the equipment design, as well as a performance enhancement for the different additives have been discussed. This chapter deals with studies on the rheological characterizations of the selected polymers. The viscosity of the polymer solutions was observed under shear rate using rheometer and the effect of the concentration of the polymer on viscosity behavior was observed. The effect of the salt addition on the density of the solvent as well as polymer solutions was observed. The effect of the temperature on the density and viscosity of polymer solution was also observed.

3.2 Selection of the polymer(s)

Polymers as drag reducing agents are very favorable additives of research on the drag reduction of various solvents for many decades. In this study, the polymers were selected on the basis of their properties as well as from the literature survey done during the study. Based on literature survey, two water-soluble and one oil-soluble polymer were selected. These three polymers are as follows:

3.2.1 Water soluble polymers

a) Guar gum
b) Gum arabic or Gum acacia

3.2.2 Oil soluble polymer

c) Poly dimethyl siloxane

The properties of the selected polymers are as follows:

Guar gum is a naturally occurring water-soluble high molecular weight biopolymer. It consists of polysaccharides of galactomannans of a linear chain of (1-4) linked β-D- mannopyranosyl units with (1-6) lined α-D-galactopyranosyl residues as side chains [100]. It is believed that the greater branching of the guar gum is responsible for its easier hydration and hydrogen bonding. Due to the predominance of the aggregates in guar gum, the behavior of the solution is viscoelastic, which has also been reported for many drag reducing additives [101].

Properties of the guar gum depend upon the solvent medium. Guar gum swells and dissolves in the polar solvents and forms a strong hydrogen bonding; while, with nonpolar solvents, it shows weaker hydrogen bonding [102].

The viscosity and the dissolution of the guar gum depend on the particle size, pH and temperature. With an increase in the concentration, the viscosity of the solution increases; and in case of shear rate, the guar gum solution shows shear thinning behavior. Shear thinning behavior of the solution increases with increase in the molecular weight and viscosity of the solution. The viscosity of the solution of guar gum generally depends upon the hydration rate. In cold water, guar gum powder hydrates rapidly. A minimum of 2 hours hydration has been recommended in literature [103] for proper hydration and to achieve the maximum viscosity.

Numerous industrial applications of the guar gum lead to increased research on its properties and improvements. Guar gum is used in many industries sucha as dye industries to make the dye solution thicker, oil well stimulation for hydraulic fracturing, explosives, drug delivery, food industries, and paper and pulp industry [99, 102, 103]. In the past few years, the use of guar gum has been increased in hydraulic fracturing due to its high viscosity. During oil well drilling, guar solution is poured to widen the crack. In recent years, guar gum is being used as a drag reducing agent in single- as well as multi-phase flow systems [106–109]. Guar gum is a good gelling agent, emulsifier and binding agent.

Gum arabic is the exudates from the Acacia seyal tress, also known as acacia gum. The carbohydrate part of the gum arabic is a highly branched structure consisting of a 1,3-linked β-D-galactose core with branching through 3-and 6-linked galactose, 3-linked arabinose [110]. Some studies showed that gum arabic solution shows Newtonian behavior when dissolved in water. But, in general, this depends on the concentration of the gum arabic in the solution. Up to 50 s^{-1} solution shows Non-Newtonian behavior and after that, it shows Newtonian behavior as reported in some studies [110–113]. Gum arabic can easily dissolve in the water. The increase in the viscosity of the gum arabic solution is quite less as compared to the guar gum solution. This is also a naturally occurring high molecular weight polymer, which is easily available. It is used as a binder, stabilizer and emulsifying agent in food applications [114–116]. It is also used as water-oil emulsion stabilizer. It is also used in many other applications like microencapsulations, as an antimicrobial agent, anti-inflammatory, in drug delivery as well as in nanotechnology for dispersing of nanoparticles [110].

Polydimethyl siloxane (PDMS) is a silicone based polymer and is the most widely used silicon-based organic polymer. PDMS is known for its properties and applications in different fields. Polydimethylsiloxane is a transparent highly viscous liquid polymer having different rheological behavior under different conditions. Polydimethylsiloxane is used in different areas like microfluidic devices, lubricants, medicine, cosmetic fields, etc. It is used as antifouling and antifoaming agents in lubricants. Due to its hydrophobic properties, the polydimethylsiloxane is used in the production of microfluidic devices.

3.3 Preparation of the polymer solutions

The preparation of polymer solution plays a vital role in the drag reduction phenomenon. The polymer used for drag reduction is generally of high molecular weight and more susceptible to degradation with shear. So, before injecting in turbulent flow, utmost care was taken during preparation of solutions to avoid the degradation and reduction in the performance of the polymers. The following steps were followed to prepare the master solution of the polymer, which can later be diluted according to the desired concentrations.

1. The polymers used in this experimentation were either in the powder form or in gel form. The biopolymers which were soluble in water (guar gum and gum arabic) were in powder form, while the polydimethylsiloxane which is an oil-soluble polymer, was used in the gel form.
2. The polymer solution was stirred by using mechanical impeller instead of magnetic stirring to avoid any shear effect. The solution required for experimentation was in high volume. Initially, the solution was stirred using magnetic stirrer, but a scission effect was observed after 2 hours. The speed required for more volume was in magnetic stirring was quite high to avoid lump formation, which is not in the case of impeller. The size of the impeller was large enough to produce 5 litres at lower speed.
3. First, the solvent like water/oil was stirred using impeller for 5-10 minutes without the addition of any polymer powder to make the vortex stable.
4. The required amount of the polymer was weighed on the weighing machine to make the master solution of 10000 ppm concentration.
5. The powder was added in the solvent in small portions in different time intervals to avoid any lump formations in the solution while stirring.
6. The speed of the impeller was kept 200-300 rpm during the addition of the polymer powder.
7. After addition of the required quantity of the polymer in the solvent, the speed of the impeller was set around 300 rpm and the solution was stirred for 7 hours to reach the

biopolymers at their maximum dilution and viscosity. Stirring time of solution depends upon hydration rate. Guar gum is rapidly soluble in cold water and require 2-4 hours for proper hydration. In this case the polymer was dissolved at 25 ^oC so hydration rate was slower and take around 5-7 hours to reach at maximum viscosity. So, based on some pilot experiments 7 hours was selected as optimum time for stirring.

8. After 7 hours, the stirring of the solution was stopped and the polymer solution was kept for overnight for proper hydration.
9. For dissolution of the polymer in the oil, the required gel was weighed and poured in the oil while stirring.
10. In the case of the oil-soluble polymer, the speed of the impeller was kept 800 rpm during the addition of the polymer gel, because, the viscosity of the oil was quite high as compared to aqueous solution.
11. The oil-polymer solution was stirred at 500 rpm for 4 hours and the solution was kept for 3 hours before experimentation.
12. When stirring with impeller was done, there was a formation of microbubbles in the oil, which cannot be easily escaped. So, to remove all bubbles from the solution, it was kept idle for 3 hours after stirring.

3.4 Fluid properties

In case of drag reduction, preparation of the polymer and its rheological properties play an important role. To estimate the change in the rheological properties, viscosity as well as density were measured. During experimental tests, various parameters were optimized to reduce observational errors. The various variables that were optimize to reduce the observational errors were calibration of pressure sensors, hydration rate, temperature, stability of polymer master solution etc.

3.4.1 Rheological properties

In order to measure the rheological characterization of the polymer, viscosity plays an important role to know the behavior of the fluid at high shear. The viscosity of the different polymers like guar gum and gum arabic with the same mesh size was measured using viscometer. For the low shear rate, the Brookfield viscometer was used and for high shear rate, MCR 52 series Rheometer (Anton Paar, Germany) was used. The temperature for the rheological measurements was maintained around 25±0.5°C. The shear rate of the rheometer was maintained from 0.01 s^{-1} to 1000 s^{-1}. The following procedure was followed for viscosity observation: -

(a) For Brookfield viscometer, the spindle ST-32 was used, for which about 9 ml solution is required. This viscometer was rotational type viscometer. The speed of the viscometer was set at 60 rpm as prescribed by the manual to avoid any turbulence while observation. A continuous observation of the data points was recorded by using Rheocalc software.

(b) For shear Viscosity, Rheometer was used from 0.01 s^{-1} to 1000 s^{-1} shear rate to continuously observe the behaviour of the polymer solution with shear rate. The rheometer was cone-plate type with angle 1^{o}.

3.5 The viscosity of polymer solutions

Viscosity plays an important role to predict the behavior of the polymer solutions with a change in the concentrations of the polymer additive. Changes in the viscosity affect the flow properties of the fluids significantly. In general, addition of the polymer leads to an increase in the viscosity of the solvent. But, the behavior of the solvent with polymer additive can be predicted with the application of shear rate. On the basis of the behavior of the solution under shear, it can be broadly classified into the following two types:

3.5.1 Newtonian fluids
3.5.2 Non-Newtonian fluids

Newtonian as well as non-Newtonian fluids are briefly defined as:

3.5.1 Newtonian Fluids

Newtonian fluids are the fluids which follow Newton’s law of viscosity. It states that for incompressible Newtonian fluids in laminar flow, the resulting shear stress is equal to the product of the shear rate and viscosity of the medium. In the case of Newtonian fluids, there is no change in the viscosity with respect to the rate of shear applied. For example, water, glycerine, alcohol, etc. are Newtonian fluids. The curve of the Newtonian fluids between shear rate and shear stress is always linear.

3.5.2 Non-Newtonian fluids

Non-Newtonian fluids are those fluids in which the curve between the shear stress and shear rate is non-linear. These fluids do not follow a particular trend of rheology. These types of fluids do not exhibit the same viscosity at the same temperature and pressure. The value of the viscosity depends upon the flow conditions such as flow geometry, shear rate developed within the fluid, time of shearing, and kinematic history of the sample, etc. Non-Newtonian fluids are categorized into three types:

1) The fluids in which the rate of shear is depended only upon the current value of shear stress or vice versa. These are known as time independent, generalized Non-Newtonian fluids.
2) Time-dependent systems are far more complex materials in which the relation between the shear stress and shear rate depends upon the time of shearing and kinematic history.
3) The visco-elastic fluids which show both elastic solid and viscous fluid behaviour and can have recoil recovery after some deformation.

3.6 Effect of the polymer concentration of guar gum/gum arabic/ poly dimethyl siloxane on the viscosity of the solution

Both biopolymers were dissolved in the water with different concentrations of the polymer and the increase in the viscosity was measured. For both the polymers, concentrations of the polymer were so chosen that during the experimentation on drag reduction, the concentration was varied from 50 ppm to 300 ppm. As fluid was injected directly into the boundary layer of the pipe flow, the concentration of the master solution used was high during the injection.

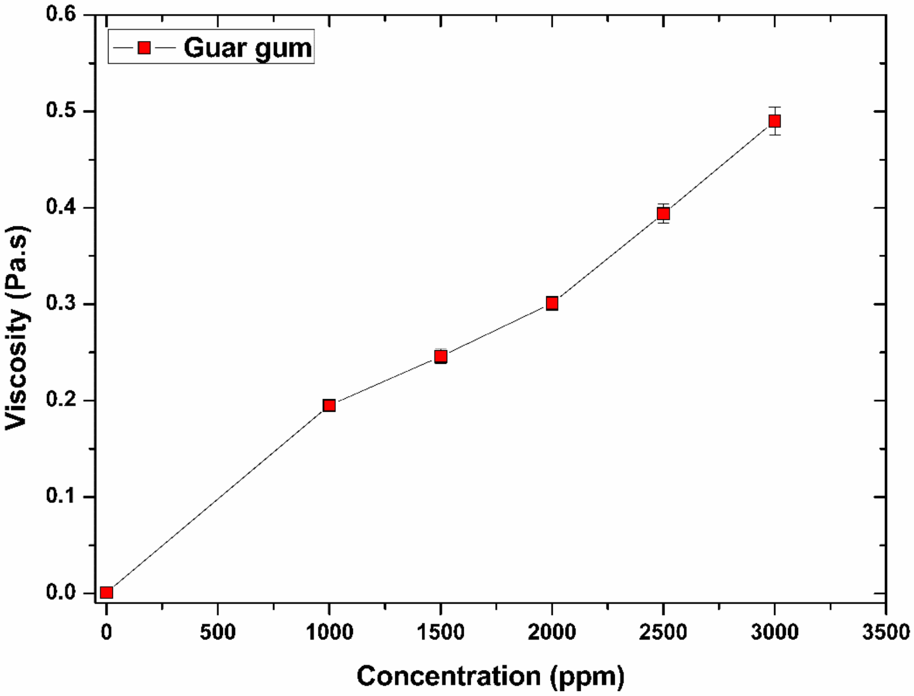


Figure 3.1: Viscosity of the solution with the addition of the guar gum at different concentrations.

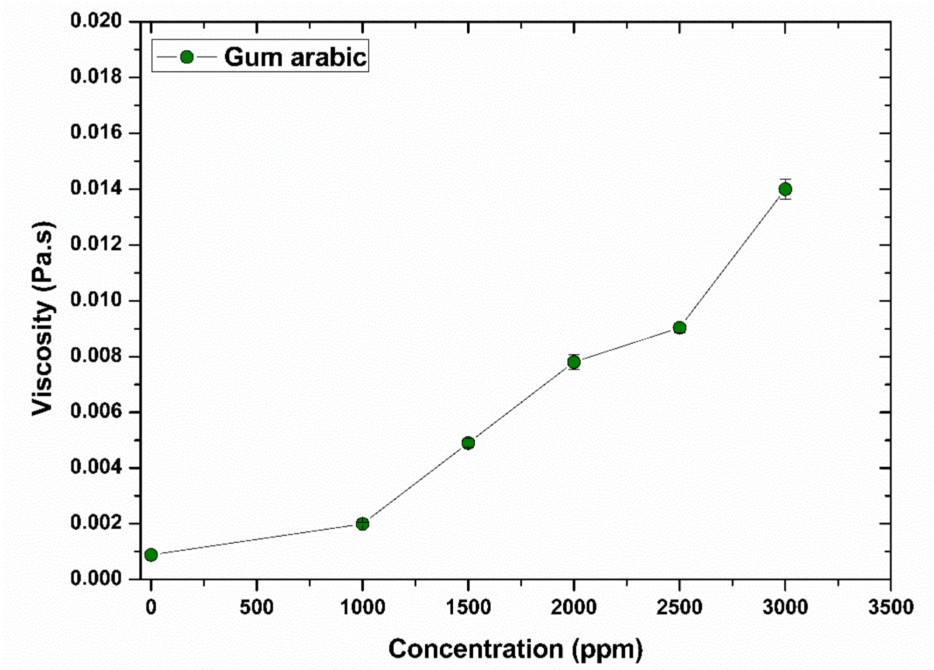


Figure 3.2: Viscosity of the solution with the addition of gum arabic at different concentrations.

It can be observed from Figure 3.1 that the addition of the guar gum leads to an increase in the viscosity of the water. For the concentration of the guar gum with 1000 ppm, the increase in the viscosity was almost 200% more than the solvent value, which is only 1.24% for gum arabic in Figure 3.2.

The maximum increase in the viscosity of the guar gum solution was 549% from the solvent value for 3000 ppm concentration. But, for the gum arabic polymer at 3000 ppm, the maximum increase in the viscosity was 14.7% from the solvent value. For guar gum, at 1500 ppm the viscosity was 0.246 Pa.s, which was 275% more than the solvent value and for other concentrations of 2000 ppm and 2500 ppm, it was almost 337% to 447% more than the water viscosity.

The increase in the viscosity of gum arabic solution was quite less as compared to gum arabic, which was 4.5%, 7.85% and 9.14% for 1500 ppm, 2000 ppm and 2500 ppm, respectively. The rapid increase in the viscosity of the guar gum as compared to gum arabic was due to its hydration rate. The rate of hydration for guar gum solution is much higher than gum arabic solution, which causes the high viscosity of the guar gum solution [99, 103, 105, 115]. The hydration rate of the guar gum is faster in cold water than at higher temperatures.

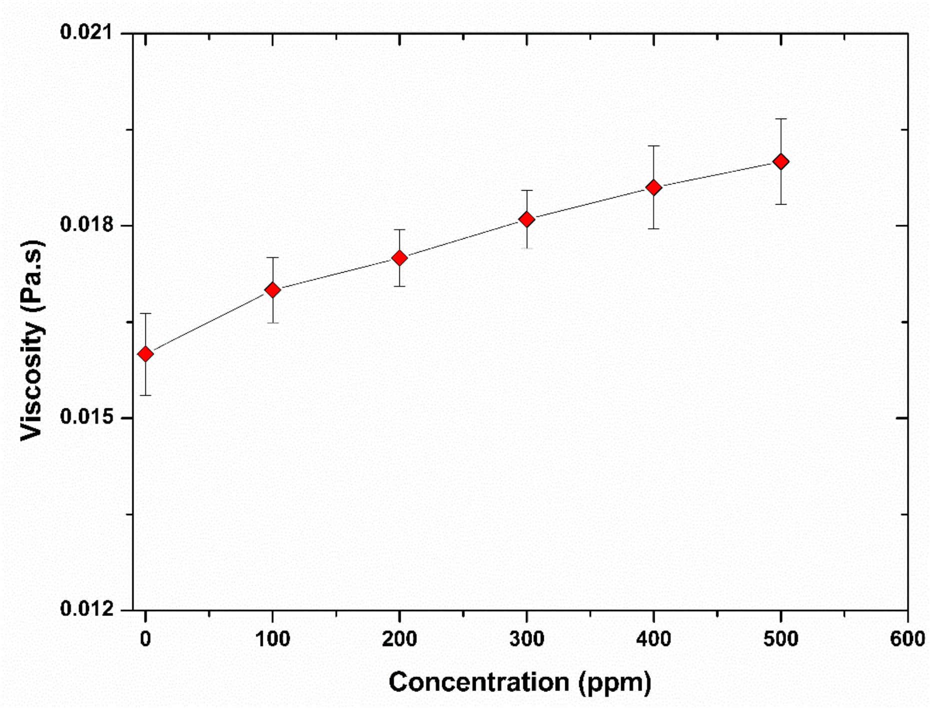


Figure 3.3: Effect of Polydimethyl siloxane concentration on the viscosity of the oil.

In the case of poly dimethyl siloxane, the concentration of the polymer was varied from 100 ppm to 500 ppm. The effect of the different ppm of the PDMS is shown in Figure 3.3. It can be seen from Figure 3.4 that with an increase in the concentration of the polymer, there was an increase in the viscosity of the overall solution. With the addition of the 100 ppm of PDMS, the viscosity observed was 0.017 Pa.s, which was 6.25% more than the solvent viscosity. In the case of the 200 ppm, 300 ppm, and 400 ppm solutions, the increase in the viscosity was 9.37%, 13.12%, and 16.25%, respectively, more than the solvent viscosity. For the highest concentration, the increase in the viscosity of the solution was 0.019 Pa.s, which was 18.75% more than the solvent viscosity.

3.7 Effect of the shear rate on the viscosity of the guar gum, gum arabic and polydimethyl siloxane solution

The effect of the shear rate and concentration on the shear viscosity is shown in Figure 3.4. It was observed that the guar gum solution shows Non-Newtonian behavior when the shear rate was applied. With an increase in the shear rate, the viscosity of the solution was continuously decreasing, which is known as shear thinning behaviour. This is true for all the concentrations (1000 – 3000 ppm) of the guar gum.

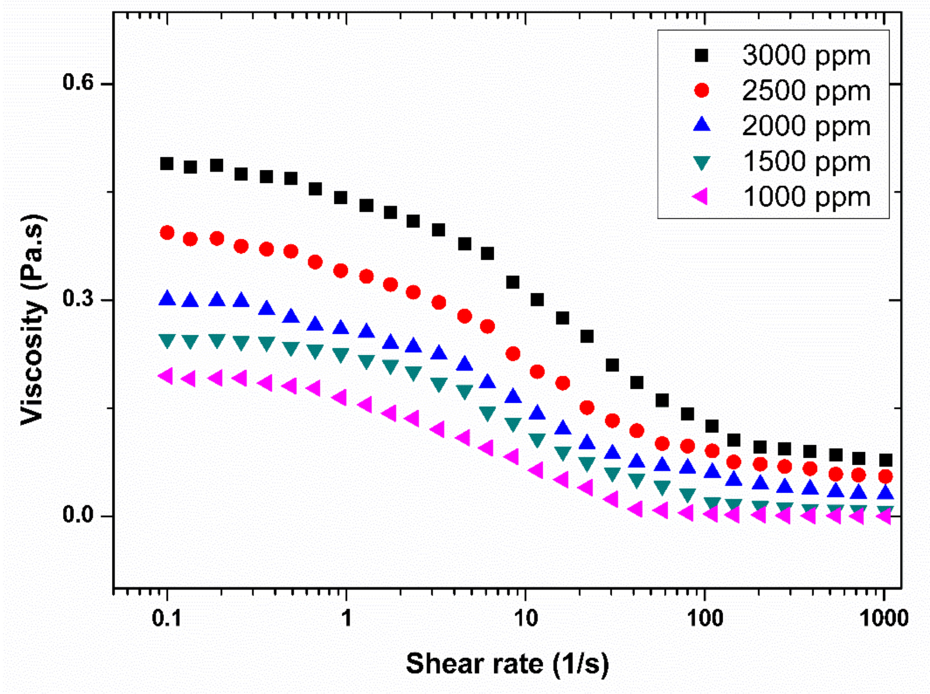


Figure 3.4: Effect of concentration of guar gum on shear viscosity.

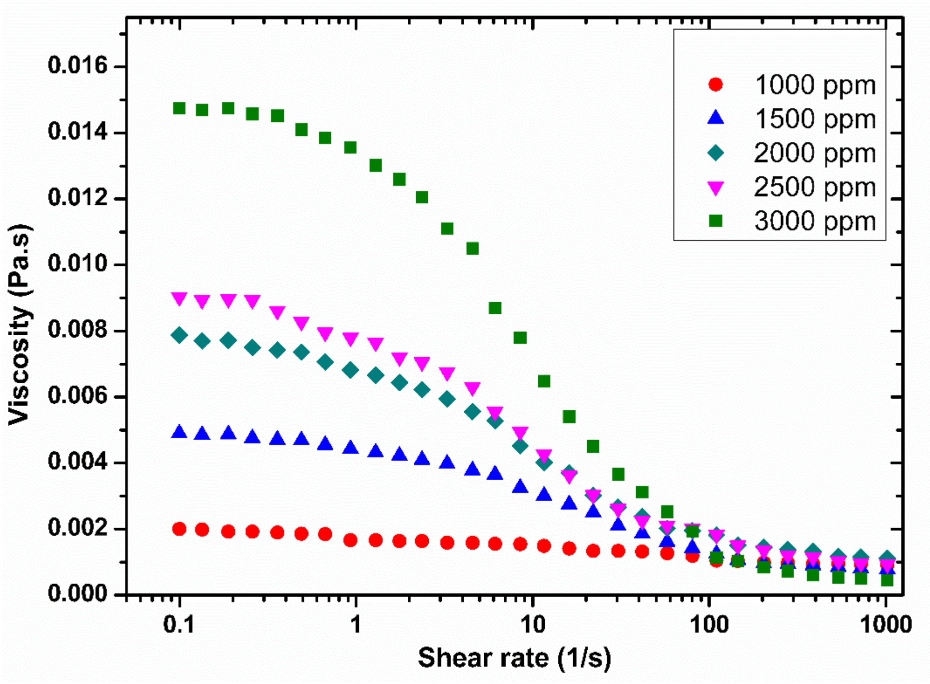


Figure 3.5: Effect of gum arabic concentrations on shear viscosity.

The shear thinning behaviour of the solution at different concentrations was quite rapid for initial shear rate, which decreased after 100 s^{-1}. However, after this shear rate, there was some continuous decrease in the viscosity of the solution. For gum arabic solution, the viscosity behaviour is shown in Figure 3.5. Gum arabic solution at higher concentrations showed shear thinning behaviour; but, for the low concentrations like 1000 ppm, the solution showed Newtonian behaviour. Even for the higher concentration (3000 ppm), the shear thinning effect was observed up to 70 s^{-1}; but, after that, the behaviour was Newtonian. Because, the increase in the viscosity was high for higher concentrations as compared to the lower concentrations of the polymer solutions. The behaviour of the shear thinning was because, at the lower shear rate, the intermolecular entanglements that were disrupted by the lower shear rates were replaced by the new interactions between the different partners, so, at the lower shear rate, the deformation was quite less. But, at a higher shear rate, when the external deformation rate imposed was high, a continuous breakdown of the entanglements occurs, which in turn leads to a continuous decrease in the viscosity with shear rate [117].

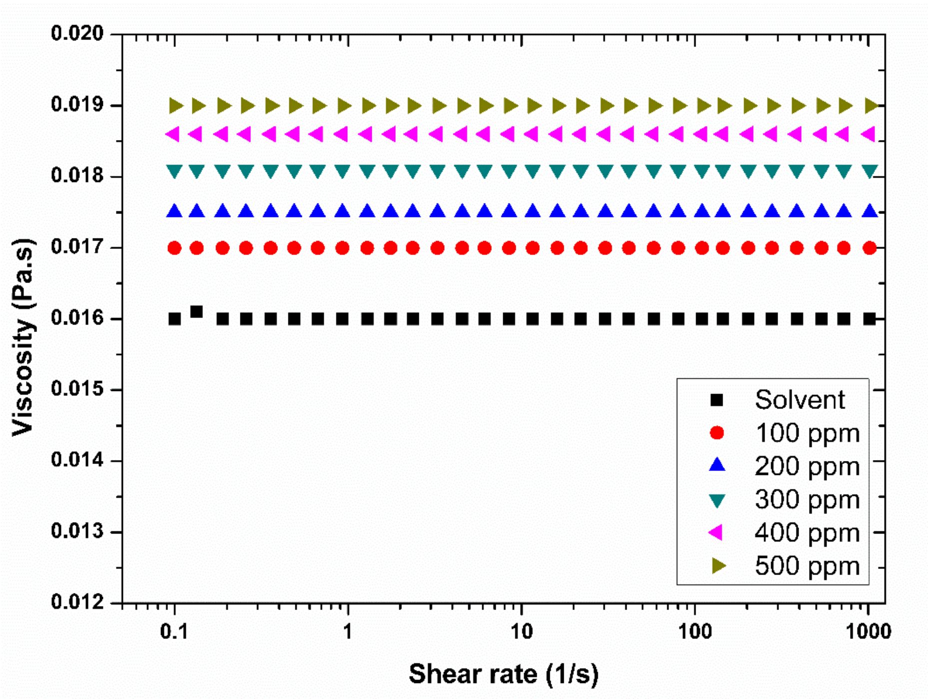


Figure 3.6: Effect of Poly dimethyl siloxane concentration on shear viscosity.

The effect of the concentration of the PDMS on the shear viscosity are shown in Figure 3.6. It can be seen from Figure 3.7 that the behaviour of the oil at zero concentration of the PDMS was Newtonian type with shear rate. For the higher concentration of the PDMS in the solvent, there was a considerable increase in the viscosity, but, the overall behaviour of the fluid was always Newtonian type. When the concentration of the polymer in the oil was 500 ppm there was 18.75% increase in the viscosity of the solution; however, for all the concentrations of the solution, the behaviour of the fluid under the shear rate was Newtonian type.

