DRAG REDUCTION BY POLYMERS IN TWO-PHASE FLOW IN A SMALL PIPE DIAMETER

BY

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I dedicate my thesis work to my family and my friends.

A special feeling of gratitude to

my loving parents,

Brothers,

and my sisters

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Full Name : MUSTAFA SALAH MUSTAFA AHMED

Thesis Title : DRAG REDUCTION BY POLYMERS IN TWO-PHASE FLOW IN A SMALL PIPE DIAMETER

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Increasing the pipeline flow capacity and throughput by reducing the pressure losses is the key parameter for industrial applications. Introducing a few amounts of high molecular weight polymers in the pipeline along with flow direction became an effective technique to reduce the losses and operational costs of pumping facilities as well.

In this study the effect of adding the drag reducing polymers (DRP) on the pressure drop has been experimentally investigated for a horizontal pipe carrying two-phase flow of air and water mixture. Moreover the ability of these polymers to damp turbulence waves and changing flow regime have been tested at various conditions.

An experimental set-up has been constructed using a test section of 0.4 inch ID, an acrylic tube is used for visual observations of the flow patterns. With the presence of DRP the Pressure drop reduction occurred in all flow configurations and the maximum drag reduction percent (%DR) was 80% for the intermittent flow regime utilizing 200 ppm polymer concentration.

Furthermore different empirical correlations have been developed to predict the pressure drop after the addition of DRP. The correlations showed low discrepancy for a wide range of water and air flow rates.

ملخص الرسالة

الاسم الكامل: مصطفى صلاح مصطفى أحمد

عنوان الرسالة: تأثير بوليمرات الفقد الاحتكاكي في نظام ثنائي الطور ولأنابيب ذات أقطار صغيرة

التخصص: الهندسة الميكانيكية

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إن زيادة سعة تدفق خطوط الأنابيب والإنتاجية عن طريق الحد من فقودات الضغط هي المفتاح الرئيس في التطبيقات الصناعية .إدخال كمية قليلة من البوليمرات عالية الوزن الجزيئي في خطوط الأنابيب مع إتجاه التدفق أصبحت تقنية فعالة للحد من الفقودات والتكاليف التشغيلية لمحطات الضخ أيضا.

في هذا البحث، تمت دراسة تأثير وجود البوليمرات المقللة للإحتكاك (DRP)على انخفاض الضغط في الأنابيب الأفقية التي تحمل تدفق ثنائي الطور من خليط الهواء والماء. تم إستخدام قسم اختبار أنبوب الاكريليك ذو قطر داخلي 0.4 بوصة للملاحظات البصرية ومعرفة نوع السريان. باستخدام البيانات التجريبية التي تم الحصول عليها في وجود البوليمرات المقللة للإحتكاك (DRP) حدث انخفاض فقودات الضغط في جميع أنماط السريان. أقصى نسبة مئوية للفقد (DR%) كانت حوالي80٪ عن طريق وضع بوليمرات فقط بتركيز 200 جزء من المليون في خط أنابيب.

وبالإضافة لذلك تم تطويرعدة معادلات تجريبية مختلفة للتنبؤ بهبوط الضغط بعد إضافة DRP. أظهرت هذه المعادلات إنخفاض في التباين لمجموعة واسعة من معدل تدفق المياه و الهواء.

CHAPTER 1

INTRODUCTION

1.1 Flow patterns

A particular type of geometric distribution of components is called a flow pattern or regime. Different flow regimes may occur due to the deformable interface between the phases as they move along with the pipe, these heterogeneous mixtures create more fluctuation and could affect the hydrodynamic behavior of the flow.

The determination of such flow patterns cannot solely be obtained using one factor, therefore different factors or parameters might be used to predict the flow regime as follows; velocity, viscosity, void fraction and density of each component, in addition to pipe diameter and it's geometry.

The observation of the flow patterns by visual inspection is the most used technique for identifying the regime with the assist of a high-speed photography subjected to the wall of a transparent (acrylic) tube. The flow pattern that may appear in two-phase (Gas-Liquid) flow system in horizontal pipes can be classified into four groups as seen in figure 1.1:

- Stratified flow (Stratified-Smooth and Stratified-Wavy).
- Intermittent flow (Slug flow and Elongated-Bubble flow).
- Annular flow.

- Dispersed-Bubble flow.

Figure 1.2 illustrates the various flow regimes that could occur in vertical flow configurations. The formation of each flow regime and it's transition depend on various factors:

- The operational parameters such as gas and liquid flow rates,
- The geometrical variables (pipe diameter and inclination angle).
- The physical properties of the tow-phase, gas and liquid densities, viscosities and the surface tension.