3.8 Effect of temperature on the viscosity of the guar gum and gum arabic and PDMS solutions

After observations of the effect of the concentration of the polymer on the viscosity of the solution, the effect of the temperature was studied. The temperature of the solution was varied from the 25°C to 45°C for different concentrations, and the effect on the viscosity was observed. The effect of temperature on the viscosity of the guar gum and gum Arabic is shown in Figures 3.7 and 3.8, while the effect of the temperature on the polymer solution (PDMS) in oil is shown in Figure 3.10. It can be seen from Figure 3.8 that for guar gum solution when the concentration of the polymer was 1000 ppm, the maximum decrease of the viscosity from 25°C to 45°C was 9.74% and for 1500 ppm, this decrease in the viscosity with the temperature was about 4.4% to 22.7% from 30°C to 45°C. This decrease in viscosity with increase in concentration of the polymer from 2000 ppm to 3000 ppm was 20% from the initial value at 25°C. For 30°C, the average decrease in the viscosity was 2.5%, which was almost 7% for 35°C. The maximum drop in viscosity of the polymer solution was observed at 45°C, which was about 20%.

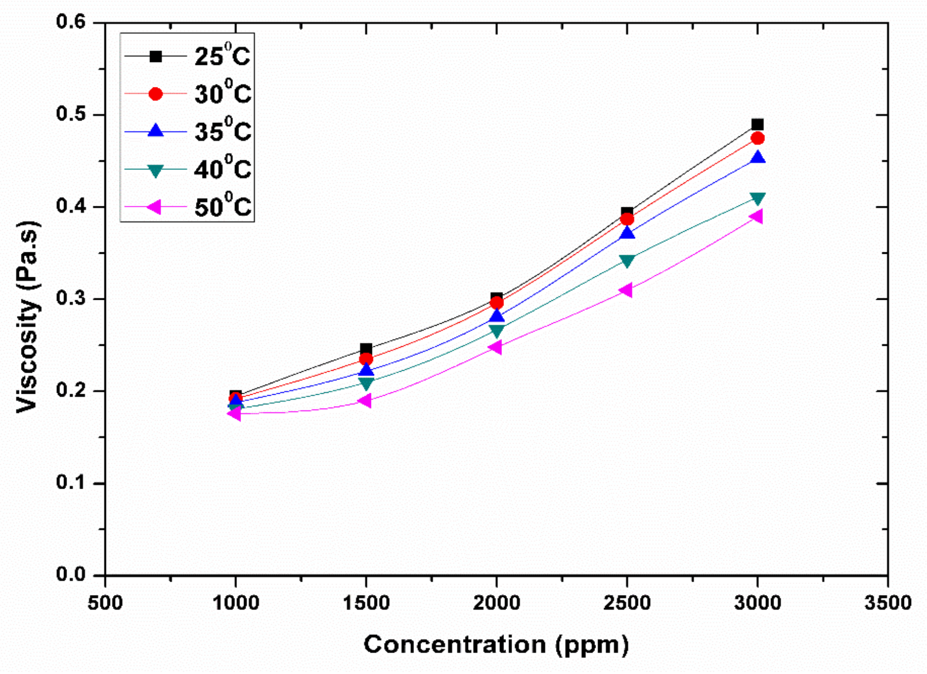


Figure 3.7: Effect of temperature on the viscosity of the guar gum solution.

It was observed that for lower concentrations of the guar gum solution, the decrease in the viscosity with temperature was less as compared to the higher concentrations. Similar behaviour was observed for the gum arabic solutions, for which, the decrease in viscosity with increase in temperature was very rapid as shown in Figure 3.8.

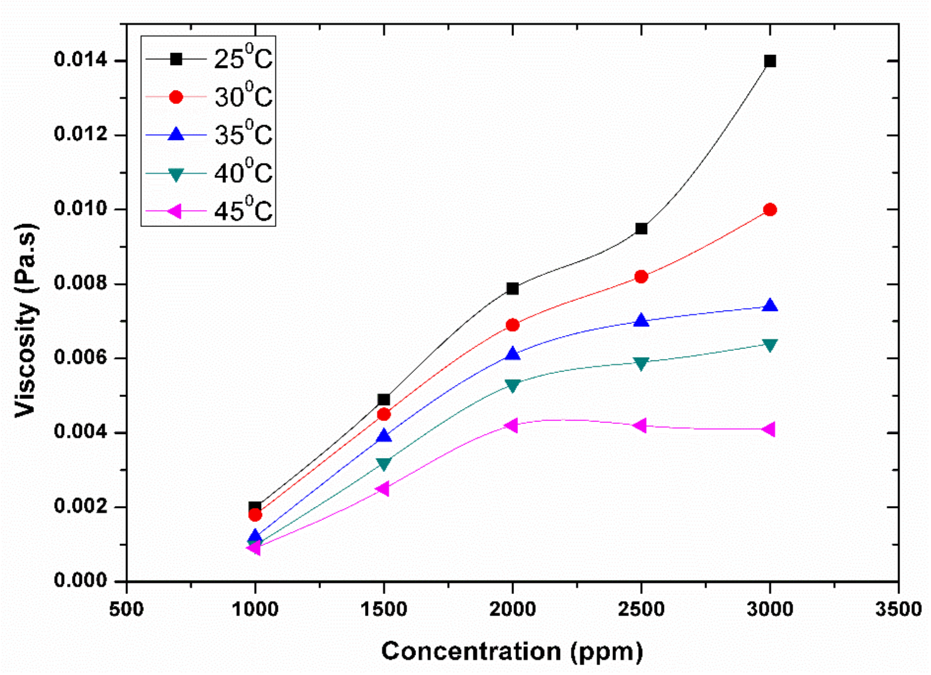


Figure 3.8: Effect of temperature on the viscosity of the gum arabic solution.

The change in the viscosity for the gum arabic solution was more rapid as compared to the guar gum solution. For 1000 ppm of the gum arabic solution, the decrease in the viscosity at 25°C was about 10%, which further increased to 40% at 35°C. For 40°C and 45°C, the decrease in the viscosity was 51% and 54%, respectively.

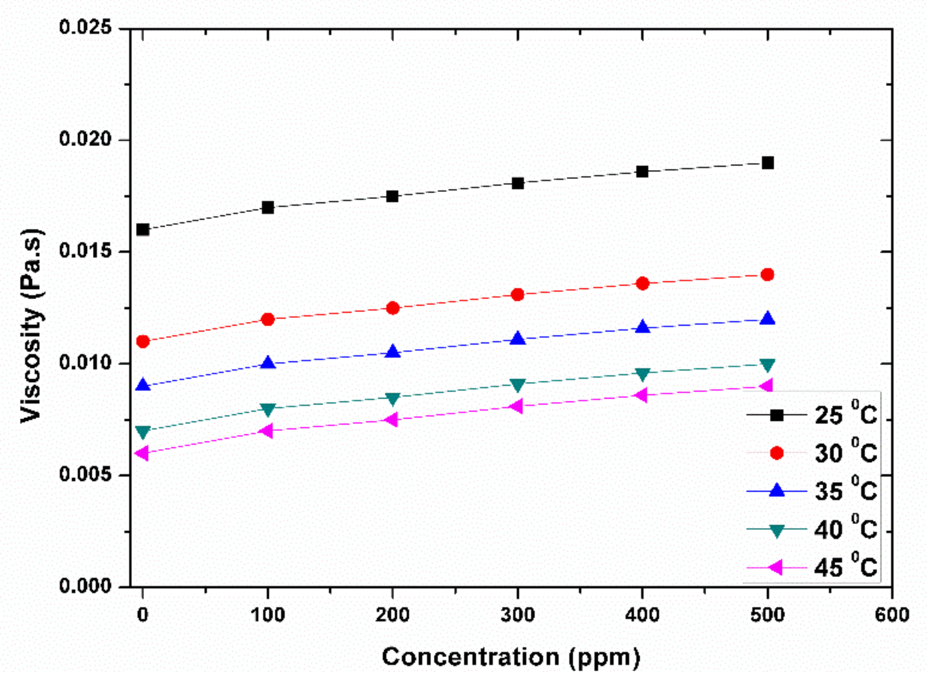


Figure 3.9: Effect of temperature on the viscosity of the PDMS solution.

For 1500 ppm of gum arabic solution, the decrease in the viscosity was 8.1% and at 45°C, the decrease was 48.9%. Similar behavior of the solution was observed for the higher concentrations (2000 ppm – 3000 ppm) of the polymer solution. It was found that for lower temperatures (25°C – 35°C) of the gum arabic solution, the average decrease in the viscosity was about 10% (1000 ppm) to 28.5% (3000 ppm).

The average decrease in the viscosity of the gum arabic solution at 35°C for all concentrations was 31.26%. At 40°C, the average decrease in the viscosity of the solution from the initial value (25°C) was 42.6%, which was 55.3% at 45°C for all concentrations of the polymer as shown in Figure 3.8. It was found that in case of guar gum, the change in the viscosity of the solution was significant for higher concentrations of the gum arabic solutions.

The effect of the temperature and concentration for oil-soluble polymer PDMS is shown in Figure 3.9. It can be seen from the figure that for oil-soluble polymer, there was also a significant decrease in the viscosity of the solution with a change in the temperature. But, for the PDMS solution, the change in the viscosity with temperature was more than that of the water-soluble polymer solutions. For 30°C, the average change in the viscosity of the solution was almost 27% for all the concentrations, which was only 13% for gum arabic solutions. With an increase in the temperature from 30°C to 35°C, the average change in the viscosity of the solution of the oil-soluble polymer was about 39%. The maximum change in the viscosity of the solution was observed at the 45°C, which was almost 55% from the initial value of the viscosity at 25°C.

3.9 Effect of concentration and temperature on the density of the polymer solutions

After the study of the viscosity of the polymer solution, the effect of the salt concentration and the temperature was observed on the density of the solution. The density of the solution was measured by using specific gravity bottle. Initially, a 5 ml solvent was weighed on a calibrated weighing scale and then, another 5 ml solution was weighed which contains salt or polymer dissolved in it. The effect of the KCl salt and the temperature is shown in Figure 3.11. Since the concentration of the polymer in the water was in ppm, so, there was no change in the density was observed in case of the water-soluble polymers. But, in the case of PDMS, there was a change in the density of the oil with an increase in the concentration.

The effect of KCl salt on the density of the solution was observed because, in Chapter 4, the shear degradation of the water-soluble polymers was studied. So, to calculate the flow properties, the change in the rheological properties was observed. The change in the density of water with concentration of KCl salt is shown in Figure 3.10.

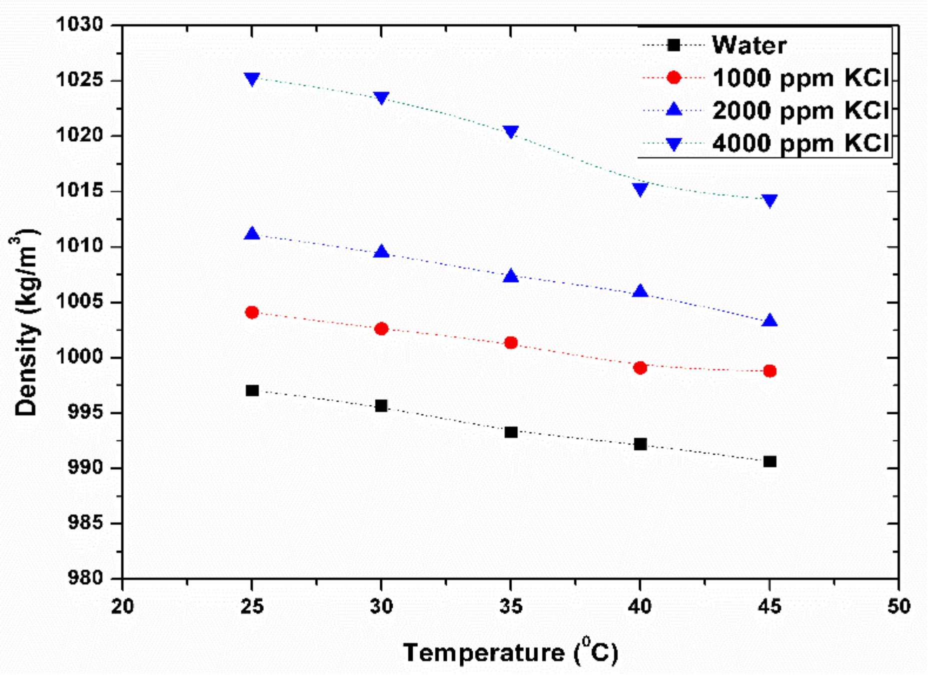


Figure 3.10: Effect of the salt concentration on the density of the water.

It can be seen from Figure 3.10 that when the temperature of water was 25°C, the density was 997.04 kg/m^3. It was observed that with an increase in the temperature from 25°C to 45°C, the density of water decreased from 997.04 kg/m^3 to 990.63 kg/m^3. For water, a maximum of 0.64% decrease in the density was observed at 45°C as compared to 25°C. Then, the effect of the KCl salt was observed on the density. At 25°C, with the addition of the 1000 ppm on the salt concentration, the density of the solvent was changed to 1004.09 kg/m^3 from 997.04 kg/m^3 at 25°C. With further increase in the concentration of the salt, the density of the solvent was 1011.2 kg/m^3 at 2000 ppm and 1025.30 kg/m^3 at 4000 ppm of KCl. It can be seen from the bar graph that with the addition of the salt at 25°C, the increase in the density of the solution was 2.85% with 4000 ppm of salt concentration. After observation of the density at 25°C, the effect of the temperature on the density was observed. It can be seen from Figure 3.10 that with an increase in the temperature of water from 25°C to 45°C, the maximum change in the density was about 0.64%. For 1000 ppm of the salt concentration, the change in the density was 0.14% at 30°C and

0.52% at 45°C. For the 2000 ppm of salt concentration at 30°C, the change in the density was 0.15%, which was 0.18% for 4000 ppm salt concentration. At a higher temperature of 45°C, the change in the density of the solution was 0.77% for 2000 ppm and 1.09% for 4000 ppm of KCl salt concentration.

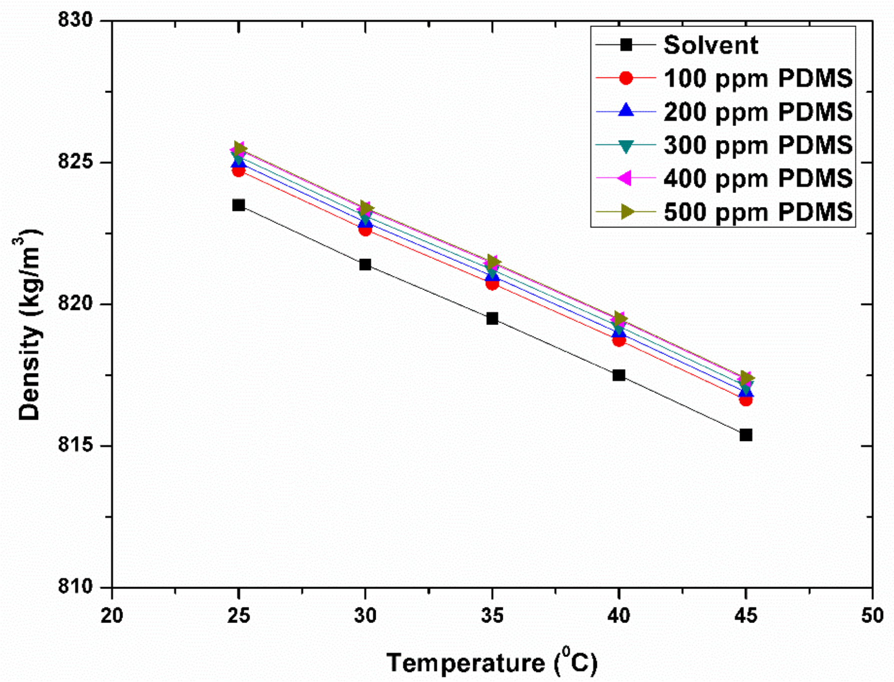


Figure 3.11: Effect of polymer concentration on the density of the oil.

In the context of this, for the PDMS solution, the change in the density was different from that of the polymers soluble in water. The change in the density of oil with temperature was more than that of water. When the temperature was 30°C, the change in the density of the solvent was 0.28%, which further increased to 0.48% at 40°C, and the maximum decrease in the density of the oil was 0.98% at 45°C. With an increase in the concentration of the PDMS in the oil, an increase in the density was observed. The maximum increase in the density with 400 ppm of the PDMS was 0.23% at 25°C. With an increase in the temperature for different concentrations of the PDMS, a decrease in the density was observed. The average decrease in the density for all concentrations of the PDMS in oil was almost 0.5% at 35°C, which further decreased to almost 1% at 45°C.

3.10 Summary

In the present work, a detailed study on the rheological characterization of the polymer solutions was done. The effect of the concentration on the viscosity of the solvent was observed and the effect of the shear rate was also observed to investigate the behaviour and the flow properties of polymer solutions. The effect of the temperature on the viscosity of the polymer solutions was observed. After observation of the viscosity of the polymer solution, the effect of the temperature was observed on the viscosity as well as the density of the polymer solutions. The maximum increase in viscosity for guar gum, gum arabic and PDMS was 500%, 14.7% and 16.25% respectively. There was 20% decrease in viscosity for guar gum solution, with rise in temperature from 25 ^{o}C to 45 ^{o}C. This change was almost 55% in case of PDMS and gum arabic solution.

CHAPTER - 4

DRAG REDUCTION IN SINGLE-PHASE FLOW

4.1 General

This chapter deals with the effect of the selected polymers on the drag reduction percentage on single-phase flow. The effect of the various concentrations of the selected polymers as well as Reynolds number on the maximum possible drag reduction was observed. After finding an optimum polymer concentration of the polymer at which maximum drag reduction was observed, then degradation study of the polymer was done with the same concentration.

4.2 Drag reduction study for single-phase flow

In this study, as two polymers were water-soluble polymers and one polymer was oil soluble so the first water-soluble polymers were tested in the turbulent water flow and the oil-soluble polymer was tested in oil turbulent flow. The effect of the Reynolds number and the concentrations of the guar gum, gum arabic and polydimethylsiloxane was observed on the maximum possible drag reduction.

4.2.1 Experimental Methodology

The experimental set-up is shown in Figure 4.1 was used to observe the effect of polymer solution on frictional drag. A circular galvanized iron pipe with an internal diameter 19.05 mm and length 3048 mm was used. A distance of 1520 mm (test section) was kept between the two pressure tapings. A digital pressure transducer (Honeywell STD730, USA) having an accuracy of 0.05% and range –7 to 7 bar was used to measure the differential pressure by connecting it to a data acquisition system. The injection point was kept before the first pressure tapping and the distance from the injection point to the first pressure tapping was kept 150 mm to ensure proper mixing/distribution of the polymer solution as per the mixing length defined by Ranade and Mashelkar [47]. No in-line mixing device was used downstream the injection point. However, the reservoir was equipped with a mechanical impeller in addition to heating and cooling arrangements. The impeller was operated only during the injection period at a low speed (< 30 rpm) to avoid polymer degradation in the reservoir.

The injection tube of 5 mm diameter was kept parallel to the flowing stream near the wall to avoid any disturbance during the injection. The flat perforated tip of the injection pipe (having five holes of ~1 mm each) creates a sprinkling effect and enhances the degree of mixing. The velocity of injection fluid (~1.7 m/s) was within the range of fluid velocity in the pipe (0.8–2.3 m/s). Therefore, the average strain rate generated is insignificant as compared to the critical strain rate associated with mechanical degradation of polymers [118]. The type of injection of the polymer solution was diffusing injection (see [119]) for more details on different approaches to drag reduction).

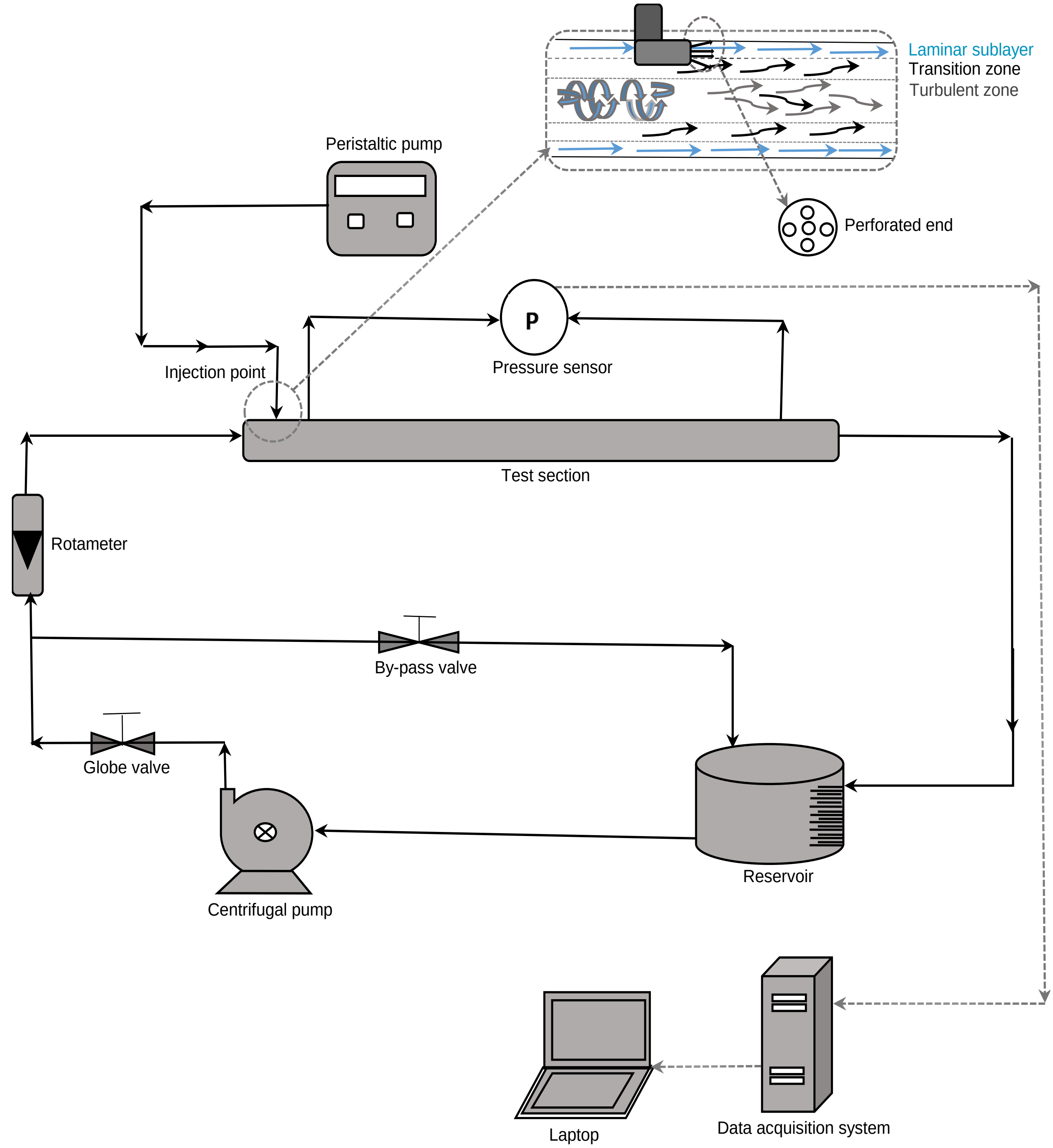


Figure 4.1: Experimental set-up used for drag reduction studies.

A centrifugal pump was used to maintain the flow rate (3000 rpm, max.). A rotameter was used to measure the flow rate from 800 to 2400 L/h with the uncertainty of ±1.5%. A peristaltic pump was used to inject the polymer solution (400 mL/min). This also avoids the mechanical degradation of polymer solution during the controlled injection. Figure 4.1 also presents a brief mechanism of drag reduction in a turbulent flow. A detailed explanation of this phenomenon is available elsewhere

[120]. Water was collected in a reservoir, which was connected to the centrifugal pump. Rotameter was connected after the bypass valve to observe and ensure fully developed turbulent flow in the test section. The polymer solution was injected (400 ml/min) for the first 2.5 min and no degradation was noticed during this period. The actual degradation started during the continuous recirculation of the bulk fluid (after complete injection of polymer) and corresponding results are discussed in section 4.2.4. After the completion of one loop, the water was returned to the reservoir, which was again recirculated (for 1400 cycles) to determine the mechanical degradation of polymer solution with number of passes. Various parameters and their ranges used during experimentation are given in Table 4.1.

Table 4.1: Various parametric conditions and range used during experimentation.

Parameter	**Units**	**Range/Type**
Flow rate of bulk fluid	l/h	800–2400 (adjusted as per the required Reynolds number)
Reynolds number	-	17700, 19900, 22100, 24400, 26600, 28800, 31000, 33200, 35400, 37700, 39900, 42100, 44300
Biopolymer used	-	Guar gum (100 mesh powder)
Biopolymer concentration		
(a) in the injected fluid	ppm	1000, 1500, 2000, 2500, 3000
(b) in the bulk solution	ppm	50, 75, 100, 125, 150
Salt used	-	Potassium chloride (KCl)
Concentration of salt		
(a) in the injected fluid	ppm	1000, 2000, 4000
(b) in the bulk solution	ppm	50, 100, 200

Some of the injected polymers may accumulate inside the loop (including the test section) due to the interaction between the polymer and metal surface, nature of the polymer, and also the flow pattern. This could be the reason for the differences noticed in the drag values for fresh water before and after the experimentation with different polymer solutions. To avoid the error resulting from polymer accumulation, the reservoir, and the test loop was thoroughly washed several times (with 1:5 ethanol and water mixture) after each experiment and the results of water were validated with that of initial/previous results.

Since the flow through the pipe was turbulent, the calculations for various outcomes were done by using different formulae described below. For all the flow regimes of Newtonian and non-Newtonian fluids, the mean shear stress at the wall (τ_w) in a straight pipe having diameter D with fully developed flow is given by equation (4.1).

$$\tau_w = \frac{D}{4}\frac{\Delta P}{\Delta x} \tag{4.1}$$

Here, ΔP is the pressure drop along the length Δx. To calculate the friction factor (f) from the calculated shear stress, equation (4.2) was used.

$$f = \frac{\tau_w}{\frac{1}{2}\rho u_m^2} \tag{4.2}$$

Here ρ is density and u_m are the mean velocity of the fluid in the pipe. The formulae used to evaluate the friction factor in laminar and turbulent flow are given by equations (4.3) and (4.4), respectively.

$$f = 16/\mathrm{Re} \tag{4.3}$$

$$\frac{1}{\sqrt{f}} = 4\log_{10}\left(\mathrm{Re}\sqrt{f}\right) - 0.4 \tag{4.4}$$

The Reynolds number (Re) and friction factor (f) were calculated based on the properties of bulk solution and the flow rate of the bulk solution was adjusted accordingly to maintain a constant Reynolds number during the experiments. Equation (4.5) gives the expression for Virk's MDRA at which friction factor approaches to an asymptotic value.

$$\frac{1}{\sqrt{f}} = 19.0\log_{10}\left(\mathrm{Re}\sqrt{f}\right) - 32.4 \tag{4.5}$$

The percentage of drag reduction was calculated by measuring the corresponding pressure drop and friction factor 'f' using equation (4.6).

$$\text{Drag reduction, DR (\%)} = \left[\frac{f_s - f_p}{f_s}\right]_{\mathrm{Re}=const} \times 100 \tag{4.6}$$

Where 'f_s' is the friction factor for solvent (water) and 'f_p' is the friction factor observed after injection of polymer solution [5].

4.2.2 Effect of addition of guar gum in water flow

To investigate the effect of the addition of guar gum, the percent drag reduction (DR) was studied for different polymer concentrations (1000–3000 ppm) by varying the Reynolds number from 17000 to 45000 at 25 ^{o}C. The viscosity measurements for the reservoir solution at different time intervals during experiments revealed the Newtonian behaviour of the bulk fluid. From these results, as shown in Figure 4 (a), it is clear that the drag reduction depends on both concentration and Reynolds number, which is in accordance with that reported by Warholic et al. [42]. Also, it was observed that the friction factor decreases as the Reynolds number is increased. It was observed that the maximum drag reduction of 71.4% was achieved at 3000 ppm concentration and 45000 Reynolds number. The percentage of drag reduction increased with turbulent strength i.e. Reynolds number and this observation is in good agreement with the literature [121]. With an increase in concentration of the polymer, viscosity of the solution increases, which affects the Reynolds number. A minimum of 40% drag reduction was noticed even at low concentration of polymer (1000 ppm) and at low Reynolds number (17000). The change in the drag reduction was significant at Reynolds numbers up to 35000 and thereafter a negligible change (< 3%) was observed. The reason behind the significant drag reduction observed under high turbulent conditions can be explained by the hypothesis of Bakewell and Lumley [122], which states that the expansion of the polymer molecules occurs in the flow outside of viscous sublayer due to variation in the strain rate.

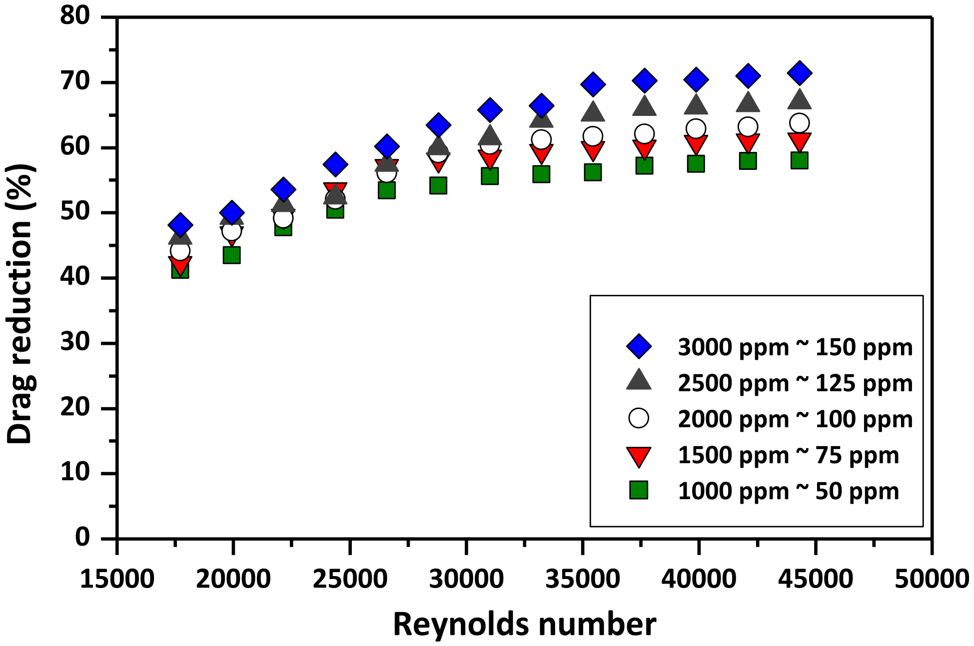


Figure 4.2: Effect of concentration and Reynolds number on drag reduction.

Due to these variations, effective viscosity increases, which dampens the formation of small eddies causing drag reduction. Due to the drag reduction, there are significant savings of energy in the form of pumping power. In the present study, 1000 ppm of guar gum in the injection fluid resulted in a maximum of 53% drag reduction, whereas, an equivalent concentration of the same polymer in a pre-mixed solution (50 ppm) yielded 16% drag reduction in a rotating disk apparatus [123]. Further, 2000 ppm of biopolymer in the injection fluid resulted in 60% drag reduction, while, its equivalent concentration in pre-mixed solution (100 ppm) yielded only 24% drag reduction in a rotating disk. Also, 3000 ppm of guar gum in the injection mode resulted in 71% drag reduction, however, an equivalent concentration of this biopolymer in a pre-mixed solution (150 ppm) in a circular pipe yielded only 18% drag reduction [124]. Some cases in which heterogeneous injection of synthetic polymer or surfactant was done, also compared with the existing system. A series of experimentation was performed by [125], in which synthetic polymer was injected centrally in the pipe and was able to observe 60% drag reduction. A similar study was done by [126] using surfactant solution injected in the side wall of rectangular closed system. With use of surfactant solution, the maximum drag reduction possible in acrylic section was about 50%. Therefore, it can be concluded that the injection of polymer in the boundary layer exhibits better drag reduction ability than using pre-mixed solutions.

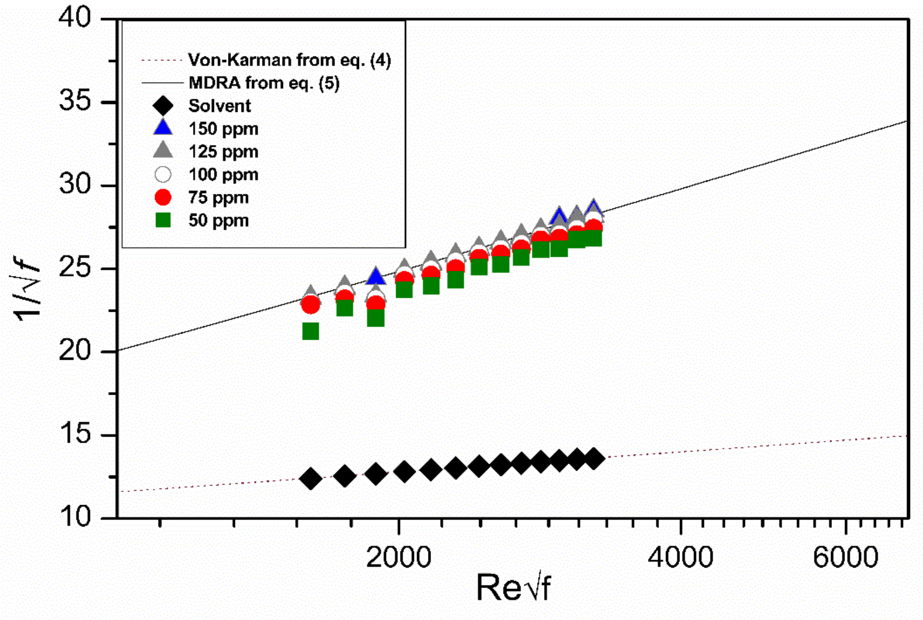


Figure 4.3: Friction factor vs. Reynolds number.

To validate the system, the obtained results were compared with two theoretical relations viz., Prandtl-Karman law (P-K law) and Virk’s MDRA as shown in Figure 4.3. From this figure, it can be observed that the results obtained for the turbulent flow of water in pipe were closely fitted to the P-K law given by equation (4).

4.2.3 Effect of salt on the drag reduction percentage

A similar set of experiments (discussed in section 4.2.2) were performed with 3000 ppm of polymer concentration and different Reynolds numbers by adding KCl salt (concentrations 1000, 2000 and 4000 ppm) and the results are shown in Figure 4.4. Results revealed that the addition of KCl salt to the polymer solution has a negative effect on drag reduction. The drag reduction values decreased with increasing the salt concentration. The maximum drag reduction achievable for 3000 ppm polymer concentration (71.4%) decreased to 67.14%, 63.44% and 43.68% for salt concentrations of 1000, 2000, and 4000 ppm, respectively. The reason for this observation could be as follows.

Mixing of a polymer with a solvent at low temperature without any ionic species/electrolytes leads to the disordered state of the polymer molecules. However, with the addition of salt to the polymer solution, the side chains collapse down to the backbone due to charge screening [127] [128]. Due to this phenomenon, the molecules of the polymers form rod-like shape [122, 126, 127].

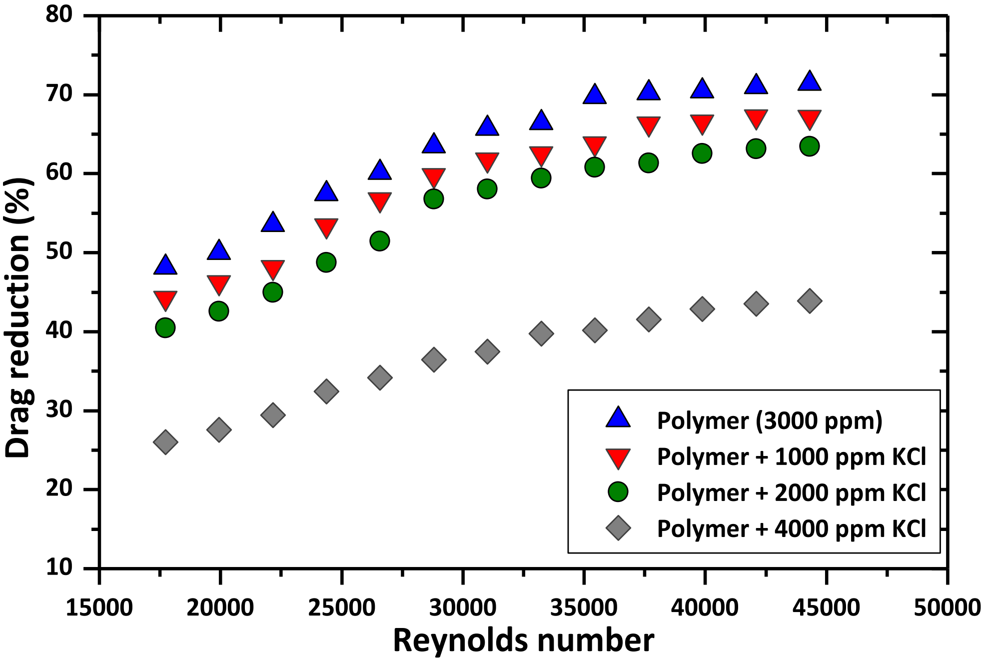


Figure 4.4: Effect of KCl concentration on drag reduction percentage.

Addition of salt to the polymer solution leads to the transition of molecules from a disordered state to ordered state causing stretching of the polymer backbone, which also results in increased rigidity of the polymer molecules. A polymer in its ordered state experiences more drag and is less sensitive to fatigue. Therefore, the percentage of drag reduction decreased and shear stability (or resistance to mechanical degradation) increased with the addition of salt. A number of studies have been reported on this conformational change on the basis of viscosity reduction with various salts like NaCl and KCl [122, 124–128].

4.2.4 Effect of salt concentration on shear stability or degradation of guar gum

The mechanical degradation of polymer solutions is still a subject of research interest, because, this results in a continuous loss of effectiveness of the polymer. When the polymer molecules undergo a high shear rate in the impeller of a centrifugal pump, they experience mechanical degradation due to continuous scission of the polymer molecules. A number of studies have been done so far to understand the behaviour of different polymers under high shear conditions using rotating disc apparatus and cylindrical rheometer [86, 120, 129–131].

During this experimentation, a constant (and minimum) pressure drop was observed during the injection period and it continued up to 40 cycles. However, it increased significantly in the subsequent cycles. This indicates that the mechanical degradation was caused mainly by the recirculation pump and not because of diffusion effects during the injection. The shear stability of guar gum solutions was investigated with and without the addition of KCl salt by evaluating the percentage drag reduction with a number of passes (*Np*). The results obtained for different concentrations of polymer and salt at the maximum Reynolds number of 45000 are shown in Figure 4.5. It can be seen from this figure that when the polymer was used without the addition of salt, there was a continuous reduction in the effectiveness of the polymer solution with a number of passes (*Np*).

The drag reduction percentage of 3000 ppm polymer solution, as shown in Figure 4.5a, was 71.4% initially, and it reduced to 47% after 1400 passes through the pump (i.e., 34% decrease in the drag reduction relative to the initial value). Similar behaviour was observed for the other four concentrations of polymer (decrease of about 47%, 51%, 59%, and 62%, respectively, for 2500, 2000, 1500 and 1000 ppm) as shown in Figure 4.5(b-e). It can be seen from these plots that the decrease in drag reduction effectiveness of the polymer was more rapid initially (up to 750 passes) and then it became steady. This may be due to the sensitivity of the polymer chain under high turbulent shear, causing a continuous break down of the polymer chains upon contact with the impeller of the pump.

There was almost 50% decrease in the effectiveness of the polymer solution under high shear after 1400 passes. With the addition of KCl salt, there was a slightly negative effect on the percentage of the initial drag reduction, but the shear stability of the polymer solution became more effective than the solution without salt. It was found that the addition of the salt to polymer makes it 20-25% more shear stable than that of polymer without salt.

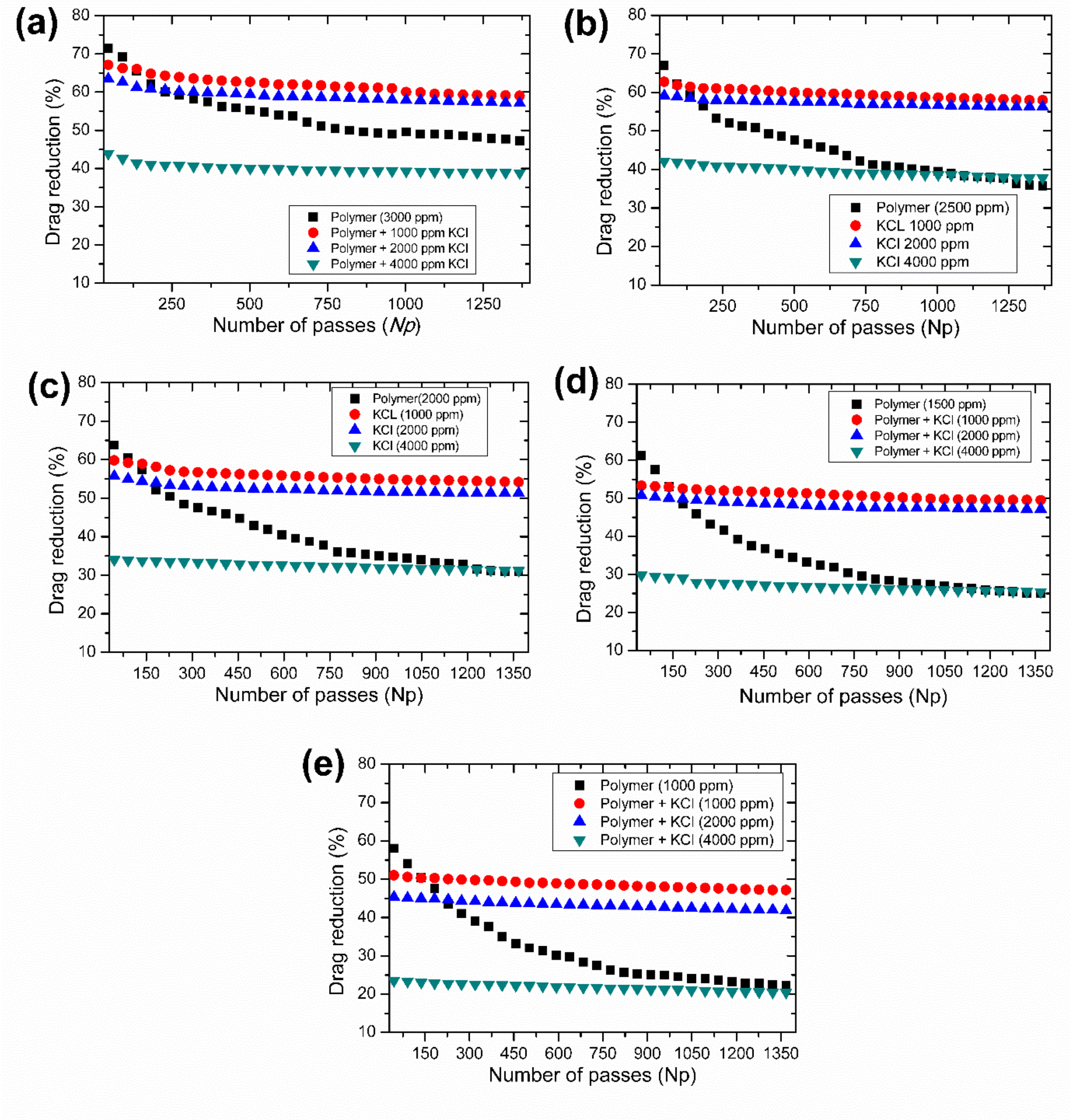


Figure 4.5: Variation of percentage drag reduction with a number of passes for different polymer concentrations (a) 3000 ppm (b) 2500 ppm (c) 2000 ppm (d) 1500 ppm (e) 1000 ppm.

This type of behaviour may be due to the fact that addition of salt increases the rigidity of polymer and makes it more complex, which in turn makes it more stable and effective under high shear conditions [123].

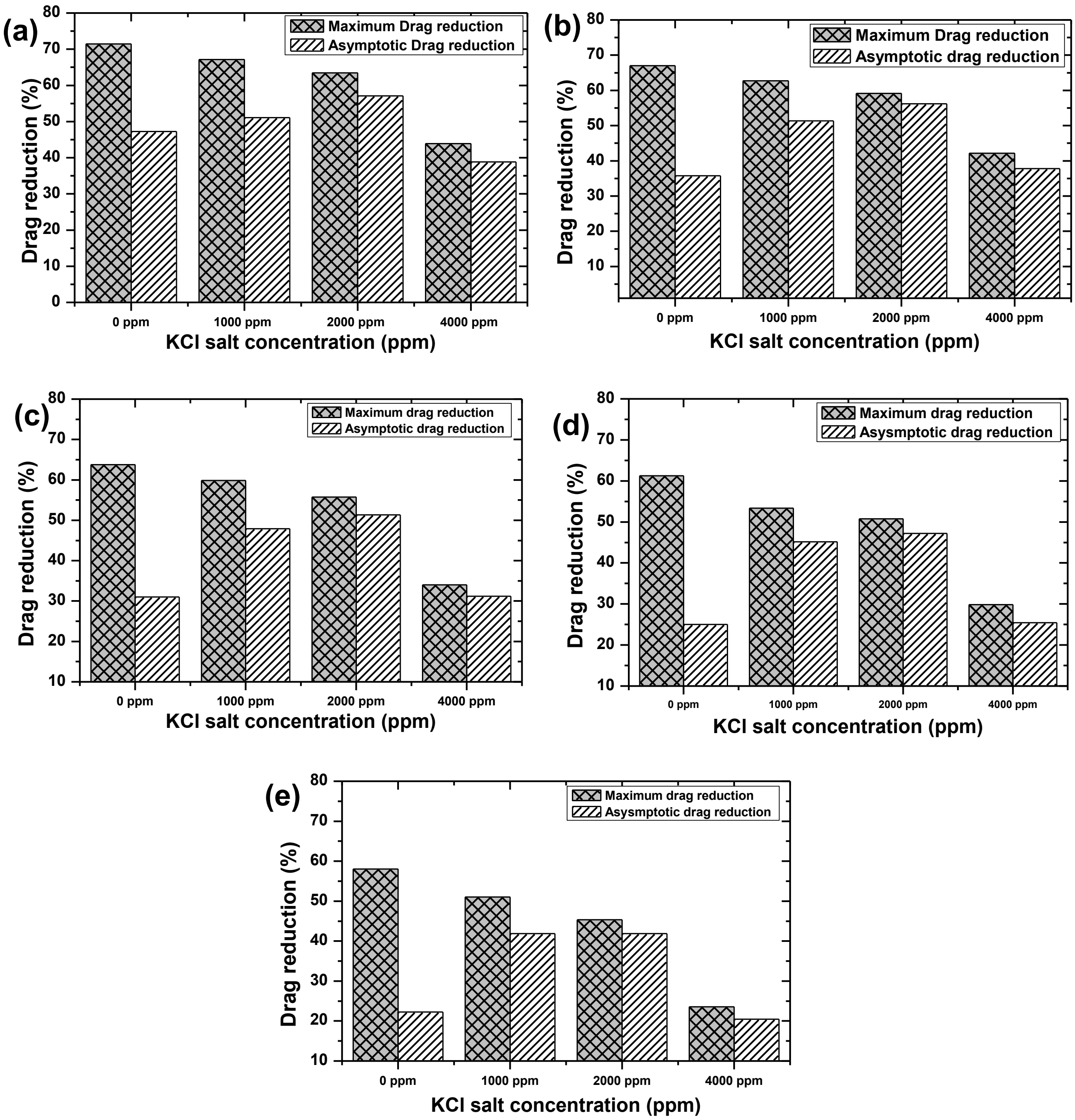


Figure 4.6: Comparison of maximum possible drag reduction with the asymptotic value of drag reduction for polymer concentrations of (a) 3000 ppm (b) 2500 ppm (c) 2000 ppm (d) 1500 ppm (e) 1000 ppm.

It can be observed from the plots of Figure 4.5 that when the salt concentration was 1000 ppm, the initial drag reduction was 67.4%, which is slightly lower than that of the polymer solution without salt. But, when the solution passes through the pump for almost 1400 times, the effectiveness of the solution was observed to be 60%. In this case, the average decrease in the percentage of effectiveness from its initial value was 11%, which was far better than the solution without the addition of salt (i.e. 50%). This result is in accordance with the literature [135], wherein the authors reported a 15% decrease in the effectiveness of a buffer solution for a λ-DNA solution.

Similarly, a better result was observed for 2000 ppm of salt concentration in the polymer solution. It can be observed from Figure 4.5(c) that for the salt concentration of 2000 ppm, the average loss in the effectiveness was only 7% from its initial value even after 1400 passes. This remained 4% in the case of 4000 ppm of salt concentration. However, the 4000 ppm of salt concentration was found to have a more negative effect on the percentage of drag reduction as compared to 1000 and 2000 ppm concentrations.

For a salt concentration of 4000 ppm, the maximum available drag reduction percentage was 43.38% and it became 38.87% after the completion of 1400 passes. This indicates that the addition of a high concentration of salt (4000 ppm) leads to high shear stability. On the other hand, it resulted in very low drag reduction values, which are far below the values that can be achieved without the addition of salt. Similar results were noticed for the other four concentrations of the polymer (2500, 2000, 1500 and 1000 ppm), as shown in Figure 4.5(b-e).

It can be observed from Figure 4.5 that though the initial drag reduction values with the addition of low to moderate amounts of salt (1000–2000 ppm) were lower than that of original polymer, the final drag reduction values were significantly higher than the polymer solution without salt. This resulted in better average drag reduction values relative to the original polymer solution. For 3000 ppm of polymer concentration without the addition of salt, the average drag reduction was 54%. This value increased to 58.6% and 59%, respectively for the salt concentration of 1000 and 2000 ppm. However, the average drag reduction observed with 4000 ppm of salt (40%) was far lower than that of other concentrations of salt. Similar behaviour was also observed for 2500 and 2000 ppm of polymer concentrations, for which the maximum average drag reduction (57.2% and 52.4%) was noticed with 2000 ppm of salt. On the other hand, for a polymer concentration of 1500 ppm, both 1000 and 2000 ppm salt concentrations resulted in the same average drag reduction (52%) and for a polymer concentration of 1000 ppm, a salt concentration of 1000 ppm resulted in the maximum average value (45.2%). These results indicate that 2000 ppm of salt concentration is optimum for high polymer concentrations (3000–2000 ppm), whereas, for low polymer concentrations (1500–1000 ppm), a salt concentration of 1000 ppm is sufficient to achieve the best average drag reduction without compromising upon the shear stability.

For a better understanding of the phenomenon, the maximum drag reduction values for different proportions of salt are compared with the minimum/asymptotic value, where the drag reduction became almost steady (Figure 4.6). The mechanical degradation of the polymer was found to depend on the number of passes as well as the polymer-solvent interactions. The degradation rate of the polymer chain becomes more severe due to the continuous breakdown of molecules [88]. Hence, the degradation rate of polymer without the addition of salt (represented by the difference between the initial and final drag reduction values) was found to be more rapid. It can be noticed from Figure 4.6, that there was an appreciable change in the shear stability of the polymer solution with the addition of salt. Of the two salt concentrations 1000 and 2000 ppm, the 2000 ppm showed more consistent and better results. The change in the average drag reduction for 2000 ppm was 7%, whereas it was 11% in the case of 1000 ppm salt concentration. For 4000 ppm of salt concentration, the decrease in the percentage of drag reduction was only 4%, however, this concentration had a more negative effect on the average drag reduction percentage.

4.2.5 Effect of addition of gum arabic in water flow

in the study of drag reduction with guar gum, the concentration of the polymer as compared to the bulk solution was kept 50 – 150 ppm but with gum arabic, the concentration was kept 50 – 300 ppm. The reason behind to keep the concentration of the gum arabic more was its less effect on the drag reduction with a difference of 25 ppm in each concentration as well as the maximum possible drag reduction with guar gum was observed at 300 ppm of polymer concentration. So, with a pilot run of the experiment, the Reynolds number was kept the same but the concentration was varied to get the maximum drag reduction with the selected polymer. Parametric conditions kept during the experimentation are shown in Table 4.2.

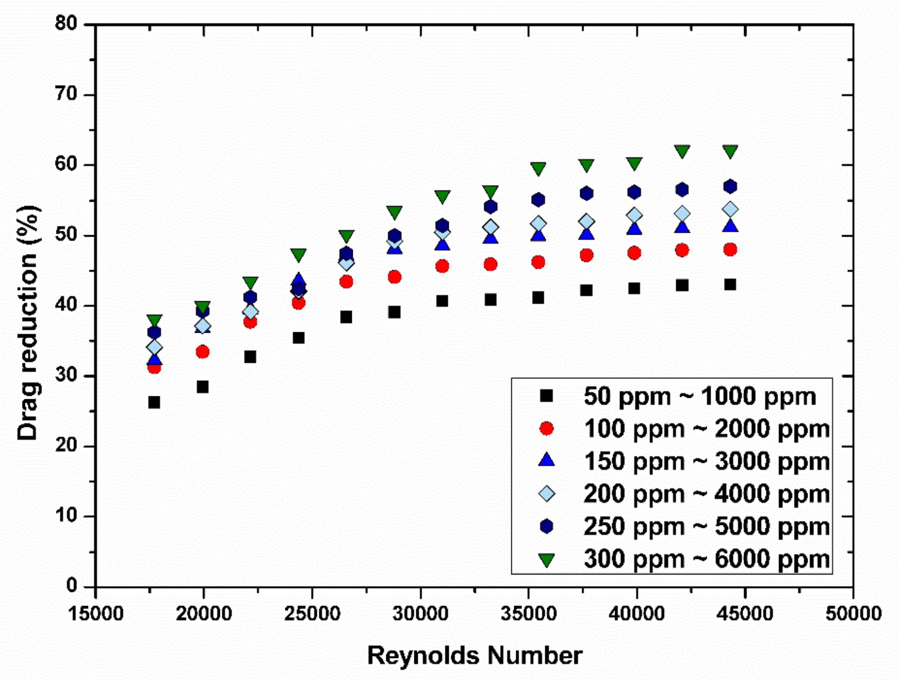


Figure 4.7: Effect of concentration and Reynolds number on drag reduction percentage.

The effect of the drag reduction percentage with Reynolds number and concentration of the polymer (gum arabic) is shown in Figure 4.7. it can be seen from Figure 4.7 that with an increase in the concentration the drag reduction percentage also increases. The minimum drag reduction percentage 26.25% was observed with 50 ppm of the gum arabic concentration at 17723 Reynolds number. The maximum drag reduction 62.15% was with 300 ppm of the concentration of the polymer at 44039 Reynolds number. It was observed that similar to the case of guar gum, the drag reduction percentage also rapidly increased from 17000 to 37000 Reynolds numbers. A significant effect of the concentration was observed at different Reynolds number. The maximum drag reduction percentage increases with increase in the concentration of the polymer in the bulk solution. When the concentration of the polymer was 50 ppm the minimum drag reduction, percentage was 26.25% and maximum drag reduction was 43.02% when the Reynolds numbers was 44039. In the case of the 100 ppm of the polymer solution the minimum drag reduction percentage was 31.25% and the maximum was 48.02%. Similarly, for the higher concentrations like 150 ppm, 200 ppm, 250 ppm ad 300 ppm the minimum drag reduction values observed were 32.25%, 34.15%, 36.23%, and 38.12% respectively as shown in the Figure 4.7.

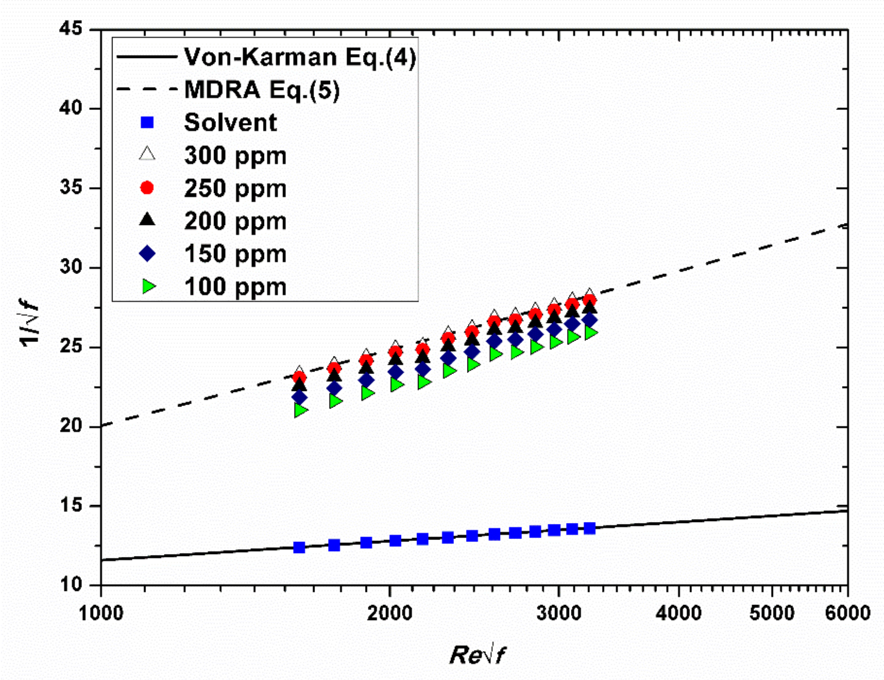


Figure 4.8: Friction factor v/s Reynolds number.

Table 4.2: Various parametric conditions and range used during experimentation.

Parameter	Units	Range/Type
Flow rate of bulk fluid	L/h	800–2400 (adjusted as per the required Reynolds number)
Reynolds number	-	17700, 19900, 22100, 24400, 26600, 28800, 31000, 33200, 35400, 37700, 39900, 42100, 44300
Biopolymer used	-	Gum arabic (100 mesh powder)
Biopolymer concentration		
(a) in the injected fluid	ppm	1000, 2000, 3000, 4000, 5000, 6000
(b) in the bulk solution	ppm	50, 100, 150, 200, 250, 300
Salt used	-	Potassium chloride (KCl)
Concentration of salt		
(a) in the injected fluid	ppm	1000, 2000, 4000
(b) in the bulk solution	ppm	50, 100, 200

The maximum possible drag reduction values observed at different concentrations 150 ppm, 200 ppm, 250 ppm ad 300 ppm was 51.22%, 53.75%, 56.99%, and 62.15%, respectively. It was observed that there was a rapid increase in the drag reduction percentage up-to 33000 and 35000 values but after the 35000 the average increase in the drag reduction values were 3%-5%.

To validate the experiments in the turbulent flow the observed values were fitted in the Prandtl-Karman (known as P-K law) equation and the Virk's maximum drag reduction asymptotic model as shown in Figure 4.8. The observed values were fitted into the model.

4.2.6 Effect of the KCl salt on the maximum drag reduction percentage

A set of experiments were performed using a maximum concentration of the polymer 6000 ppm or 300 ppm in bulk solution. The KCL salt was added in the polymer at different concentrations and the drag reduction percentage was observed with similar Reynolds numbers. It was observed that when the salt was added into the polymer solution there was a negative effect on the drag reduction. There was a decrease in the drag reduction values when the concentrations of the KCl salt was increased. It was observed that there was 5.2% decrease in the drag reduction percentage when the salt concentration was 1000 ppm, which further increases to almost 8% for 2000 ppm of the salt concentration and 18% for 4000 ppm of the salt concentration.

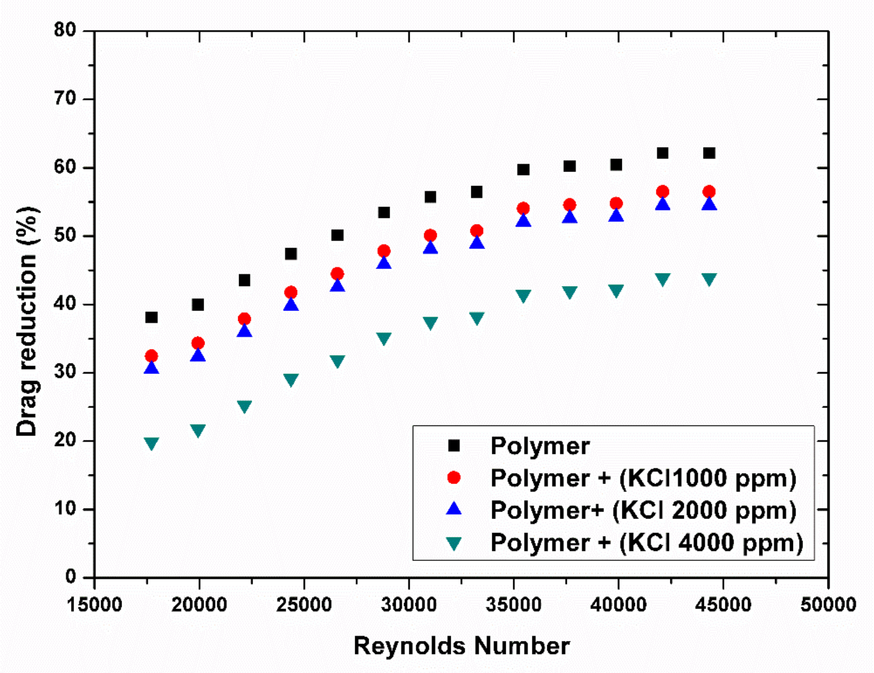


Figure 4.9: Effect of the salt concentration on the maximum possible drag reduction.

The reason behind this negative effect of the drag reduction was similar for different natural polymers like when salt was added into the polymer solutions there was the collapse of the side chains of the polymer. This collapse leads to the transition of the disordered state of the chains to an ordered state. In the ordered state, the polymer molecules experience more drag as compared to the disordered state, which is the reason for the negative effect on the drag reduction percentage.

4.2.7 Effect of salt concentration of the shear stability or degradation of gum arabic

The effect of the KCl salt concentration was observed on the gum arabic solutions of different concentrations. It was observed in the case of the guar gum that there was almost 47% improvement in the shear degradation with the addition of the KCl salt.

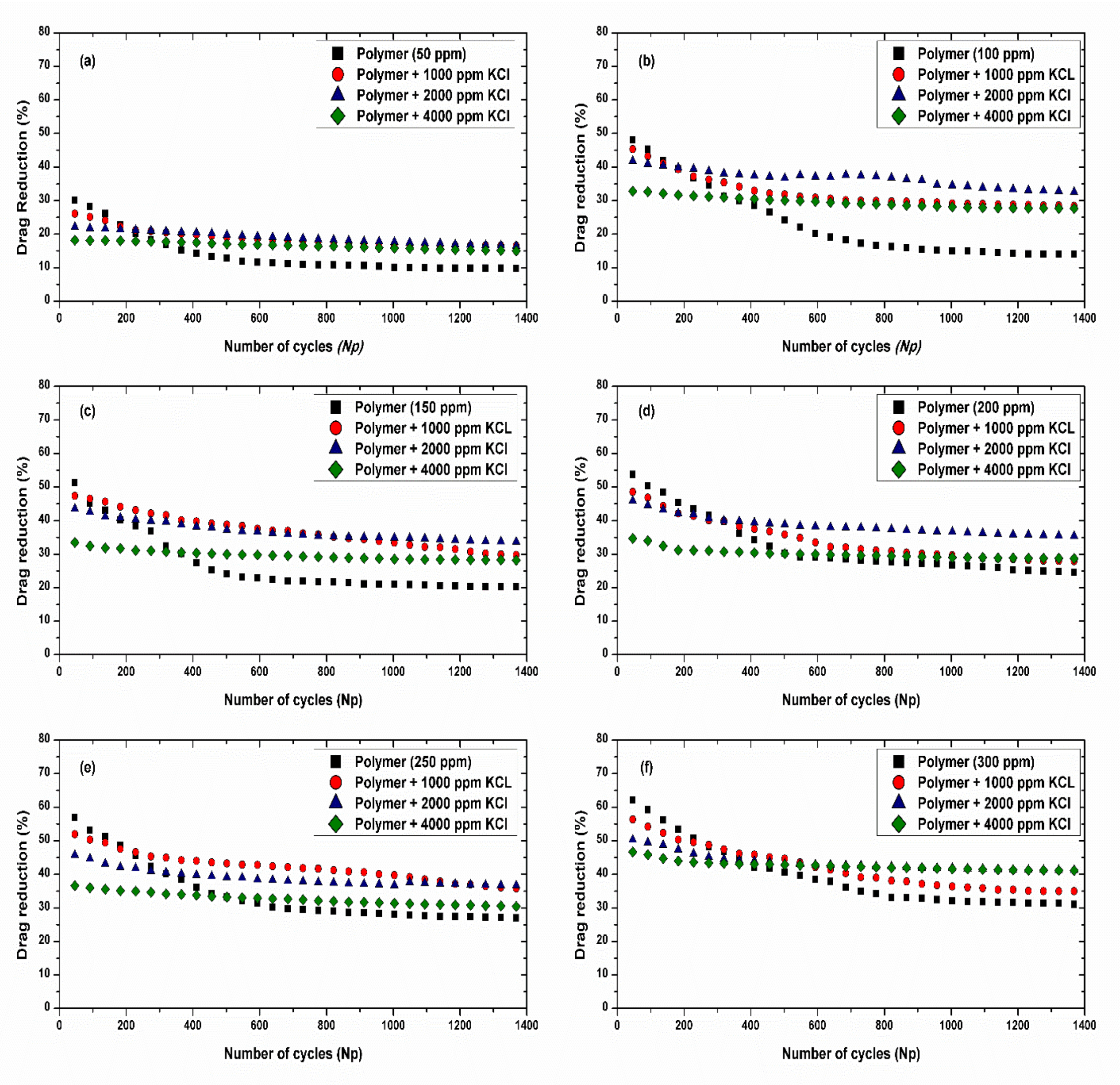


Figure 4.10: Variation of percentage drag reduction with a number of passes for different polymer concentrations (a) 50 ppm (b) 100 ppm (c) 150 ppm (d) 200 ppm (e) 250 ppm (f) 300 ppm.

The KCl salt was added in the gum arabic solution as the same concentrations (1000 ppm- 4000 ppm) were used for the guar gum to compare the effect on both polymers. In Figure 4.10 it can be seen that there was a considerable effect of the KCl salt concentration on the shear stability of the gum arabic solution. Initially, the gum arabic solution was tested without being the addition of any salt in the polymer solution with 1400 number of passes. Similar to the guar gum solution the shear stability of the gum arabic solution was also tested on maximum Reynolds number 45000. Initially, the solution was run for 1400 cycles without the addition of any salt. The continuous degradation of the solution was observed in the form of pressure drop. then the solution was again run with different concentrations of the salt to observe the effect of the salt on the degradation behaviour of the polymer solution.

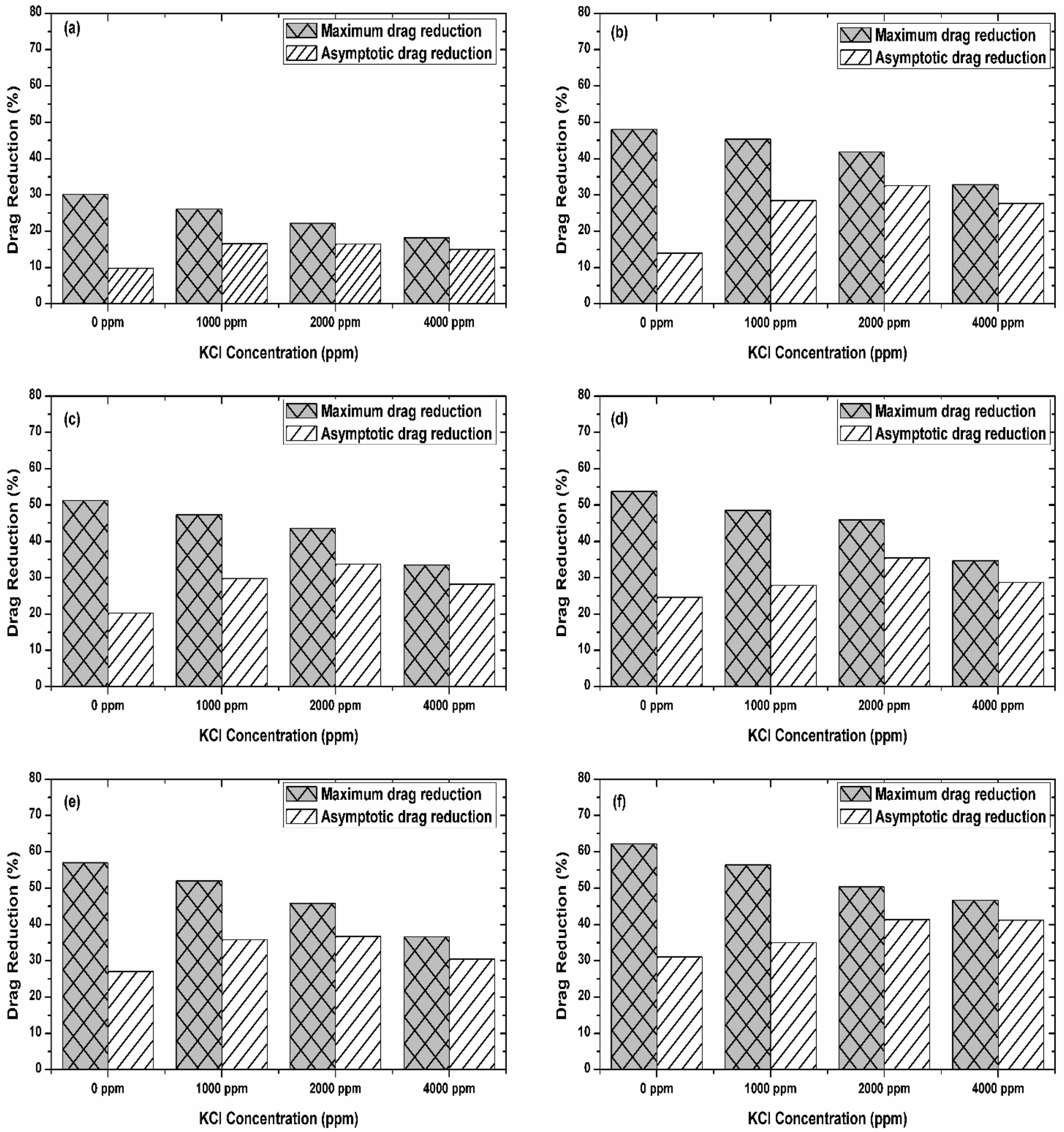


Figure 4.11: Comparison of maximum possible drag reduction with the asymptotic value of drag reduction for polymer concentrations of (a) 50 ppm (b) 100 ppm (c) 150 ppm (d) 200 ppm (e) 250 ppm (f) 300 ppm.

During the testing of the shear degradation of the polymer solution, it was found that when the concentration of the gum arabic was 50 ppm corresponding to bulk solution the total loss of the effectiveness in the polymer was about 65.3% which was 70.99% for 100 ppm of gum arabic solution. With the addition of the salt concentration 1000 ppm, the average decrease from its final value was only 37.9% as shown in Figure 4.10. Which further improved when the concentration of the KCl salt was 2000 ppm, the loss in the effectiveness from the initial value was 23.8%. When the concentration of the salt was 4000 ppm the loss of the effectiveness was only 15.81% from its initial value. Similarly, for the higher concentration, the experiments were performed and the effect of the salt concentration was noted down. It was found that when the there was no addition of the salt in the polymer solutions the average reduction in the effectiveness in the polymer after 1400 cycles were almost 60% which remain 37% after the addition of 1000 ppm of the concentration of the salt. For 2000 ppm of the concentration of the salt in the polymer solution the average reduction in the effectiveness of the polymer performance was about 20% to 22% for all the concentrations of the polymer solution. An average 15% loss in effectiveness of polymer was observed with maximum concentration (4000 ppm) of the salt.

For better understanding and comparison of the degradation of the polymer solution, the maximum and the asymptotic values were shown in the form of a bar graph in Figure 4.11. it can easily differentiate the effect of the addition of the salt on the shear stability of the gum arabic polymer solutions. From Figure 4.11 it was observed that the degradation of the polymer solutions without the addition of the salt is quite rapid. After the addition of the salt, there were significant improvements in the stability of the solution was found. The average enhancement in the shear stability of the gum arabic solution with the addition of the salt was found to be almost 40%. This is due to that when the salt was added into the polymer solution the rigidity of the polymer increased, which make it more stable in shear conditions.

4.2.8 Effect of the Polydimethyl siloxane (PDMS) concentration on the drag reduction of oil.

In the above study, both polymers were water-soluble polymers. but in one-phase flow, the oil-soluble polymer was also tested to find out the best possible drag reduction additive. Polydimethylsiloxane (PDMS) was used as an oil-soluble polymer and the mineral water white oil grade-II (0.016 Pa.s viscosity) was used as a solvent in a flow system. The polymer concentration in the flow was varied from 100 ppm to 500 ppm. The preparation of the polymer is explained in the chapter. 3. Since the viscosity of the oil was quite high so using oil as a solvent it was difficult to maintain the high Reynolds number. The Reynolds number for the oil flow was maintained from 4500 to 10000. A similar type of injection method was used for the oil flow system was tried to found the best possible drag reduction using oil-soluble polymer. The molecular weight of the polydimethylsiloxane was 1,17000 approximately and was in a highly viscous gel form. The effect of the PDMS concentration and the Reynolds number is shown in Figure 4.12.

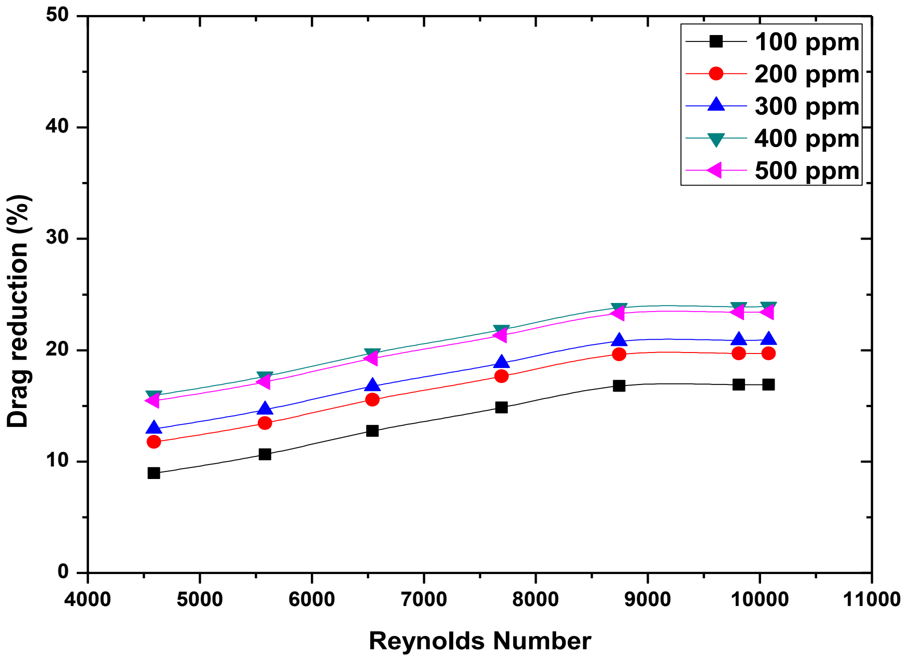


Figure 4.12: Effect of the Reynolds number and concentration of the PDMS on drag reduction percentage.

It can be seen from Figure 4.12 that when the concentration of the polymer was 100 ppm and the Reynolds number were 4592 the minimum drag reduction percentage was 8.95%. Which increased to 11.76% when the concentration was 200 ppm. For the higher concentrations at the same Reynolds number, the maximum drag reduction was observed 12.95%, 15.95% and 15.46% for 300 ppm, 400 ppm, and 500 ppm respectively. The maximum drag reduction percentage (23.9%) was observed at 400 ppm of the polymer concentration when the Reynolds number was 10000. There was an effect of the Reynolds number and the concentration of the polymer was observed. It was observed that the drag reduction percentage increased with an increase in the Reynolds number of the flow. But the drag reduction percentage change for higher Reynolds number was less as compared to the initial Reynolds number. In the case of concentration, the drag reduction percentage was increasing with the increase in the concentration of the polymer up to 400 ppm. At 500 ppm there was a decrease in the drag reduction percentage.

4.3 Effect of the injection positions on the maximum drag reduction percentage

To find the effect of the injection position on the maximum drag reduction percentage the maximum Reynolds number and the concentration at which maximum drag reduction was observed were selected. The position of the injection was divided into 5 different lengths from the internal pipe surface to the centre of the pipe. The effect of the positions of the injection is shown in Figure 4.13 and 4.14 for guar gum and gum arabic solution respectively. The injection was also done in the two forms (a) with perforation (b) without perforation. It can be seen from Figure 4.13 and 4.14 that there is a significant effect of the injection positions in the maximum drag reduction percentage.

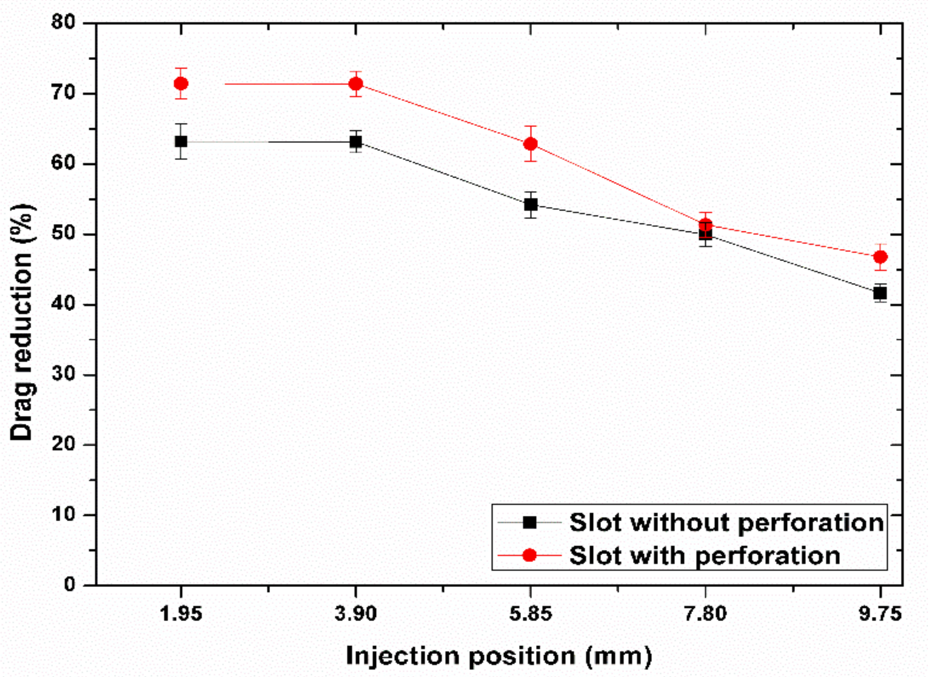


Figure 4.13: Effect of injection position on drag reduction percentage for guar gum.

It can be seen from Figure 4.13 and 4.14 the comparison of the effect of the variation of the injection position for guar gum and gum arabic solutions. The experiments were performed at a maximum Reynolds number to find the effect of the perforation and without perforation injection. In both cases, the slot injection with perforation end was seeming more effective than the without perforation end. The reason behind this variation may be the formation of threads of polymer solution during the injection. When there was perforation at the injection end the mixing, length required for diffusion of polymer threads required was also less. When there was no perforation at the end there was single thread formation and the time and mixing length required to diffuse the polymer molecules in flow was more, which leads to decrease in the drag reduction percentage. In case of guar gum, when the injection was near the surface of the pipe, i.e. 1.95 mm and 3.9 mm with perforation end there was not any variation in the drag reduction percentage was observed.

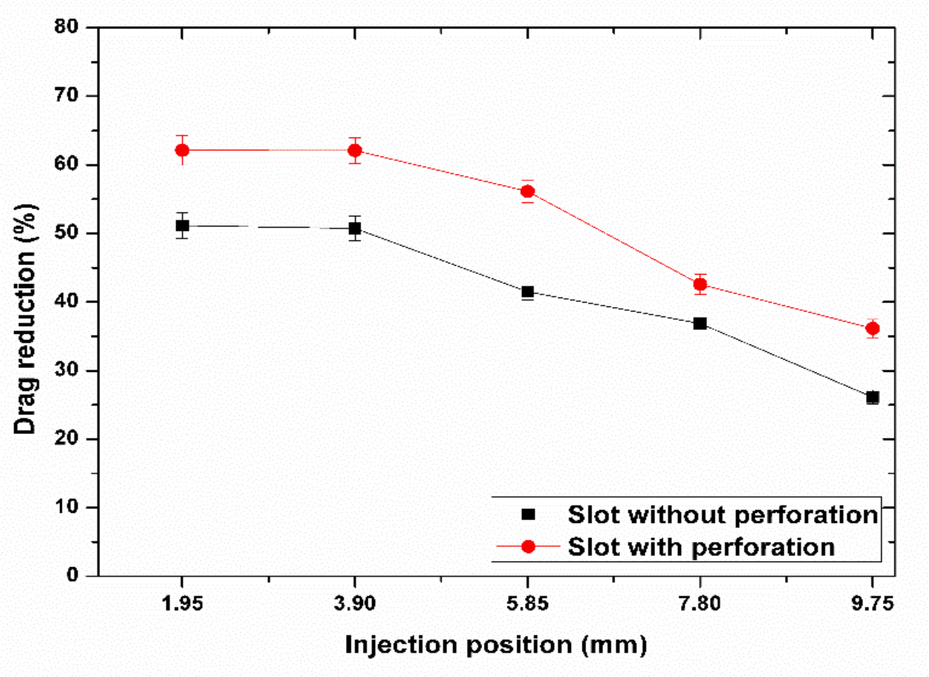


Figure 4.14: Effect of injection position on drag reduction percentage for gum arabic.

The maximum drag reduction was observed as 71.45%. But for the same injection length, when the injection end was not perforated the drag reduction percentage was 63.19% which was almost 8% less than that of the perforated end. Similarly, when the injection depth was 5.85 mm and 7.85 mm the observed drag reduction percentage was 62.85% and 51.35%. When the injection of the polymer was in the centre of the pipe system the minimum drag reduction, percentage was observed 46.78% with the perforated end. In the case of gum arabic with perforation end, the maximum drag reduction was observed at 1.95 mm and 3.9 mm injection depths. The difference in between these two injection positions was almost negligible but when the injection position was more (62.15%) than these positions there was a significant decrease in the drag reduction percentage value. At 5.85 mm, 7.8 mm and 9.75 mm the drag reduction percentage was observed about 56.1%, 42.6%, and 36.15%, respectively. For without perforated end the drag reduction percentage was 51.15% for 1.95 mm injection position which was almost 10% less than the perforated end. For further positions of the injection without perforation like 5.85 mm, 7.8 mm and 9.75 mm the drag reduction percentage was 41.5%, 36.86%, and 26.12%, respectively, as shown in Figure 4.14. for guar gum, there was 34.5% decrease in the drag reduction percentage from its initial value with perforation end but in case of without perforation, the decrease from its initial value was almost 31%. For gum arabic, the decrease in the drag reduction percentage with injection position in perforation end was 41.8% and without perforation was 48.93% from its initial value.

It was not easy to maintain Reynold number same as guar gum and gum arabic case, so the Reynolds number were quite low in case of PDMS solution. When the effect of injection position was observed in case of PDMS, there was not considerable change in drag reduction value was observed.

Many authors have found that heterogenous injection or injection near the boundary layer is more effective as compared to the homogenous drag reduction [136–138]. the reason behind may be due that the drag reduction phenomenon is a boundary layer phenomenon. When the polymer directly injected near the boundary layer the interaction of the polymer can be more effective. In other words, the drag reduction phenomenon occurs near the buffer zone as explained in the chapter-ii, because there is the continuous formation of the eddies in the turbulent flow which travels towards the pipe surface. The buffer zone is just after the viscous sublayer, so when the polymer injected near the surface it directly interacts with the eddies near the buffer zone and suppresses to produce the maximum drag reduction effect.

4.4 Summary

In the present study, the effect of the concentration and the Reynolds number was investigated on the maximum possible drag reduction percentage for both water as well as oil soluble polymer solutions. Both the water-soluble polymer were biopolymers and were able to produce a significant amount of drag reduction percentage with different concentrations. The maximum drag reduction achieved in case of guar gum was 71.4% at 150 ppm concentration of solution. While the maximum drag reduction was 62% at 300 ppm for gum arabic and 23.9% for PDMS at 400 ppm solution. The effect of the KCl salt was observed on the shear stability of the polymer solution with number of passes. It was found that KCl salt was able to enhance the effectiveness of the polymer solution under high shear conditions. The oil soluble polymer was able to produce considerable drag reduction percentage but the effect was quite less than that the water-soluble polymer solutions. The effect of the injection positions was studied with and without the perforation end.

CHAPTER - 5

DRAG REDUCTION IN HORIZONTAL LIQUID – LIQUID SYSTEM

5.1 General

This chapter deals with the drag reduction in water/oil flow by using the same additive used in single-phase flow. In the previous chapter both polymers were tested on the Reynolds number ranges from 17000-50000 at different concentrations. In this chapter, both polymers were used in water/oil flow system to investigate their effectiveness in two-phase flow.

5.2 Drag reduction Study for two-phase flow

In the present study, a heavy oil (mineral oil) was used to investigate transportation through a circular pipe. Since the transportation of heavy oil is an energy-intensive process, water was used to reduce energy consumption and pressure drop. The transportation of oil mixed with water is a complex process to investigate because of two-phase flow and variation of flow patterns with the velocity of the mixture. The effects of the oil fraction, mixture velocity, flow patterns and concentration of the biopolymer on drag reduction were investigated. In this study, instead of using premixed solutions, the polymer solution was injected directly into the boundary layer of the flow system. The polymer solution was heterogeneously mixed in water using a peristaltic pump to obtain the desired concentration. A sufficient number of pilot-scale experiments were performed to select the optimum concentrations for experimentation and other parameters for this study. The experiments were performed with guar gum and gum arabic polymers by keeping the parameters same in both cases.

5.2.1 Experimental methodology

An experimental set-up was fabricated to investigate the drag reduction in two-phase (liquid-liquid) flow as shown in Figure 5.1. A galvanized iron (GI) pipe having inner diameter 19.5 mm was used for the experimentation purpose with a total length of 60 m and test section of 30.50 mm. At the end of the GI pipe length, an acrylic pipe of the same diameter having length 0.5 m was used to observe the flow structure during the continuous experimentation. A differential pressure transducer (Honeywell, ST 3000 series, USA) having accuracy ±0.2% was used to determine the pressure drop across the length of the test section.

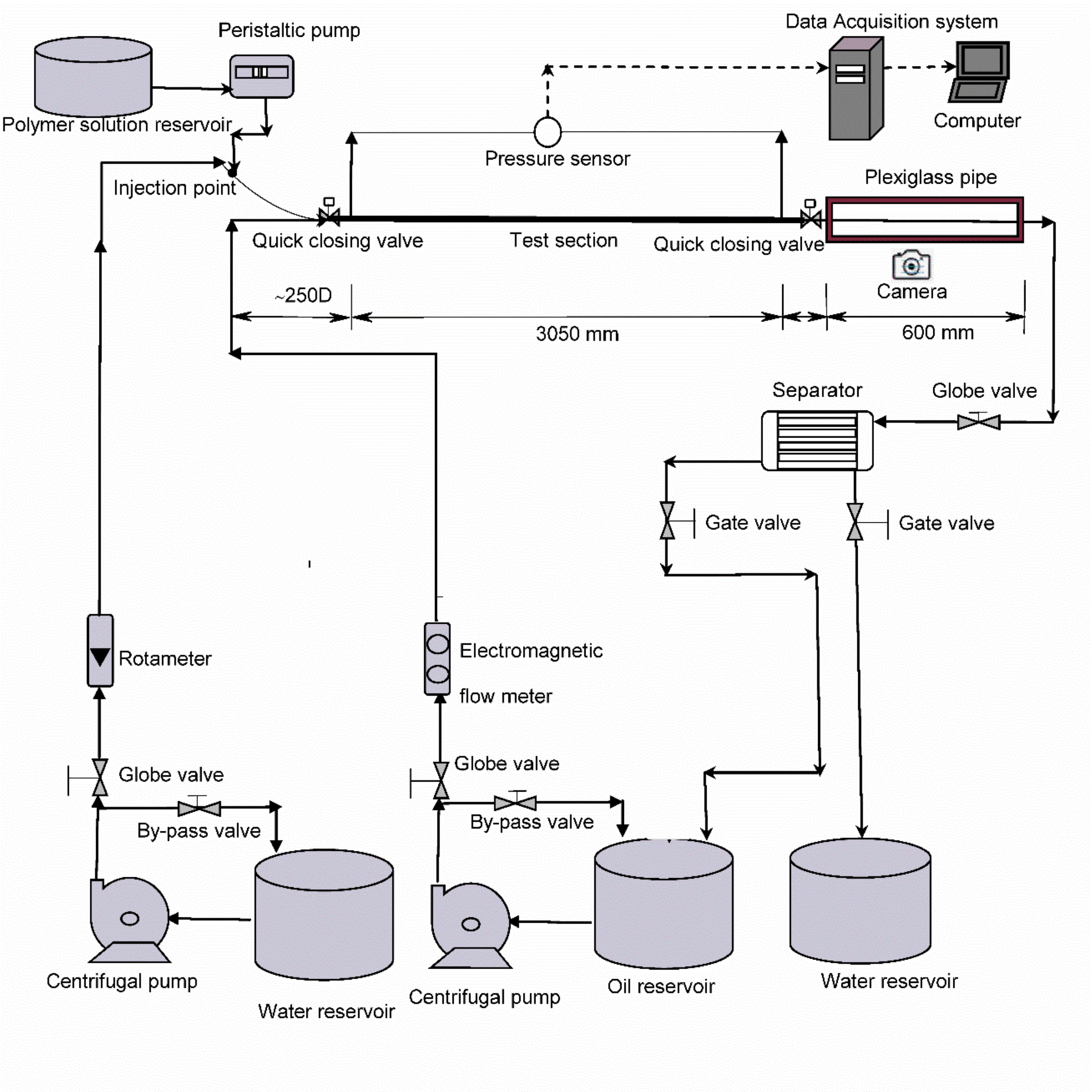


Figure 5.1: Schematic diagram of experimental set-up for two-phase flow

At the inlet section, the fluids were mixed through a Y-junction located at an appropriate length (≈ 250 times the pipe diameter) from the test section with diameter same as that of the test section to minimize the mixing effect. The polymer was injected by using a peristaltic pump connected before the mixing joint. The injection of the polymer in the boundary layer was done as per the similar method as explained in the single-phase flow study. The angle of the pipe before the mixing point was kept close to 32^o for smooth flow and to avoid the cross-jet flow of the polymer solution. The diameter of the hole for injection of the polymer was kept 2 mm and the inlet design is shown in Figure 5.2. The peristaltic pump was used to minimize the degradation of the polymer before injection.

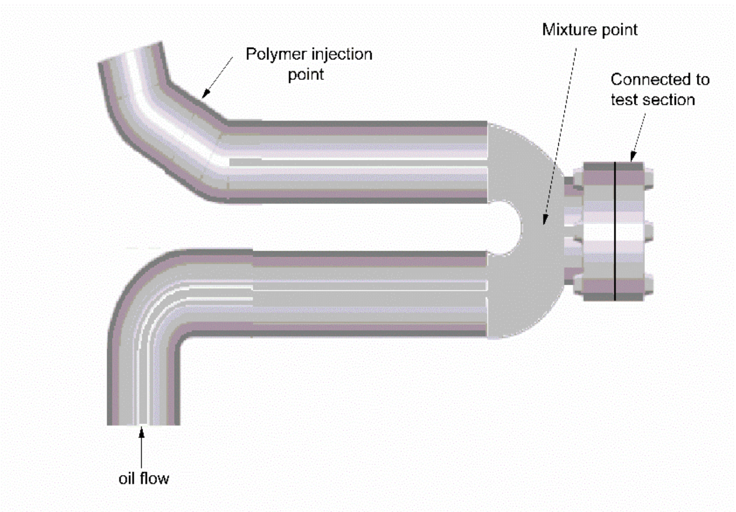


Figure 5.2: Schematic representation of inlet design.

The transducer was installed at an appropriate distance to avoid entrance effects during turbulent flow. To check the calibration of the transducers, some experiments were performed on single phase and compared the observed pressure drop with calculated values. These were plotted against the measured pressure drop value, and R^2 is shown in Figure 5.3. The validity of the experimental set up was checked by plotting friction factor values against the Reynolds number and comparing with the Blasius equation as shown in Figure 5.4. Water and oil were circulated through the pipe using two centrifugal pumps connected to two reservoirs having water and oil, respectively. Properties of the fluids used are given in the Table 5.1. A variable area type flowmeter was used to control the flow rate of water having maximum flow rate 70 L/min (±0.25%) and for oil electromagnetic flowmeter was used to measure the oil flow rate (Iotaflow, ±0.3%).

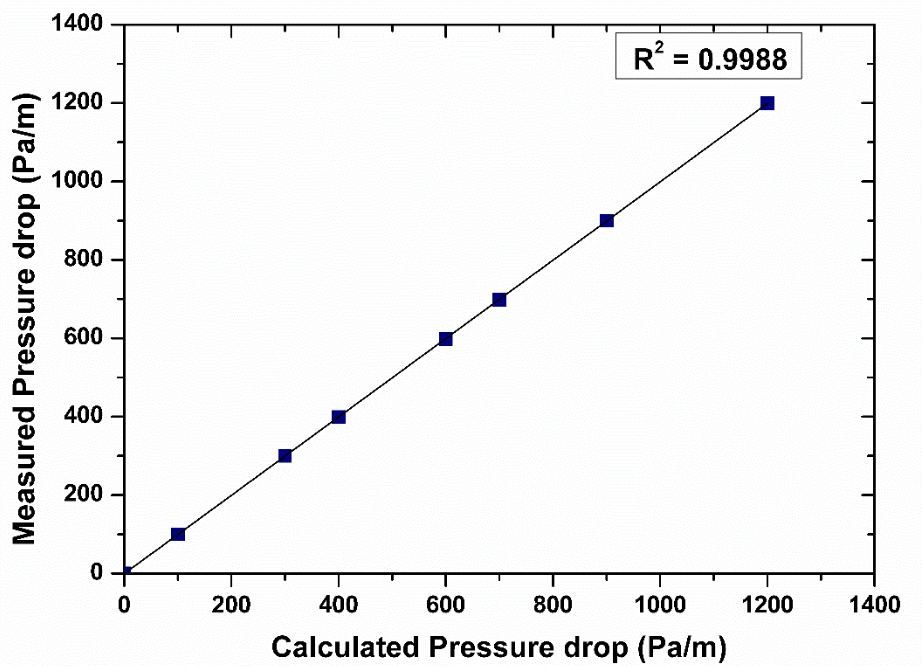


Figure 5.3: Measured and calculated values of pressure drop.

Table 5.1: Properties of the fluids used.

Fluid	**Density (kg/m^3) at 25°C**	**Viscosity (cP) at 25°C**
Water (tap water)	997	0.890
Mineral oil (water white base oil)	819	16

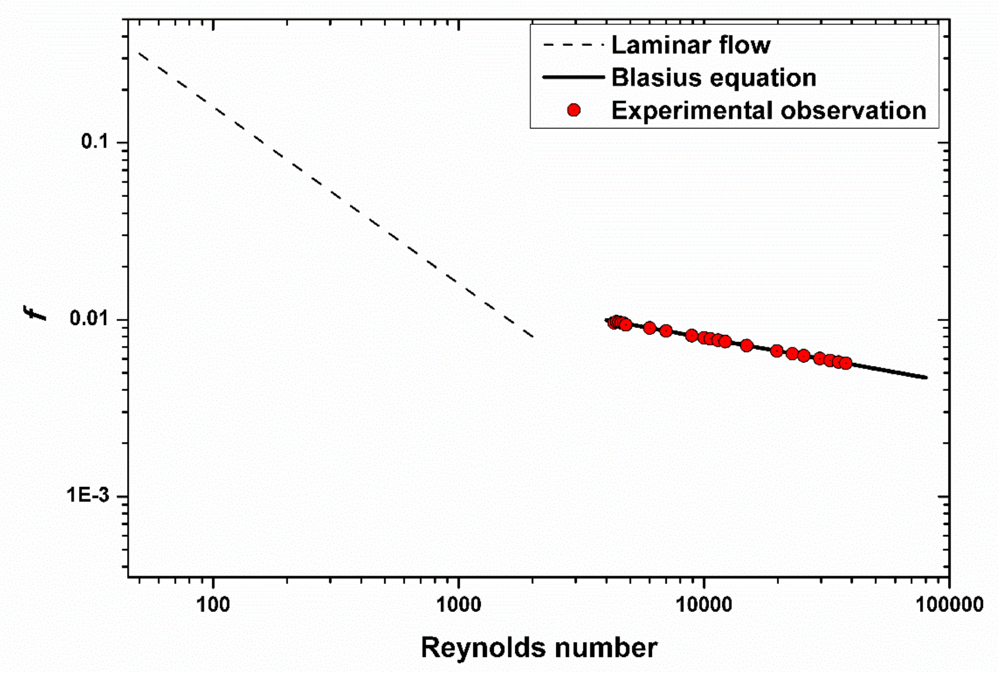


Figure 5.4: Validation of test system with the Blasius equation.

The speed of the pump was adjusted so as to achieve the required concentration of the polymer in the bulk solution. After passing through the test section, the mixture was sent to a separator tank where the oil and water were separated out. Since the densities of these two fluids are different, their separation can be achieved easily. Additionally, baffles were used in the separator to slow down the movements and enhance the separation. Then the oil was returned to the reservoir through drain valves and the aqueous phase was collected in another tank because it contains some polymer. The polymer solution was added continuously to fresh water to minimize degradation effect. During the drag reduction experimentation, the mixture velocity was varied from 0.6 m/s to 3 m/s and the oil fraction was varied between 0.1 and 0.7. The mixture Reynolds number range was varied as 9179–46145 for 0.1 oil fraction, 5156–25784 for 0.3, 2886–14431 for 0.5 and 1621–8108 for 0.7 oil fraction. The velocity of the mixture was so selected that the drag reduction experiments were done in the dispersed flow region. During the experimentation, the effect of the mixture velocity on the flow pattern was continuously observed through visual observation. A different section made of Plexiglas material was joined after the length of the test section to visually inspect the flow pattern using a camera (Sony RX10 II, 1920×1080, 960 fps). A data acquisition system was connected to the system for continuous recording of observations during the experimentation. Each experiment was performed three times and the average error noticed in pressure drop was less than 1.2% and uncertainties during experimentation are shown in Table 5.2. As the fluid flowing through the pipeline was in the mixed flow, the characteristics of flowing fluid were calculated as follows.

Velocity of the mixture, $U_m = \frac{Q_T}{A}$ (5.1)

where 'U_m' is mixture velocity, 'Q_T' is the total volumetric flow rate and 'A' is a cross-sectional area of pipe [139]. Total volumetric flow rate 'Q_T' can be calculated as [140]:

Total discharge, $Q_T = Q_o + Q_w$ (5.2)

Where 'Q_o' is the volumetric flow rate of oil and 'Q_w' is the volumetric flow rate of water. Further the fraction of the water and oil can be calculated as:

Fraction of oil $\phi_o = \frac{Q_o}{Q_T}$ (5.3)

Fraction of water $\phi_w = 1 - \phi_o$ (5.4)

Drag reduction percentage was calculated as:

$$\text{DR}\,(\%) = \left(\frac{\Delta P_{\text{without polymer}} - \Delta P_{\text{with polymer}}}{\Delta P_{\text{without polymer}}} \right) \times 100 \tag{5.5}$$

Table 5.2: Uncertainty during experimentation.

Sr. No.	**Parameter/instrument**	**Uncertainty**
1.	Flowmeter (70 L/min, max.)	±0.25%
2.	Electromagnetic flowmeter	±0.3%
3..	Pressure drop	1.2% (average)

5.2.2 Flow Patterns for guar gum solution

Flow patterns observed during this experimentation are shown in Figure 5.5, which are broadly classified into four types to understand the transition of the flow with oil fraction. Descriptions of these four types of flow patterns are as follows:

Stratified (ST) flow pattern: In stratified flow pattern, liquid with lower density flows in the upper layer and fluid with higher density flows in the lower layer of pipe flow. This type of flow pattern exists at very low mixture velocities. The stratified flow can be further classified into two categories namely stratified smooth and stratified wavy. The flow pattern observed at very low velocity is generally described as a stratified flow shown in Figure 5.5 (a_1). In the present study, stratified wavy pattern (Figure 5.5(a_2)) was observed up to a mixture velocity of 0.1 m/s without the addition of the polymer, as shown in Figure 5.6(a). When the polymer was added into the flow, the stratified pattern existed up to the velocity of 0.2 m/s. With the addition of the polymer, the pattern was slightly wavy with decreased amplitude. This observation is in accordance with the results reported by Edomwonyi-Otu et al.[78].

Dual continuous (DC) flow pattern: Dual continuous flow pattern is generally a stratified flow pattern with mixing at the interface along with the dispersion of the oil-in-water and water-in-oil. This type of flow pattern is observed at slightly higher mixture velocity than the stratified flow, which may lead to turbulent mixing of the two phases at the interface. This type of transition or flow pattern occurs when the flow turbulence of the dominant phase is sufficiently high to break the interphase layer into stable droplets [65, 138]. Since the two flow patterns occur simultaneously, this type of flow is described as a dual continuous flow pattern [99, 65]

This type of flow pattern was observed at the mixture velocities between 0.2 m/s and 0.5 m/s, but, the observation of the DC flow pattern at 0.2 m/s mixture velocity was only limited to low concentrations of oil (≤ 0.2 volume fraction) in water.

For the mixture velocities of 0.3 m/s and 0.4 m/s, the DC flow pattern existed up to 0.7 and 0.65 volume fractions of oil, respectively, as shown in Figure 5.5. And for the mixture velocity of 0.5 m/s, this flow pattern was observed up to 0.5 volume fraction of oil [139, 140]. The dual continuous flow pattern vanished beyond the mixture velocity of 0.5 m/s. When the polymer was added into the flow, there was the disappearance of the dispersion at the interface. This may be due to the fact that the addition of polymer leads to suppression of turbulence mixing at the interphase. Due to the suppression of the turbulence mixing, the flow pattern changed from dual continuous to stratified flow.

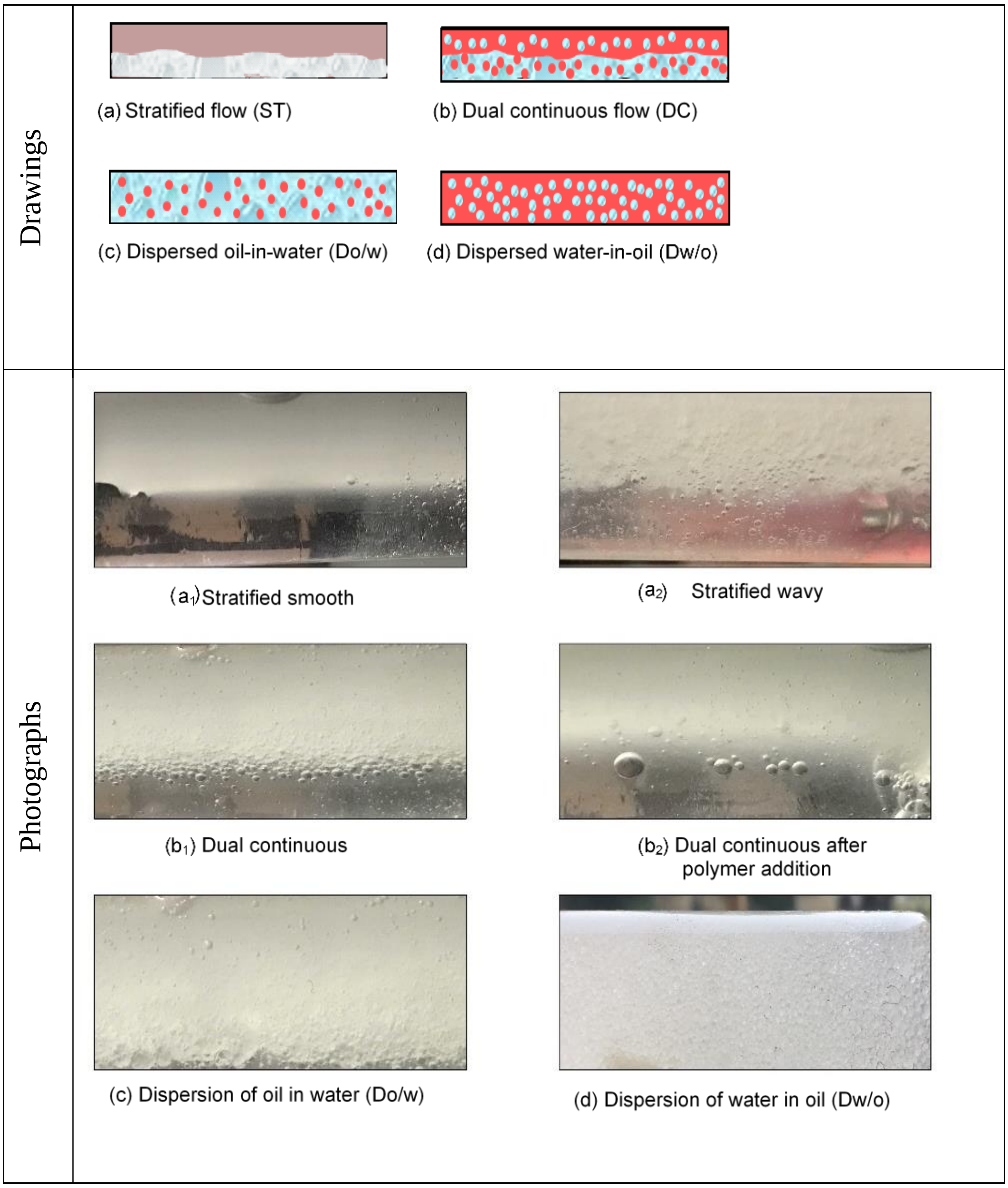


Figure 5.5: Representation of different flow patterns observed in two-phase flow: (a) Stratified (ST) flow (a_1: stratified smooth, a_2: stratified wavy); (b) Dual continuous (DC) flow (b_1: dual continuous without polymer, b_2: dual continuous with polymer); (c) Dispersed oil in water (Do/w); (c) Dispersed water in oil (Dw/o).

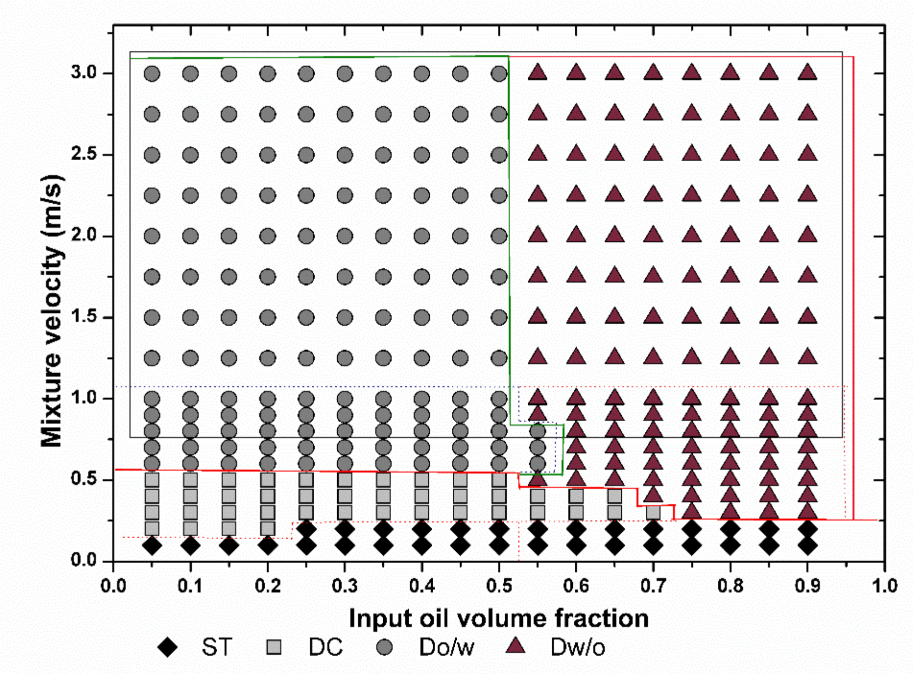


Figure 5.6(a): Flow pattern map (dotted lines represent flow without polymer addition and solid lines represent flow after addition of polymer).

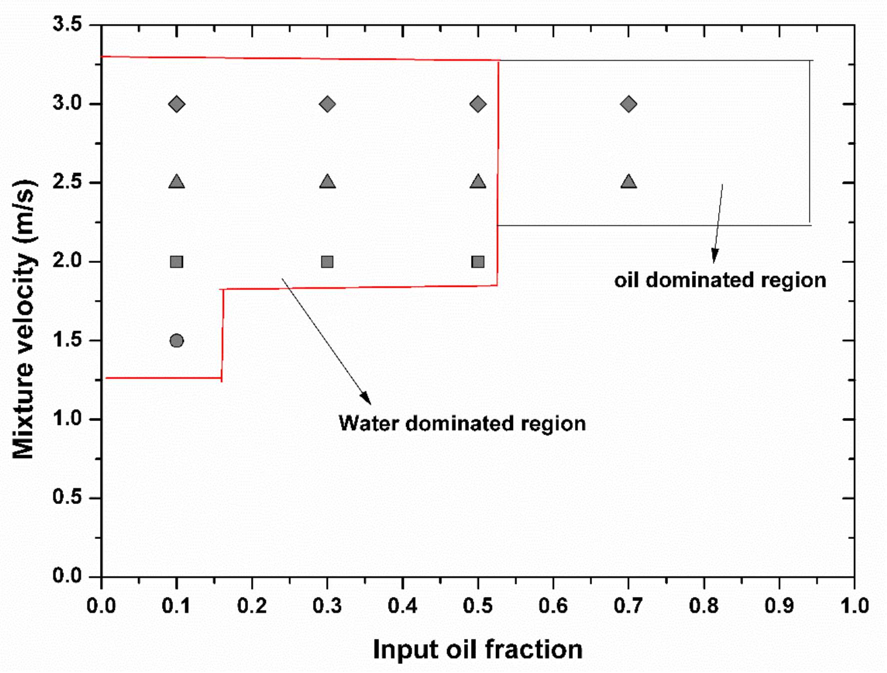


Figure 5.6(b): Points where maximum drag reduction was observed at different mixture velocities and oil fractions.

Dispersed oil in water (*Do/w*): In this region, generally two types of flow patterns are found, namely, (i) dispersion of oil-in-water as a continuous phase with water layer at the bottom and (ii) complete dispersion of oil-in-water [144]. In the former type, oil droplets are dispersed in the water phase along with some water layer at the bottom; however, in the latter case, no distinct water layer is seen [125-126, 144, 145]. In this study, dispersion of oil-in-water with a water layer was observed for mixture velocities from 0.6 m/s to 1 m/s and oil fractions up to 0.5, however, no separate water layer was observed for mixture velocities above 1 m/s (up to 3 m/s). For an oil fraction of 0.55, this flow pattern existed up to a mixture velocity of 0.8 m/s only and thereafter, the flow pattern changed. At higher mixture velocities (> 1 m/s), the oil droplets were fully dispersed in the water phase without a distinct water layer at the bottom. When the drag reduction polymer was added into the dispersed oil-in-water with and without water layer, a little stratification of the flow was observed. Up to this flow pattern, the mixture was water dominating and the drag reducing polymer was quite effective.

Dispersed water-in-oil (*Dw/o*): The dispersion of water droplets in the oil phase is known to be an oil dominating system. In this region, oil is the continuous phase and the water droplets are dispersed in the oil phase. When the velocity of the mixture was low (≤ 0.5 m/s), water was dispersed in the oil as a continuous phase along with an oil layer near the top pipe wall. But when the mixture velocity was increased, water was fully dispersed in the continuous oil phase. When drag reduction polymer was added into this phase almost no drag reduction effect was observed at low velocities (≤ 0.5 m/s); and at high velocities, the effectiveness of the polymer was quite low as compared to that of lower oil fractions. This may be due to the fact that at lower velocities in the oil dominant region, the effect of turbulence was not significant, but, at higher velocities, the movement or randomness of the droplets of water was able to produce some turbulence effect. However, the effectiveness of polymer solution (even of high ppm) in the oil dominating region was insignificant.

5.2.3 Effect of oil fraction and polymer (guar gum) concentration on the drag reduction

The effect of polymer concentration and oil fraction on drag reduction is shown in Figure 5.7 (a-d). It can be seen from the figure that when the concentration of the polymer was increased, the drag reduction percentage also increased. When the input oil fraction was 0.1 (Figure 5.7a), the maximum drag reduction percentage of almost 50% was achieved with a polymer concentration of 50 ppm at a mixture velocity of 3 m/s. A critical observation of Figure 5.7 (a) indicates that the minimum drag reduction of only 4.25% was observed at a mixture velocity of 0.6 m/s and polymer concentration of 10 ppm, which subsequently increased to 21% by increasing the velocity to 3 m/s. Similarly, for 20, 30, 40, and 50 ppm concentrations of the polymer, the drag reduction at 0.6 m/s velocity was 8.3%, 9.6%, 12.3% and 15.2%, respectively; and these values increased to 35%, 44%, 49%, and 50%, respectively, by increasing the mixture velocity to 3 m/s. For any particular oil fraction, the drag reduction was significantly affected by the mixture velocity as well as polymer concentration. This is due to the phenomenon that when the mixture velocity is increased, there is a continuous formation of turbulent eddies, which in turn causes loss of energy in the form of pressure drop. But, with the addition of a polymer in the flow, the polymer coils stretch near the turbulent eddies and suppress the formation of eddies. Due to the suppression of the turbulent eddies, a decrease in the pressure drop (known as drag reduction) is observed.

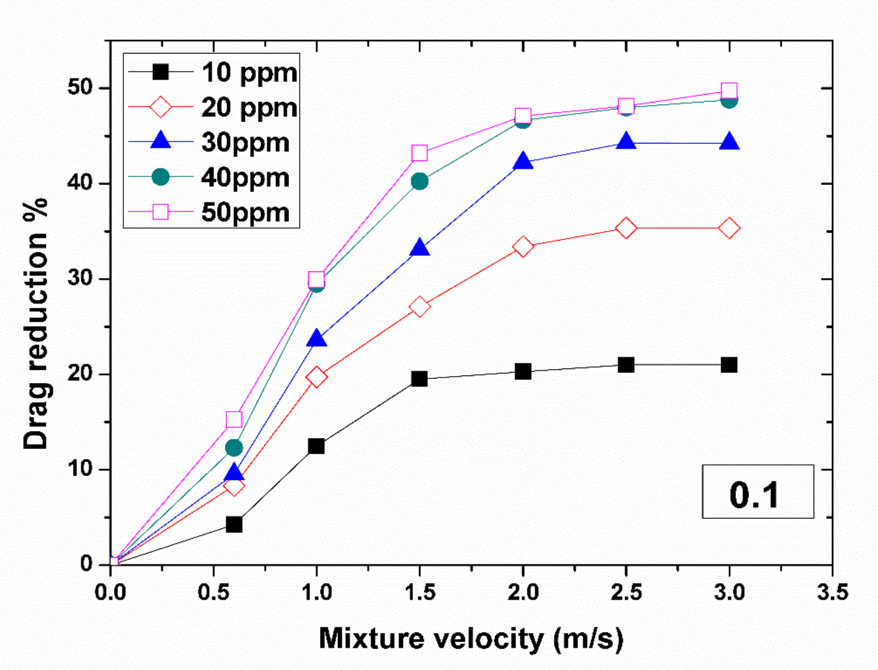


Figure 5.7(a): Drag reduction percentage against different mixture velocities and polymer concentrations: (a) oil fraction = 0.1.

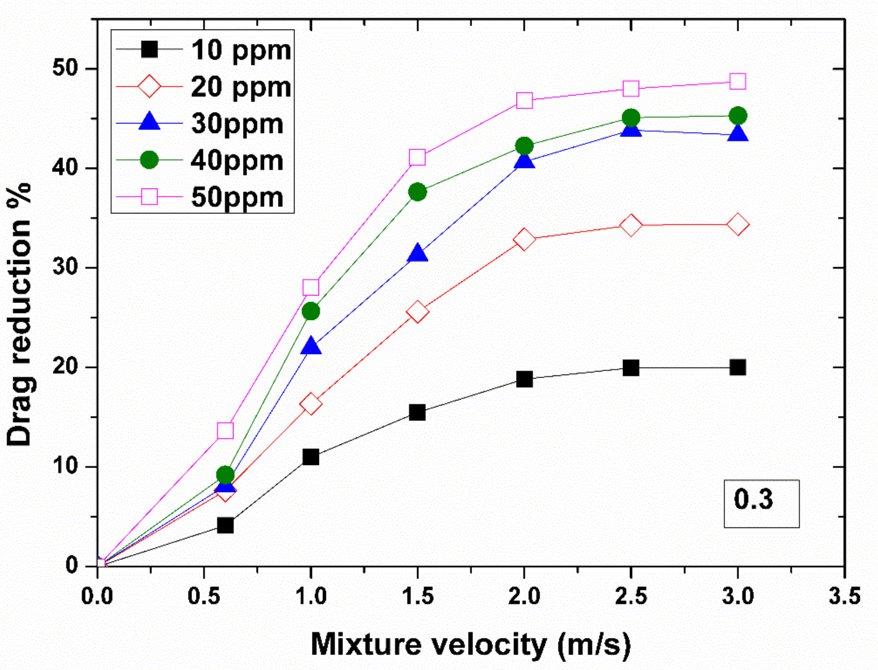


Figure 5.7(b): Drag reduction percentage against different mixture velocities and polymer concentrations: (b) oil fraction = 0.3.

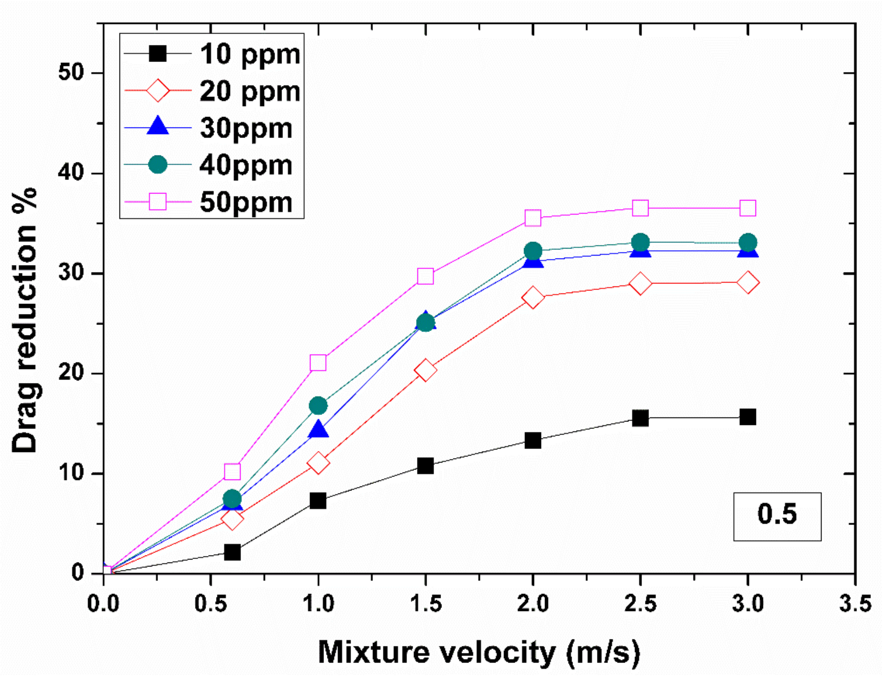


Figure 5.7(c): Drag reduction percentage against different mixture velocities and polymer concentrations: (c) oil fraction = 0.5.

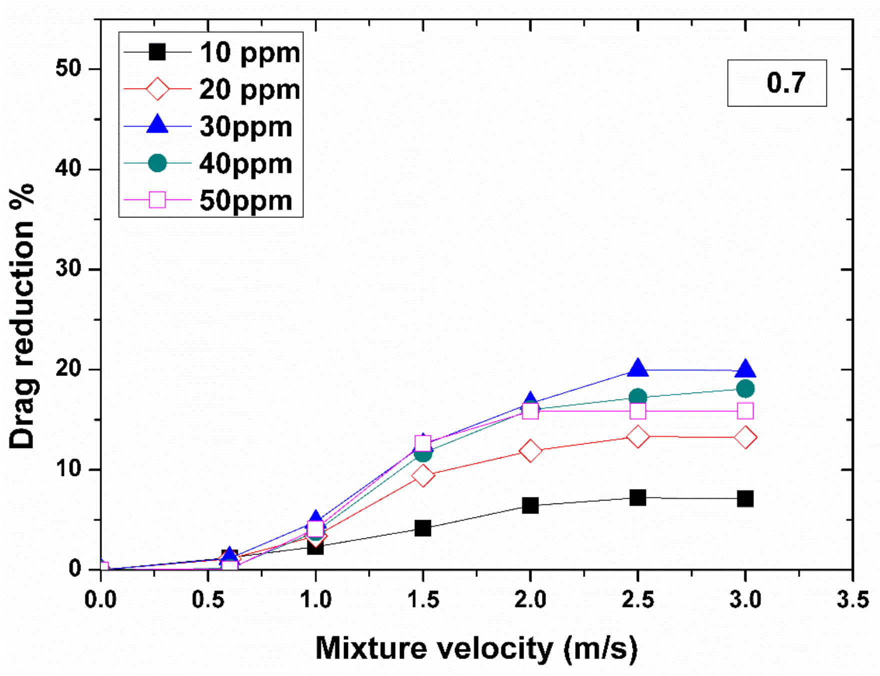


Figure 5.7(d): Drag reduction percentage against different mixture velocities and polymer concentrations: (d) oil fraction = 0.7.

It can be seen from the figure that the drag reduction percentage increased rapidly with an increase in the polymer concentration up to 30 ppm. And for high polymer concentrations (40 and 50 ppm), the difference in the drag reduction percentage is less than that of the first three concentrations. Similar results experiments were performed for two other oil fractions of 0.3 and 0.5, where it was seen that the drag reduction increases with an increase in polymer concentration and mixture velocity. However, the value of the maximum drag reduction decreased with increasing the oil fraction and high polymer concentrations (40 and 50 ppm) showed a negative effect on drag reduction (Figure 5.7(d) in the oil dominant region (i.e., 0.7 volume fraction of oil).

When the oil fraction was increased from 0.1 to 0.3, the percentage of maximum drag reduction decreased from 50% to 48.7 for 50 ppm polymer solution. The drag reduction observed in this work is greater than that reported in the literature [74, 75, 146, 147] using synthetic polymer for the same fraction of oil in water. Similarly, for the oil fraction of 0.5, the maximum drag reduction of 36.5% was observed with 50 ppm polymer at the highest mixture velocity (3 m/s), and the lowest drag reduction of 2.2% was observed with 10 ppm polymer and the lowest mixture velocity (0.6 m/s). It was observed that up to 0.5 fractions of oil, the drag reduction percentage increased with increase in polymer concentration, and on the other hand, for oil fraction of 0.7, high concentrations of the polymer (40 and 50 ppm) had negative effect on the drag reduction percentage, whose values are lower than that of 30 ppm solutions. The minimum value of drag reduction (1.2%) was observed for 10 ppm polymer concentration at a mixture velocity of 0.6 m/s.

This is because of the fact that the biopolymer used in this study is water soluble and is more effective in water dominant region (oil fraction ≤ 0.5). When the oil fraction was increased further, the effectiveness of the polymer continuously decreased and there was almost 50% decrease in the drag reduction performance of the polymer with 0.7 fractions of the oil and almost no drag reduction was observed for the high concentration of polymer (50 ppm) at low mixture velocity (0.6 m/s). Therefore, for lower concentrations of the oil (≤ 0.5), a polymer concentration of 50 ppm was found to be optimum (among the concentrations studied). And for 0.7 volume fraction of oil, a polymer concentration of 30 ppm was the optimum.

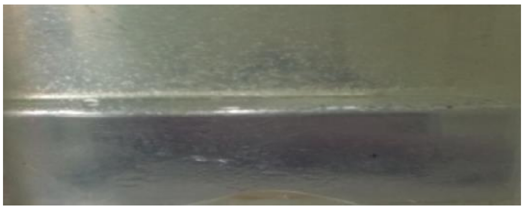
For example, at 50 ppm polymer concentration and 0.1 oil fraction, the average drag reduction was 16%, which increased to 50% by increasing the oil fraction to 0.5 with a relative increase of 212%. Similarly, for 0.1 oil fraction and 0.6 m/s mixture velocity, the maximum drag reduction with 20 ppm polymer was relatively 90% higher than that with 10 ppm polymer concentration.

In the same way, the relative increase in average drag reduction percentage with 30 ppm, 40 ppm and 50 ppm from 20 ppm was about 50%, 57%, and 60%, respectively. On the other hand, for the higher fraction of oil (0.7), Figure 5.7 reveals that the drag reduction was almost diminished by increasing the polymer concentration at low mixture velocity (0.6 m/s). Also, when the oil fraction was more than 0.7, no drag reduction phenomenon was observed. This may be due to the fact that at higher oil fraction or oil dominating region, the effectiveness of the water-soluble polymer decreases because oil was in the continuous phase and near the boundary and hence, no drag reduction was observed for 0.75 oil fraction.

5.2.4 Flow patterns for gum arabic polymer solutions.

For gum arabic solution the flow patterns observed were similar to the guar gum solution. The flow patterns observed during the experimentation with the gum arabic were also classified into four types. (a) stratified flow (ST) pattern (b) dual continuous (DC) flow pattern (c) dispersed oil in water (Do/w) (d) dispersed water in oil flow (Dw/o) as shown in the Figure 5.8. Description of these flow patterns is given in section 5.2.2.

Stratified flow pattern was observed at lower mixture velocity in the case of gum arbic solution. when the mixture velocity (0.1 m/s) was quite low stratified flow pattern was observed. The stratified flow (ST) pattern was wavy before the addition of the polymer at the interface of the oil and water. But with the addition of the polymer, the amplitude of the wavy has been decreased which leads to increase the stratified flow patterns up to 0.2 m/s mixture velocity.



(a) Stratified flow (ST)

(b) Dual continuous flow (DC)

(d) Dispersed oil in water (Do/w)

(c) Dispersed water in oil (Dw/o)

Figure 5.8: Representation of different flow patterns observed in two-phase flow: (a) stratified (ST) flow (b) dual continuous (DC) flow (c) dispersed oil in water (Do/w); (c) dispersed water in oil (Dw/o).

Dual continuous flow (DC) pattern was observed in the case of guar gum was started from 0.2 m/s mixture velocity to 0.5 m/s mixture velocity. But for 0.2 mixture velocity, the dual continuous flow was observed only up to 0.2 fractions of oil. The effect of the addition of the gum arabic polymer was similar to the guar gum. With the addition of the polymer, there was an increase in the stratification of the flow at the interface. The drops of the oil at the interface of the water and oil disappear after addition of the polymer solution leads to the transition of the dual continuous flow into the stratified flow.

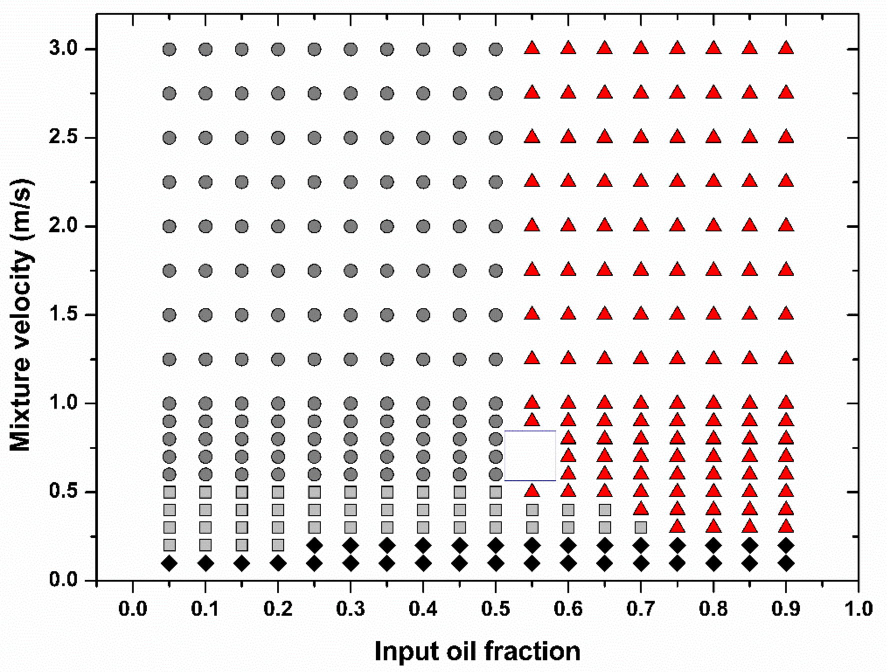


Figure 5.9 (a): Flow pattern map (square represent the change in the flow pattern as compared to guar gum solutions.).

Dispersed oil-in-water flow (D o/w) flow patterns are the patterns, in which oil droplets are fully or partially dispersed in the water. As discussed in the case of guar gum there were two types of flow patterns observed in this region (a) oil dispersed in water with water layer at the bottom and fully dispersed flow. The former patterns were observed from the 0.6 m/s mixture velocity to 1 m/s. in case of guar gum this region was extended up to 0.55 fraction of oil but in guar gum solution this region was extended up to 0.5 fractions of oil, as shown in the Figure 5.9 (a).

The layer at the bottom was observed only up to 1 m/s mixture velocity and more than the 1 m/s velocity the flow pattern was fully dispersion of the oil in the water flow. With the addition of the polymer, there was also little stratification was observed in these flow patterns. Up to this pattern map, there was a water-dominated region and beyond this, oil was more dominated than water.

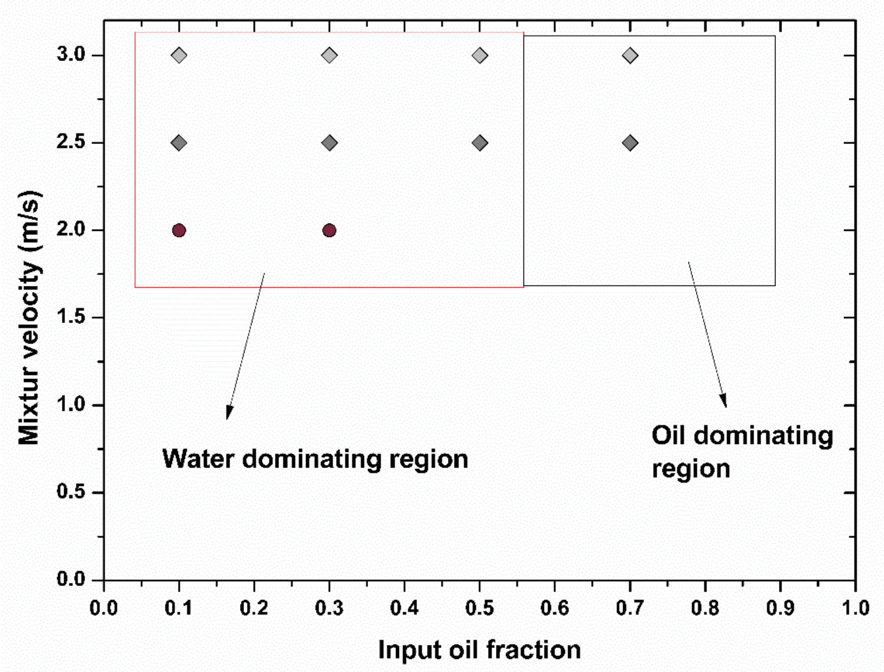


Figure 5.9(b): Points where maximum drag reduction was observed at different mixture velocities and oil fractions.

Dispersed water in oil flow (D o/w) was an oil dominating region. In this region for low mixture velocities like 0.5 m/s, the oil layer was also observed near the pipe surface which disappeared when the mixture velocity was more than 0.5 m/s. no drag reduction was observed at lower mixture velocity. Comparison to guar gum the drag reduction observed in the gum arabic solution was quite less and negligible at lower mixture velocities, as shown in Figure 5.9 (b).

5.2.5 Effect **of oil fraction and polymer (gum arabic) concentration on the drag reduction**

The effect of the polymer concentration and fraction of oil was investigated with mixture velocity on the possible drag reduction percentage. The effect of the oil fraction and concentration of the gum arabic is shown in Figure 5.10(a-d). it can be seen from the Figure 5.10(a) that when the fraction of the oil in the water was 0.1, the drag reduction observed was maximum. When the concentration of the gum arabic was 20 ppm the minimum drag reduction observed was 2% at a mixture velocity of 0.6 m/s while the maximum drag reduction at 20 ppm was 18.75% at a mixture velocity of 3 m/s. The maximum drag reduction percentage (44.16%) was observed, when the oil fraction was 0.1 at 3 m/s mixture velocity with 80 ppm of the polymer solution. When the concentration of the polymer was increased from 20 pp to 40 ppm the drag reduction at a mixture velocity 0.6 m/s was increased to 5.18%. The maximum drag reduction at 100 ppm of the polymer solution was 9.98% with 0.6 m/s mixture velocity. It can be seen from Figure 5.10(a) that the drag reduction was increased with increase in the concentration of the polymer and mixture velocity of the solution. It was found in the case of 0.1 oil fraction that the drag reduction percentage was increased rapidly with increase in the concentration of the polymer for initial mixture velocities (0.6 m/s - 2m/s). However, this increase was less for the higher mixture velocities (2.5 m/s - 3 m/s). There was an increase in the drag reduction with mixture velocity rapidly because with an increase in the mixture velocity there was a rapid increase in the turbulent strength of the flow. The increase in the turbulent strength leads to the formation of the eddies and polymer is quite affected by the turbulent strength.

At mixture velocity of 3m/s the drag reduction percentage was 32.21%, 40.97% and 44.16% for 40 ppm, 60 ppm and 80 ppm of solution, respectively.

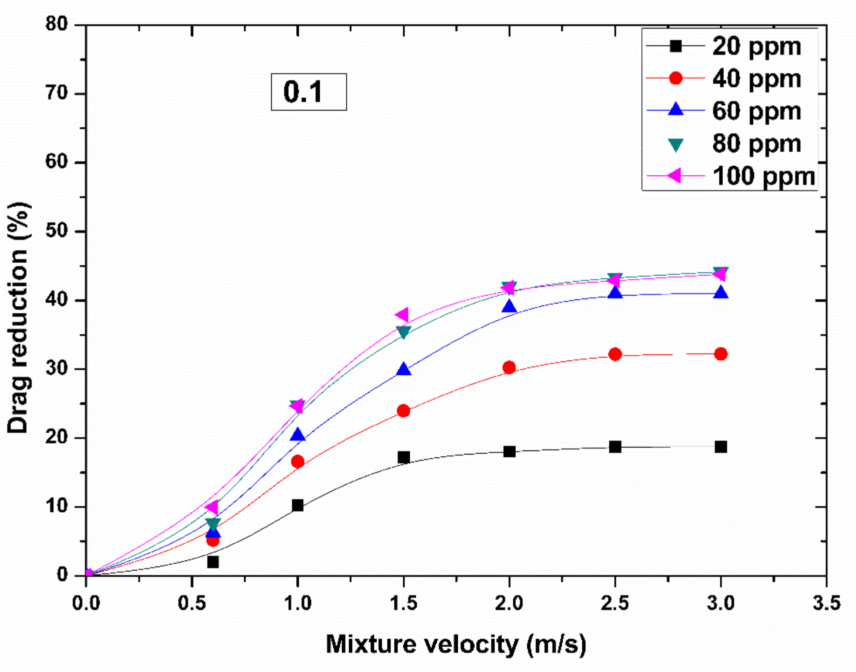


Figure 5.10(a): Drag reduction percentage against different mixture velocities and polymer concentrations: (a) oil fraction = 0.1.

When the oil fraction was 0.3 there was a considerable decrease in the drag reduction percentage for all the concentrations of the polymer solutions.

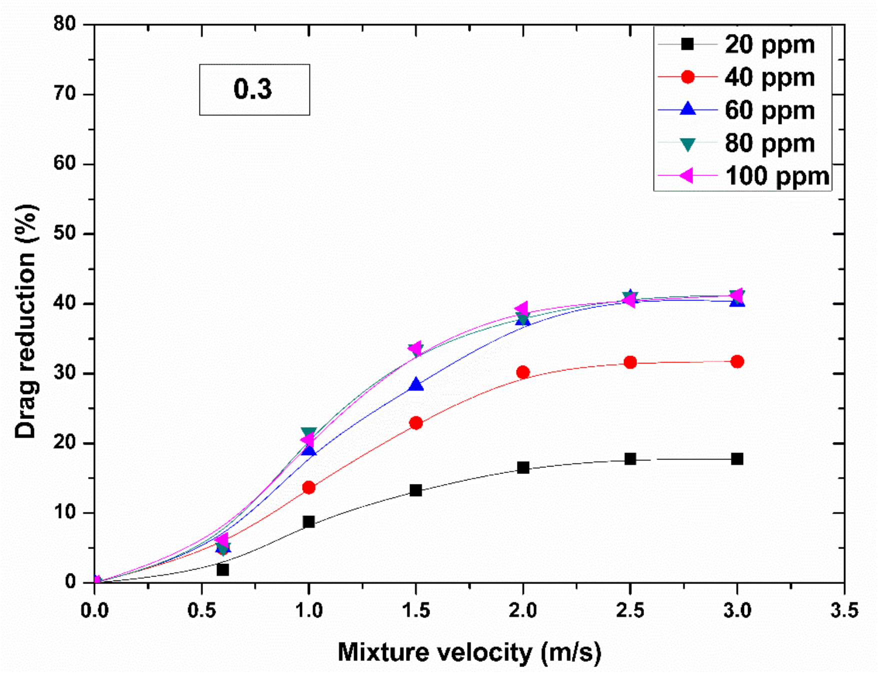


Figure 5.10(b): Drag reduction percentage against different mixture velocities and polymer concentrations: (a) oil fraction = 0.3

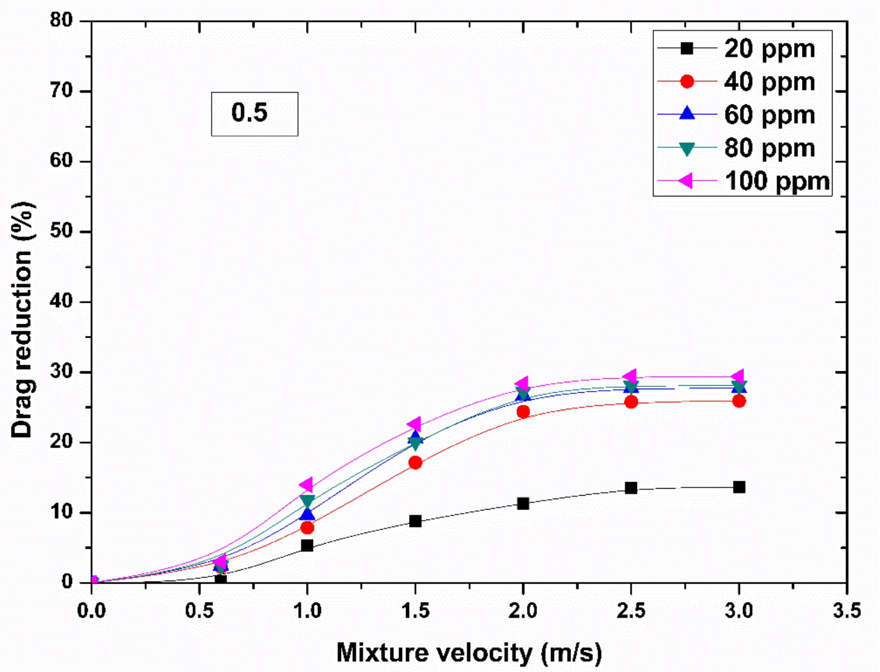


Figure 5.10(c): Drag reduction percentage against different mixture velocities and polymer concentrations: (a) oil fraction = 0.5

For mixture velocity of 0.6 the drag reduction percentage remains only 1.85% for 20 ppm and 6.15% for 100 ppm of the solution. The maximum drag reduction observed was 41.21% with 80 ppm and 100 ppm of the polymer solution at 3 m/s mixture velocity, as shown in Figure 5.10(b).

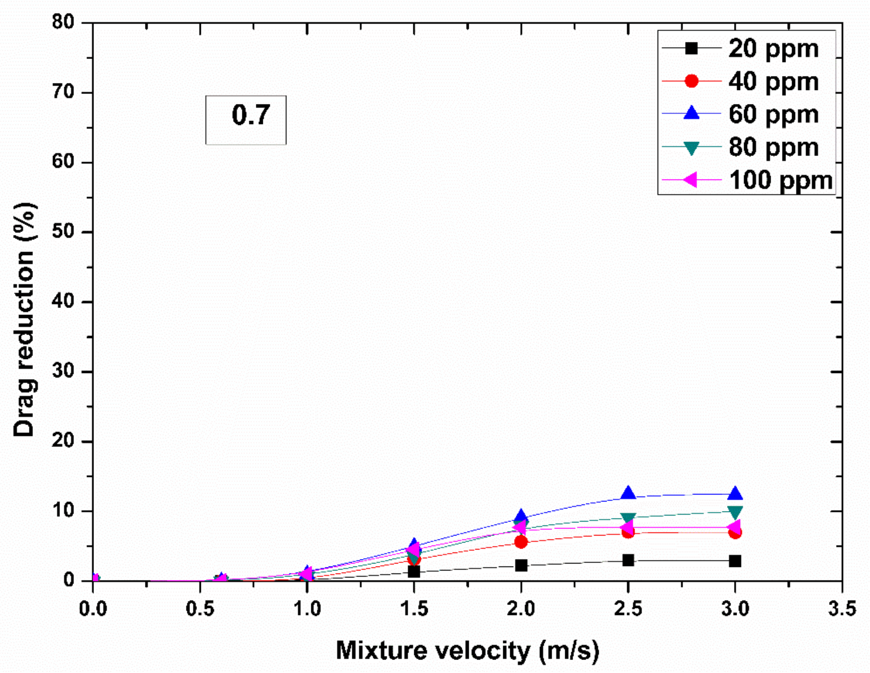


Figure 5.10(d): Drag reduction percentage against different mixture velocities and polymer concentrations: (a) oil fraction = 0.7

The minimum drag reduction percentage for 0.3 fractions of oil was 8.75% for 1 m/s at 20 ppm and the maximum was 20.51% for 100 ppm of solution for the same mixture velocity. The drag reduction percentage was 13.25% for 0.1 fraction of oil which was 17.25% for 1.5 m/s mixture velocity at 20 ppm. The drag reduction percentage observed was 17.76%, 31.72% and 40.32% for 20 ppm, 40 ppm and 60 ppm of polymer solution at maximum mixture velocity.

When the fraction of the oil was 0.5 almost negligible drag reduction was observed at 0.6 m/s of mixture velocity with a minimum concentration of the polymer. There was almost 10% - 13% drop in drag reduction percentage was observed as shown in Figure 5.10(c). The maximum drag reduction percentage decreased to 29.42% for 100 ppm of the polymer solution. Similar behaviour was observed for the 0.7 fractions of the oil. There was a continuous decrease in the drag reduction percentage with an increase in the oil fraction. The maximum drag reduction percentage was limited to 10.02% in 0.7 fractions of the oil.

It can be seen from Figure 5.10(a-d) that when the oil fraction was 0.1 there was an increase in the drag reduction with increase in the concentration of the polymer and mixture velocity.

And similar behaviour was observed for the 0.5 fractions of the oil. But when the oil fraction was more than that of the 0.3 & 0.5, and 0.7, the reverse effect of the polymer concentration was observed for higher concentrations. For 0.7 not any drag reduction effect was observed for the 0.6 m/s mixture velocity at any concentration. For mixture velocity, 1 m/s the minimum drag reduction percentage was 1.01% only for 60 ppm of polymer concentration.

Even for oil fraction of 0.7, there was a decrease in the drag reduction percentage at 100 ppm of the polymer concentration as compared to the 60 ppm of the polymer solution. It was observed that for higher mixture velocities (1.5 m/s-3 m/s) there was an increase in the drag reduction percentage was observed but the effect of the higher concentrations (80 ppm-100 ppm) was reverse. In the case of 0.7 fractions of oil, the maximum value of the drag reduction percentage was observed at 60 ppm of the polymer concentration which was 12.48% at 2.5 m/s mixture velocity. As compared to the 60 ppm of the concentration the maximum drag reduction percentage was 10.02% and 7.76% for 80 ppm and 100 ppm of the polymer solution. This type of behaviour may be due to the change of the water dispersed in the oil region from oil dispersed in the water region. Because in the 0.7 fractions of the oil the region was oil dominated region and the viscous forces were more dominated as compared to the interial forces.

5.3 Summary

In the present study, the drag reduction of the heavy oil was studied by using water/oil two-phase flow. The selected water-soluble polymers, which were able to produce a significant amount of drag reduction in one - phase flow, were used in two - phase flow system. The effect of the polymer concentration and the mixture velocity was studied to investigate the effect on the drag reduction percentage. The fraction of the oil was varied for different parameters of the two-phase flow. Simultaneously, the study of the flow patterns was done to better understand the hydrodynamics of the flow in the two - phase flow. It was found that with use of water - soluble polymer the drag of the heavy oil can be reduced up to a significant value. A maximum 50% drag reduction was observed for 0.1 oil fraction with 50 ppm concentration of polymer and mixture velocity 3 m/s. this value of drag reduction decreases to 36.5% at 0.5 oil fraction. The effect of the drag reduction was start diminishing, when the fraction of the oil was more than 0.7. Guar gum was able to produce more drag reduction as compared to the gum arabic solution but the flow patterns observed were almost similar for both polymer

CHAPTER-6

STABILITY & AGING OF WATER/OIL EMULSION

6.1 General

This chapter deals with the study in context to the stability and aging of the water-oil emulsion using polymer solutions. In the previous chapter, the two-phase flow was studied to observe the effect of the concentration, mixture velocity and fraction of oil on the possible drag reduction with the help of the guar gum and gum arabic solutions.

6.2 Water/oil flow systems

Two-phase flow like liquid-liquid or liquid-gas flow is very common in many petrochemical industries. Moreover, the transportation of two-phase flow became very popular in recent years due to its favourable properties like improvement in fluidity and less pressure drop during transportation of heavy oils. Continuous development is going on in the field of transportation of heavy oil with water and low-viscous oil dilution [63]. The flow of two-phase fluids in pipes is one of the challenging topics of research interest for many researchers due to the complexities involved in the design of two-phase flow systems [136, 148, 149]. However, a reliable method which can be feasible for all two-phase flow systems is still not found. The reason is simple; during the two-phase flow, a number of parameters like viscosity, surface properties, flow patterns, density and stability of the two immiscible liquids play a significant role on the flow behaviour [5–8]. Viscosity and density of the two immiscible liquids are important because different oils are categorized based on their viscosities. A heavy or extra heavy oil dispersed in water-like systems shows different behaviour as its viscosity and density change significantly. It is well known that when a water-like fluid is added to a heavy or extra heavy oil, there will be a significant decrease in pressure drop, which is the key to save a significant amount of energy in the form of pumping power.

In the field of two-phase flow, to reduce the pressure drop further, A few authors used drag reduction additives. Most of the drag reduction additives are soluble in single-phase only, either in water or in oil [1, 72, 75, 154]. Use of drag reduction additives was a revolutionary finding, which was first introduced in water phase flow in many industries like petrochemical for enhanced oil recovery as well as food industry, agriculture, and district heating and cooling systems. Different types of additives like polymers, surfactants, fibers, etc, are used for this purpose. Polymers are widely used advanced materials, which are found almost in every material used in our daily life. The importance of polymers has been very much highlighted because of their applications in different domains of science, technology, and industry – from basic to biopolymers and therapeutic polymers [159–164]. Almost 80% reduction in drag was found for single-phase flow of water in pipes with the use of high molecular weight synthetic polymers [19–25]. Some authors have investigated the effect of pipe diameter on water-oil hold up as well as energy analysis with the use of various drag reducing additives [80,169–172]. Recently, biopolymers have become very popular due to their environmentally friendly properties, which are able to produce the same amount of drag reduction with similar flow characteristics. A significant amount of work has been done to understand the effect of different types of polymers and their modifications to improve their performance [90, 118, 119, 123].

This study focuses on the formation of water-oil emulsions with the use of biopolymers and their stability and performance with a number of days. In most of the articles on drag reduction in single as well as two-phase flows, the polymer master solutions were used within three days of preparation to achieve consistent results [158]. Some authors reported degradation in the effectiveness of the polymer solution with time. To overcome this problem of decrease in the effectiveness of the polymer solution or stock solution with aging, various parameters were investigated to make a stock solution more stable with a number of days. In this study, the polymer solution was prepared by using a high concentration of polymer to form a gel type solution of the water-oil emulsion; and its stability and drag reduction effect with a number of days were investigated.

6.3 Materials and emulsion preparation

Two biopolymers namely, gum acacia (commercially known as gum arabic) and guar gum (Table 6.1) were purchased from M/s. Sigma Aldrich, U.S.A. and used as drag reducing additives for the formation of emulsions of water and oil. Both these water-soluble polymers have good stability and excellent emulsifying, self-enhancing, and binding properties and are used in many industries like food, paint, petroleum, etc., which make them useful for a number of applications. A mineral white oil (commercially used as a base oil for lubricants) having properties shown in Table 6.2 was purchased from Samsoil lubricants. The tap water used in this study underwent treatment prior to pumping and had a pH of 6.93. Tap water was chosen because the amount of water used during this study was quite bulk. Also, in the commercial perspective of transportation of heavy oils and extra heavy oils, the use of distilled and ultrapure water is not economically feasible. The emulsion was prepared using dry powder of both polymers in tap water.

Table 6.1: Type of polymer/oil and their concentrations used.

S. No.	Name	Concentration used in the test rig	Concentration used in stability test (master solution)
1.	Guar gum (GG)	50 ppm (relative to water phase)	GG1 (500 ppm), GG2 (1500 ppm), GG3 (3000 ppm), hydrogel (5000 ppm)
2.	Gum arabic (GA)	50 ppm (relative to water phase)	GA1 (1000 ppm), GA2 (2500 ppm), GA3 (5000 ppm)
3.	Mineral white oil	0.3 fraction	

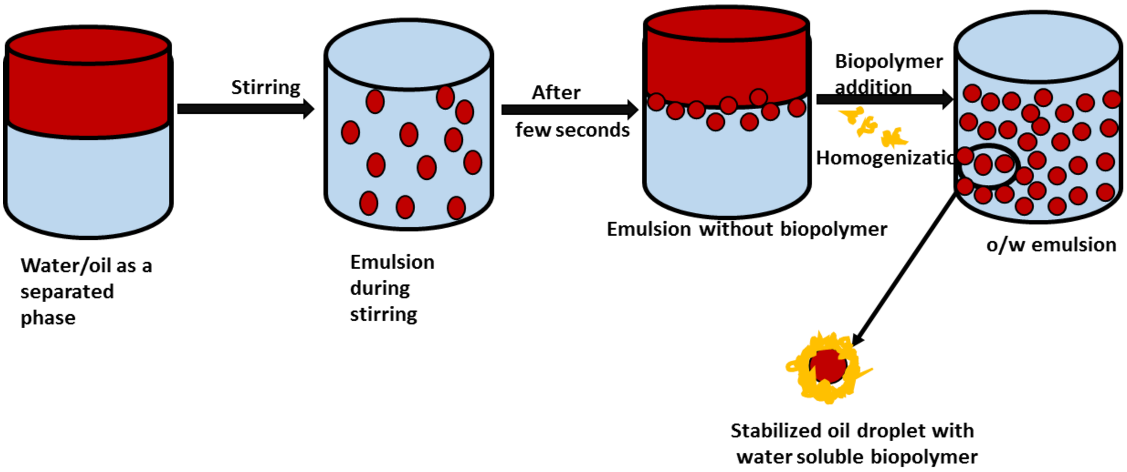


Figure 6.1: Possible mechanism of water/oil emulsion stability using biopolymer

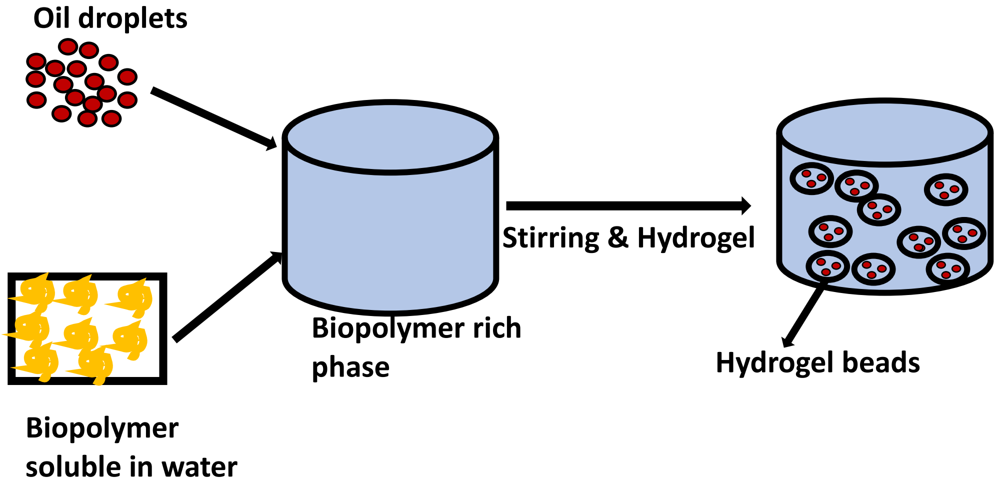


Figure 6.2: Possible formation of hydrogel using biopolymer (guar gum)

Table 6.2: Properties of fluids used

S. No.	Fluid	Density (kg/m^3)	Viscosity (cP)
1.	Water	997	0.890
2.	Oil (water white oil)	819	6

Firstly, the mixture of water and oil was stirred, and then, polymer powder was added to obtain the desired concentration slowly to avoid the formation of lumps in the solution and the mixture was stirred for 7 hours. The possible mechanisms of emulsion preparations are shown in Figure 6.1 and Figure 6.2. After stirring, the solution was kept for overnight for proper hydration. In a similar way, the hydrogel was prepared for which, the stirring was done for 24 hours. Borax of 0.05 M concentration was used as a cross-linker for the formation of a hydrogel. As the viscosity of the oil used in this work is 16 times more than that of the water phase, there is a need to select an additive which should be more rigid to sustain its degradation under two-phase flow. Therefore, guar gum and gum arabic were selected as drag reducing additives because of the rigidity of the polymer molecules. The mesh size (300) and molecular weight (5000 kDa) of both the polymers were in the same range. They were so chosen because the molecular weight has a significant effect on the drag reduction as well as degradation properties of a polymer [90, 132].

6.3.1 Stability test

The stability test was done to investigate the effect of concentration of polymer on the stability of water/oil emulsion. After preparation, the solution was transferred to the stability bottle (10 ml) and the creaming index (CI%) or emulsion percentage was measured with time.

Creaming index, $$\mathrm{CI}\ \% = \frac{H_{\mathrm{o}}}{H_{\mathrm{T}}} \times 100 \qquad (6.1)$$

where, H_{o} and H_{T} are the heights of the oil layer and total emulsion layer in the stability bottle, respectively.

Separation of oil and water was measured by using a calibrated scale and markings were also done on the stability bottle to avoid any measurement errors. The stability bottles were kept on an even surface and the creaming index data was collected continuously. Effect of concentration is shown in Figure 6.3 (a–f), wherein, the stability of the solution was presented against number of days. Three concentrations (1000 ppm, 2500 ppm, and 5000 ppm) were used for gum arabic and three other concentrations were used for guar gum (500 ppm, 1500 ppm, and 3000 ppm). It can be seen from Figure 6.3 that initially, all three concentrations of gum arabic showed almost similar separation of oil from the emulsion phase.

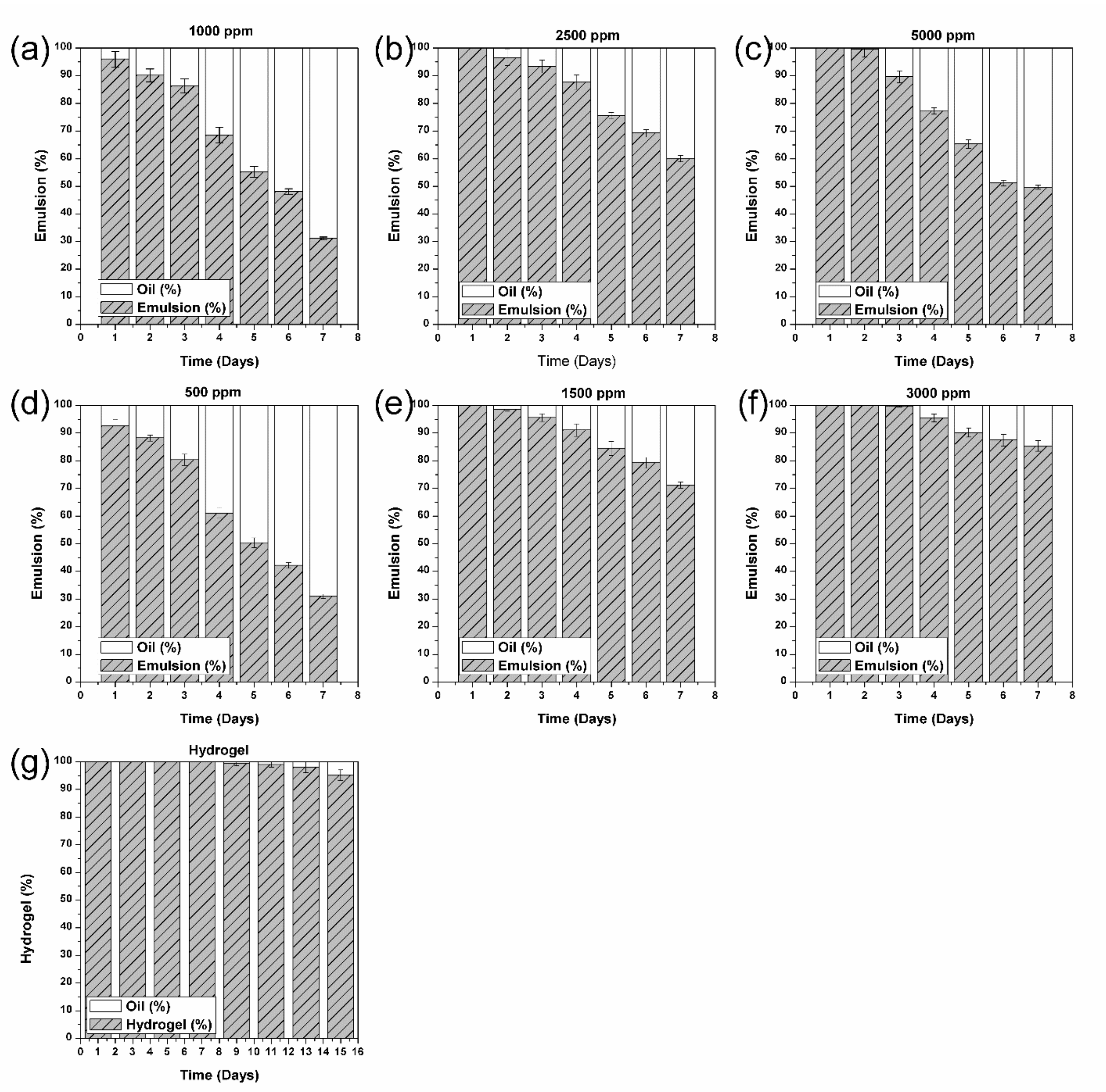


Figure 6.3: (a)-(c) Effect of concentration (1000-5000 ppm) of gum arabic on the water/oil emulsion stability with number of days; (d) – (f) Effect of concentration (500 – 3000 ppm) of guar gum on stability of water/oil emulsion stability (g) Effect of number of days on the stability of hydrogel formed with guar gum concentration (5000 ppm).

However, after 3 days, gum arabic with concentration 2500 ppm showed much better stability than the other two concentrations. After 7 days, the emulsion percentage remained at 31.17% for 1000 ppm, 59.98% for 2500 ppm and 49.67% for 5000 ppm of master solution. For guar gum, the percentage of emulsion observed after seven days was 31.5% for 500 ppm, 71.15% for 1500 ppm and 85.32% for 3000 ppm solution, which are far better than gum arabic solutions. A comparison of results indicates that the stability of guar gum solutions is superior to that of gum arabic even at lower concentrations (500 ppm, 1500 ppm, and 3000 ppm). A hydrogel was prepared with 5000 ppm of guar gum to determine the stability of high concentration of guar gum. It was observed that the stability of hydrogel was almost 100% after 9 days and it remained 95.23% after 15 days. No phase separation was noticed for hydrogel up to 10 days.

6.4 Effect on droplet diameter

The measurements of the droplet size of oil in polymer solution was performed on Brookhaven 90 plus particle size analyzer with precision ±0.6%. A small sample was introduced in the quartz cuvette and the readings were noted until the statistical convergence was reached and the average droplet size was calculated. The average size of the droplets was calculated on the basis of the area under the curve. First the solution was prepared with water and oil with required concertation of the polymer and there was no dilution was done for particle size measurements. This particle size measurement was done before the experiment. The results obtained for different samples are shown in Figure 6.4 for a quick comparison to easily understand the effect of the concentration of the polymer on the droplet size. Significant differences in the droplet diameters were observed for different concentrations of the polysaccharides. It can be observed from the bar graph (Figure 6.4) that for gum arabic, an increase in concentration of polymer leads to a decrease in size of droplets, i.e., 35±2.5 μm for GA1 and 8±1.5 μm for GA2 master solution, and a further increase in concentration of gum arabic did not yield a noticeable change in droplet size.

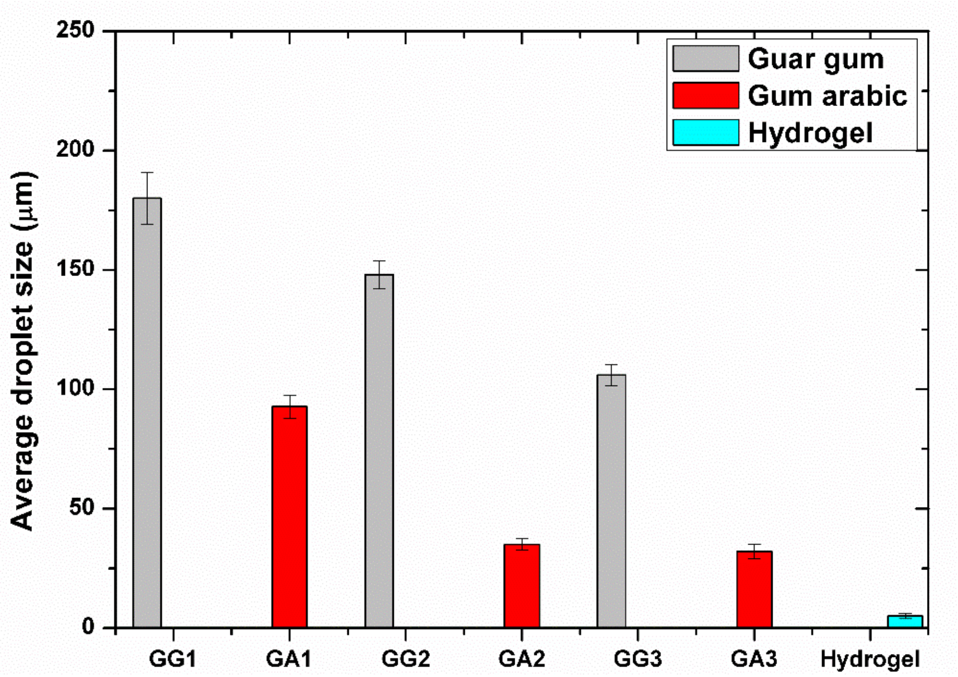


Figure 6.4: Comparison of average droplet diameter for guar gum, gum arabic and hydrogel with different concentrations.

For the polymer guar gum, the size of droplet for 500 ppm concentration was the highest (80±3.2 μm). An increase in the concentration of guar gum led to a significant decrease in the size of droplets, i.e., 42±1.68 μm for GG2 (1500 ppm) and 10±1.2 μm for GG3 (3000 ppm). The minimum droplet size was observed for the hydrogel, which was found to be 1.5±0.2 μm. This is because of the fact that an increase in the concentration of guar gum causes a significant increase in viscosity of the water phase, which slows down the mobility of the droplets [174–176]. This further leads to a reduction in coalescence during the emulsification as well as the period of storage, thereby enhancing the long-term stability.

6.5 Optical microscopy of emulsion

The dispersion of the droplets with different concentrations of guar gum and gum arabic can be compared in the optical microscopic images of Figure 6.5. A digital microscope Eclipse E100 (Nikon, Japan) was used to obtain visual images at 50 times amplification. To maintain consistency, samples were used immediately after the emulsification and the same solution was sampled for DSC measurements also. The morphology of the emulsions containing guar gum was more uniform than that of gum arabic polymer.

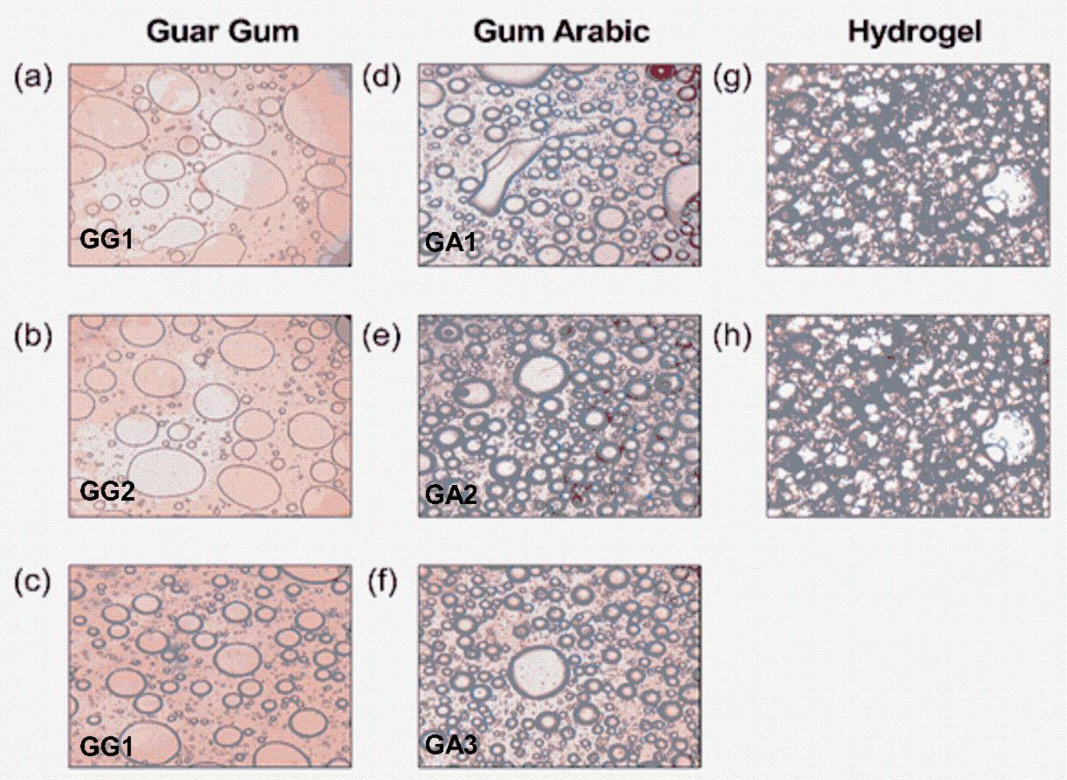


Figure 6.5: (a-c) Effect of concentration of guar gum on microstructure (at 50X) of emulsion; (d-f) effect of concentration of gum arabic on microstructure (at 50X) of the emulsion; (g-h) microstructure (at 50X) of the hydrogel.

On the other hand, a comparison of different concentrations of both polymers reveals that the emulsions containing a higher amount of polymer have more uniform droplet size. The droplets of the hydrogel are more uniform and closely packed as compared to the lower concentrations. It can be observed from Figure 6.5 that for all emulsions, the droplets were spherical in shape and the size of the oil droplets in guar gum is much larger than that of gum arabic and hydrogel. This is because of the fact that the concentrations of guar gum used were lower than gum arabic and hydrogel. With an increase in the concentration of guar gum, the size of the droplets decreased; however, for gum arabic, no significant decrease in droplet size was observed for 2500 ppm and 5000 ppm, which was also confirmed by droplet size analyzer. However, for the hydrogel, the coalescence of droplets is much higher (or denser) than the other solutions because of the high concentration and viscosity of the polymer in solution [170,173,174–177].

6.6 Experimental Facility

After formation, the average droplet size was determined; and the stability of water-oil emulsion and performance of the polymers were checked by performing experiments at 25°C on the test rig shown in Figure 5.1 in Chapter-5. A premixed solution was used to investigate the effect of polymers on drag reduction values. The solution in the reservoir was so prepared (diluting master solution) that the concentrations of both the polymers as well as hydrogel were maintained at 50 ppm. In the experimental setup, a pipe of galvanized iron material with internal diameter 19.5 mm and length 6000 mm was fabricated. To make the emulsion properly distributed, a stirrer was mounted in each of the reservoirs. The solution was circulated by using a centrifugal pump (3000 rpm max.) connected to the main reservoir. All the experiments for drag reduction were performed at a mixture velocity of 3 m/s, so that there should be dispersed flow. At dispersed flow, the formation of turbulent eddies was quite significant to observe the maximum possible effectiveness of drag reducing polymer.

Pressure transducers (ST3000 Honeywell, 10 bar max., accuracy 0.3%) were carefully mounted on the test section with proper entrance length to avoid any losses. At the end of the test section, an acrylic pipe section was joined to monitor continuous flow patterns of the solution. An electromagnetic flow meter (IOTA Flow, accuracy 0.3%) was used to measure the volumetric flow in the test section. The fluid was returned to the reservoir after passing through the test section. As the fluid flowing through the pipeline was in the mixed flow, the characteristics of flowing fluid were calculated as discussed in the chapter-5.

All the experiments were performed only in the dispersed oil-in-water region, because, the polymers are soluble in the water phase. A number of pilot experiments were performed beforehand to select the optimum parameters for experimentation. The details of the experimental parameters are given in Table 6.1. Preparation and possible mechanisms for the formation of emulsion and hydrogel are shown in Figures. 6.1 and 6.2, respectively. When the concentration of the polymer is increased, the aggregation and interfacial viscosity increase, which lead to a corresponding increase in the stability of the emulsion. According to the Stokes' law, the stability of an emulsion can be enhanced by maintaining high viscosity of the continuous phase, small droplet size or low-density difference between the continuous and the dispersed phase [182]. On the other hand, when a cross-linker was added into the polymer stabilized the emulsion, it leads to the cross-linking of the polymer chains and starts forming gel-like structure, in which, oil or dispersed phase gets trapped in the form of fine droplets, making the emulsion more stable.

6.7 Effect of polymer degradation on drag reduction percentage with aging time

In order to check the effectiveness of both the polymer solutions, a premixed solution was prepared using the polymer and master solution. Before performing the experiments, pilot experiments were performed to identify the optimum concentration (50 ppm) of both polymers that results in the maximum drag reduction percentage in water/oil flow. The fraction of the oil was kept at 0.3 during all the experiments and the obtained results are shown in Figure 6.6. Reduction in pressure drop using different synthetic polymers in two-phase flow and their various characteristics have been studied by various authors [75,79,142,149,183–185].

When the polymer gum arabic was used for the drag reduction, it was found that for the first two master solutions (GA1 and GA2), the average decrease in the drag reduction percentage was 3% from its initial value (43.26%). Further, for GA1, it decreased by 25% on the fourth day and 44% on the fifth day from the initial value. After 7 days, the decrease in maximum drag reduction percentage was 54%. For GA2 solution, degradation in the effectiveness of the polymer on 4th, 5th, 6th and 7th day was 8%, 17.65%, 25.71%, and 29.2%, respectively. For GA3, the percentage of degradation in effectiveness was found to be more than that for GA2, which was 27%, 46.7% and 51% on 5th, 6th and 7th day, respectively. This is due to the stability of GA2, which is better than that of GA1 and GA3 with number of days. Of these three concentrations of gum arabic, GA2 was found to be optimum with the least degradation as compared to other two concentrations.

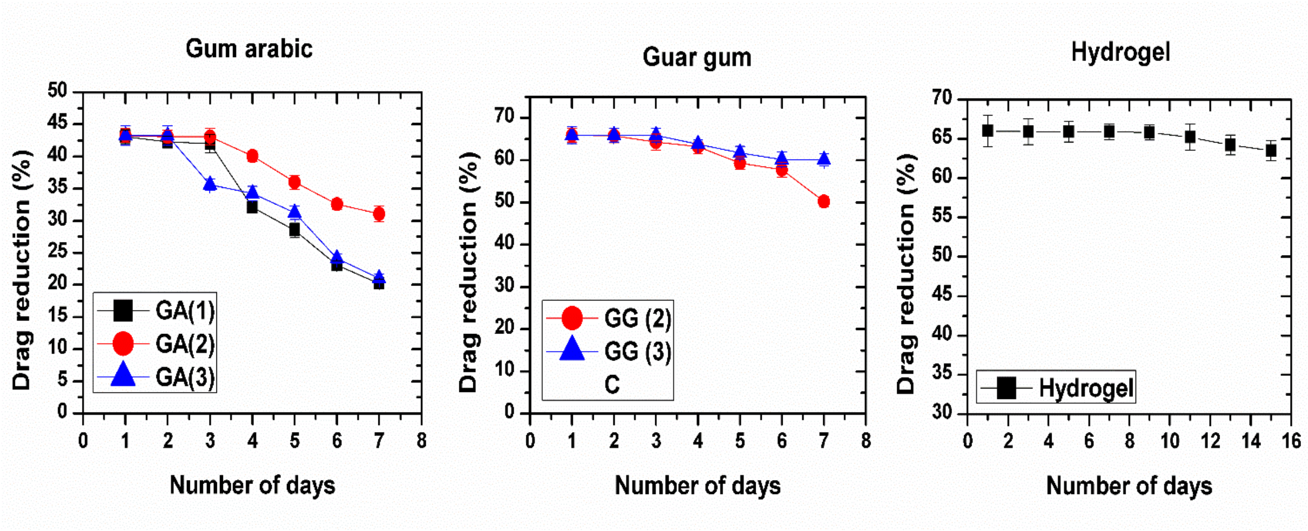


Figure 6.6: Effect of different polymers and degradation of polymers on maximum drag reduction percentage.

For guar gum polymer, the same concentration (50 ppm) and a fraction of oil (0.3) was used to compare the effect of this polymer with the former polymer (gum arabic). In a similar manner of gum arabic, three different master solutions were prepared using guar gum, but, with low concentrations. In comparison with gum arabic, guar gum was found to be more stable and the maximum drag reduction percentage (65.9%) was observed with a higher concentration (50 ppm) of the polymer. For GG1, the average decrease in the effectiveness of the polymer was 11% in first three days, which remained 63% after seven days. For GG2 and GG3, the average decrease in maximum drag reduction percentage was only 3% for first three days. After seven days, the degradation in effectiveness was 20% for GG2 and only 7% for GG3.

A hydrogel solution was also tested, which was prepared by using a high concentration of guar gum (5000 ppm), and its stability was found to be far better than the other solutions. This solution was stable for 15 days and even after 15 days, the average degradation in the polymer effectiveness was only 3.8% from its initial value.

6.8 Summary

In the present study, the effect of the concentration of the polymer was studied on the stability of the water/oil emulsion. It was found that the stability of the water/oil emulsion can increase with addition of the polymer at different concentration. The stability of the polymer solutions was observed with number of days. A similar study was done for the hydrogel solution prepared from the guar gum and was stable up to 15 days without any considerable degradation. The effect of the aging of the solution on the drag reduction percentage was also studied.

CHAPTER-7

CONCLUSIONS AND FUTURE SCOPE

On the basis of the present study, the following major conclusions were drawn from studies of the drag reduction in pipe flow of heavy oil using polymer additives.

7.1 Rheological Characterizations.

Three polymers were selected for the rheological characterization. Two polymers were water soluble polymers and one was oil soluble polymer. The effect of the concentration of the polymer as well as salt on the solvent density and viscosity was observed and following conclusions were drawn.

1. Instead of synthetic polymers, two water-soluble biopolymers were selected (a) guar gum (b) gum arabic, and one oil-soluble polymer (polydimethyl siloxane) were selected.
2. Effect of temperature and concentration of the polymer was studied. It was observed that there was an increase in the viscosity of the solvent with an increase in concentration of the polymer
3. There was a significant effect of guar gum polymer on the viscosity of the water as compared to gum arabic. The increase in the viscosity of the solvent with guar gum almost 500% more than the solvent value which was only 14.7% in case of the gum arabic solution. The rapid increase in the viscosity of the guar gum as compared to gum arabic was due to its hydration rate. The rate of hydration for guar gum solution is much higher than gum arabic solution, which causes the high viscosity of the guar gum solution
4. In the case of the oil-soluble polymer polydimethylsiloxane, the maximum increase in the viscosity of the solution was 16.25%.
5. For both the water as well as oil-soluble polymers the effect of the shear rate was observed and it was found that for all guar gum solutions, the shear thinning behaviour was observed even for the small concentration.
6. For gum Arabic solution the shear thinning behaviour was observed at the higher concentrations but for lower concentrations of the polymer, Newtonian behaviour was observed
7. For oil-soluble polymer the behaviour of the oil was Newtonian under the shear and when polymer was added at the different concentrations there was an increase in the viscosity of the solution but the overall behaviour of the solution with shear rate was Newtonian. There was no change in the viscosity with the shear rate was observed.
8. The effect of the temperature on the viscosity of the polymer solution of different concentrations was observed from the temperature 25 ^oC to 45 ^oC. There was a decrease in the viscosity of the polymer solution with an increase in temperature.

9. There was a 20% decrease in the guar gum solution viscosity at 45 ^{o}C which was 55.3% and 55% in the case of gum arabic and polydimethylsiloxane solutions respectively. It was found that in the case of guar gum and gum arabic solution the effect of the temperature was more when the concentration of the polymer was higher and for lower concentrations, the effect was less.
10. In the case of the density, there was a negligible effect of the polymer concentration was observed for water-soluble polymers but there was an increase in the density of the solvent with the addition of the KCl salt. In the case of polydimethylsiloxane, there was an increase in the density of the solution with the addition of the polymer in oil.

7.2 Drag reduction in one-phase flow

The effect of concentration of the selected polymers as well as Reynolds number on the drag reduction percentage was observed. Initially the selected polymers were tested in the one-phase flow and the following conclusions were drawn.

1. This study examined the effect of guar gum and gum arabic polymer and KCl salt concentrations on drag reduction efficiency and mechanical degradation behavior. The percentage drag reduction was found to be severely influenced by the polymer concentration and Reynolds number.
2. As the concentration of the polymer was increased, the corresponding drag reduction percentage also increased. The maximum drag reduction value observed at high polymer concentration (3000 ppm ~ 150 ppm) was 71.4% with guar gum and 62.1% for gum arabic solution (6000 ppm ~ 300 ppm). The obtained results for different concentrations of polymer were validated with the hypothesis given by Virk (i.e. MDRA). The reason behind the significant drag reduction observed under high turbulent conditions can be explained by the hypothesis of Bakewell and Lumley [122], which states that the expansion of the polymer molecules occurs in the flow outside of viscous sublayer due to variation in the strain rate.
3. Addition of polymer in injection mode near the boundary layer yielded superior drag reduction values than that of pre-mixed solutions used in literature. The effect of KCl salt concentration on the shear stability of the polymer solution was investigated.
4. The addition of KCl salt to the polymer solution makes it more rigid due to which it becomes more stable under high shear conditions. Up to 47% enhancement in the shear stability was noticed with the addition of the salt to the polymer solution (guar gum) for a Reynolds number of 45000. A polymer concentration of 3000 ppm and salt concentration 2000 ppm were found to be optimum for achieving the highest drag reduction with better shear stability.

5. The effect of addition of the salt on the drag reduction percentage was more negative in the case of gum arabic solution. But still, the addition of the KCl salt improved the shear stability of the gum arabic solution. In gum arabic polymer solution 37% enhancement in the shear stability was observed with the addition of the 2000 ppm of the KCl salt. Mixing of a polymer with a solvent at low temperature without any ionic species/electrolytes leads to the disordered state of the polymer molecules. However, with the addition of salt to the polymer solution, the side chains collapse down to the backbone due to charge screening. Addition of salt to the polymer solution leads to the transition of molecules from a disordered state to ordered state causing stretching of the polymer backbone, which also results in increased rigidity of the polymer molecules.
6. For polydimethylsiloxane, the maximum drag reduction 23.9% was observed at 400 ppm of the polymer solution injected near the boundary layer. With further increase in the concentration of the polymer the drag reduction percentage start decreasing.
7. Effect of the injection position, as well as the type of injection, was found. Two types of injection, i.e slot injection with the perforated end as well as without perforated end was investigated. A maximum drag reduction percentage was observed, when the injection was near the surface of the pipe.
8. A significant effect of the drag reduction percentage values was observed when without perforation end was used instead of the perforated end. There was an average 7% decrease in the drag reduction percentage for the same injection position for without perforated end for guar gum and an average 10% decrease in gum arabic polymer solution. The reason behind this variation may be the formation of threads of polymer solution during the injection. When there was perforation at the injection end the mixing, length required for diffusion of polymer threads required was also less. When there was no perforation at the end there was single thread formation and the time and mixing length required to diffuse the polymer molecules in flow was more, which leads to decrease in the drag reduction percentage.

7.3 Drag reduction in two-phase flow

Two water-soluble biopolymers guar gum and gum arabic were injected directly into the boundary layer in the two-phase flow system. Effect of the drag reducing polymer was studied on the pressure drop as well as on the flow patterns continuously and the following conclusions were made

1. Addition of the polymer (guar gum) was done from the stratified region to dual continuous as well as dispersed region. It was found that when the polymer was added into the flow, the stratified region was extended from lower mixture velocities (0.2 m/s) to higher mixture velocities (0.5 m/s) because of change of dual continuous region to stratified region.

2. For oil dispersed in water region for both full oil droplets dispersed in water (> 1 m/s) as well as oil droplets dispersed as well as a layer at the bottom (< 1 m/s), when drag reducing polymer was added a little stratification was observed.
3. A maximum 50% drag reduction was observed for 0.1 oil fraction with 50 ppm concentration of the polymer and mixture velocity 3 m/s. which decreases with the increase of oil fraction. When oil fraction was 0.5 maximum drag reduction was remained 36.5% for higher mixture velocity. Almost 90% enhancement was observed in the drag reduction in water dominated region with 50 ppm concentration and 3 m/s mixture velocity.
4. Up to 0.5 oil fraction 50 ppm was found to be optimum concentration but for 0.7 oil fraction 30 ppm was found to be more effective as compared to higher concentrations.
5. In case of gum arabic the maximum drag reduction percentage (44.16%) was observed when the oil fraction was 0.1, at 3 m/s mixture velocity with 80 ppm of the polymer solution.
6. The maximum drag reduction percentage decrease to when the oil fraction was 0.5. This is due to the phenomenon that when the mixture velocity is increased, there is a continuous formation of turbulent eddies, which in turn causes loss of energy in the form of pressure drop. But, with the addition of a polymer in the flow, the polymer coils stretch near the turbulent eddies and suppress the formation of eddies. Due to the suppression of the turbulent eddies, a decrease in the pressure drop (known as drag reduction) is observed.
7. In case of flow patterns with gum arabic almost similar effect was observed as that of guar gum instead the oil dominated region started after 0.5 fraction of oil.
8. The drag reduction for both polymers were more effected in the water dominated region instead of oil dominated region, because both polymers are soluble in water so they are more effective in water dominating region.

7.4 Stability and aging of water/oil emulsion

Two different polymers' master solutions were prepared to investigate the stability and degradation of effectiveness during experimentation for maximum drag reduction percentage. In a similar way, a hydrogel was also prepared using guar gum polymer with high concentration and the following conclusions were obtained.

1. The effectiveness of the polymers with aging was improved by keeping the stock solution stable for longer than the usual time period (3 days). The stability of gum arabic was found to be better for 2500 ppm solution than 5000 ppm and 1000 ppm. The concentrations of guar gum used were lower than gum arabic solutions, however, the stability was far better than gum arabic even after number of days.

2. A hydrogel solution was prepared without using any homogenizer and it was found to be highly stable for more than 15 days with least separation (3%).
3. After formation and stability, droplet size test and optical microscopy were done to confirm the stability phenomenon. After investigating the effectiveness of the biopolymers in water/oil flow with the number of days of aging, the optimum concentration was selected and hydrogel and guar gum of 3000 ppm (master solution) was found to be optimum for maximum drag reduction percentage (65.9%) than gum arabic solutions, whose maximum drag reduction percentage was only 43.26%.
4. The superior drag reduction of guar gum can be attributed to its high stability of polymer chain under turbulent conditions. Also, the molecules of guar gum are more rigid than that of gum arabic, which lead to higher drag reduction at high turbulent strength.

From there conclusions it was observed that guar gum provides maximum drag reduction.

Future Scope of work

Further suggestions or the scope of the work in the area of drag reduction with one and two-phase are as follows:

1. A number of studies has been done in one-phase flow for drag reduction with synthetic as well as natural polymers. There are some natural polymers which can have shear degradation problems like Okra, Xanthan gum etc. A detailed study can be done with different additives or salts to improve their stability.
2. Grafted biopolymers can also be studied to enhance or to improve the drag reduction percentage as well as modification in their rheological properties.
3. Injection of the guar gum and gum arabic have produced significant drag reduction percentage. Some experiments or investigation can also be explored with coating a layer of guar gum inside the pipe surface.
4. The natural polymers which are successfully able to produce good amount of drag reduction percentage in one-phase flow can also be explored for two-phase (water/oil) flow.
5. More hydrodynamics of the water/oil flow can be studied like flow patterns, hold-up and inversion point with and without addition of the polymer.
6. Recently, modification of the inner surface of the pipes has been reported in some articles to reduce the pressure drop. In most of the articles, synthetic polymers were used with spray technology. This type of work can be investigated by using biopolymers.
7. This work can be extended for futher use with the help of ANSYS software. Numerical studies can be done for more complex systems in two-phase systems.
8. By using simulation study, this system can be explored for scale-up so that it can be more effective in commercial applications.
9. Hybrid biopolymers can be grafted to observe the effect of these biopolymers on drag reduction percentage.
10. Guar gum can be changed in to gel form with addition of borax in it, which can easily stick on the surface of the pipe or plate. By using this method, experiments can be performed for modified surface and the degradation study of the layer can be investigated with respect to time.

11. Rheology of the guar gum is quite complex so further study can be done on its visco-elastic behaviour.
12. This study was limited to galvanized iron pipe material and can be further extended to other type of material to observe the effect of the same biopolymers on rough as well as smooth materials.

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LIST OF PUBLICATIONS

Journal publications (SCI)

1. Kamaljit Singh Sokhal, Dasaroju Gangacharyulu, Vijaya Kumar Bulasara, Effect of guar gum and salt concentrations on drag reduction and shear degradation properties of turbulent flow of water in a pipe, Carbohydrate Polymers, Volume 181,2018,Pages 1017-1025, ISSN 0144-8617, https://doi.org/10.1016/j.carbpol.2017.11.048. (I.F = 6.04)

2. Kamaljit Singh Sokhal, Gangacharyulu Dasaroju, Vijaya Kumar Bulasara, Formation, stability and comparison of water/oil emulsion using gum arabic and guar gum and effect of aging of polymers on drag reduction percentage in water/oil flow, Vacuum, Volume159, 2019, Pages 247-253, ISSN 0042-207X, https://doi.org/10.1016/j.vacuum.2018.10.044. (I.F =2.51)

3. Kamaljit Singh Sokhal, Dasaroju Gangacharyulu, Vijaya Kumar Bulasara, An experimental investigation of heterogeneous injection of biopolymer (guar gum) on the flow patterns and drag reduction percentage for two phase (water-oil mixture) flow, Experimental Thermal and Fluid Science, Volume 102, 2019, Pages 342-350, ISSN 0894-1777, https://doi.org/10.1016/j.expthermflusci.2018.12.012. (I.F =3.49).

Other journal publications

1. B.S. Prashant, Sumeet Sharma, D. Ganagacharyulu, Kamaljit Singh, A Review of Drag Reduction in a Turbulent Flow using Polymers, *International Journal of Engineering Research & Technology*, Volume 6, Issue 17, July 2017, 520-523, ISSN: 2278-0181.

International Conferences

1. Kamaljit Singh Sokhal, Dasaroju Gangacharyulu, Vijaya Kumar Bulasara, Effect of Reynolds Number and Concentration of Biopolymer (Guar arabic) on Drag Reduction of Turbulent Flow in Circular Pipe, *21st International conference on Fluid dynamics & Heat transfer, Sydney, Australia, Feb 27-28, 2019.*

2. B.S. Prashant, Kamaljit Singh, Sumeet Sharma, D. Ganagacharyulu, Effect of Guar Gum and Hydroxyethyl Cellulose on skin-friction drag of turbulent flow in a pipe, *Proceedings of the 24th National and 2nd International ISHMT-ASTFE Heat and Mass Transfer Conference (IHMTC-2017), December 27-30, 2017, BITS Pilani, Hyderabad, India.*