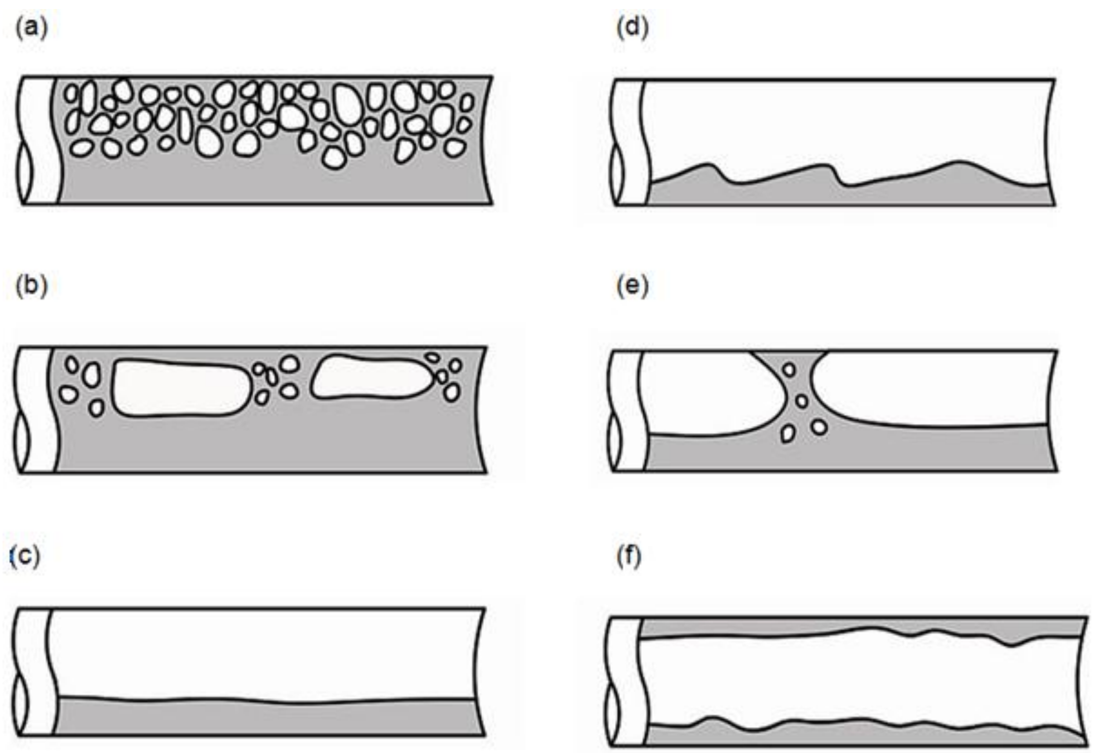

Figure 1.1: Gas-Liquid flow regimes in horizontal flow configuration. Gas-Liquid flow regimes in horizontal flow configuration. (Hewitt [1]).

(a) Bubbly flow; (b) Plug flow; (c) Stratified flow; (d) Stratified wavy flow; (e) Slug flow; (f) Annular flow.

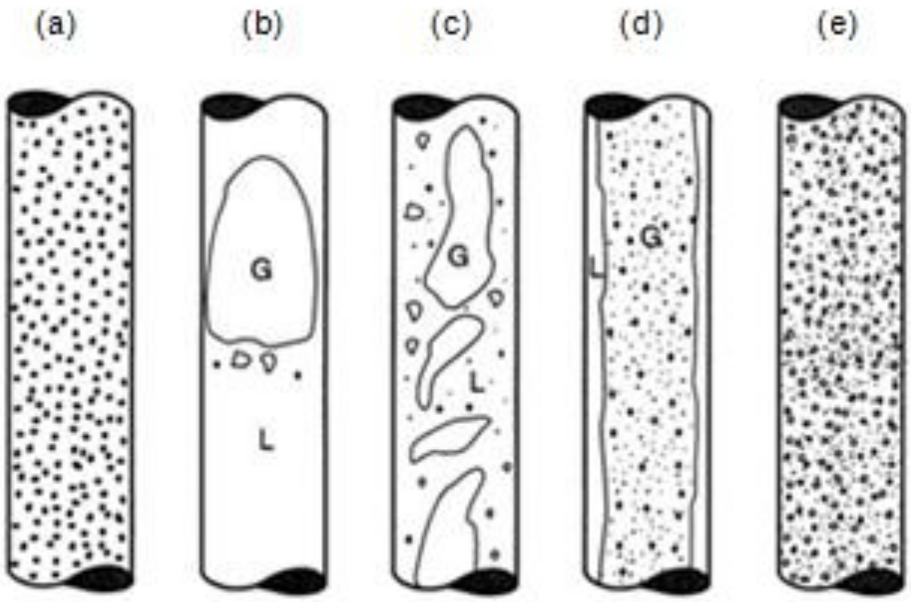

Figure 1.2: Gas-Liquid flow patterns in vertical configuration. (Abdulmouti [2])

(a) Bubbly flow; (b) Slug flow; (c) Churn flow; (d) Annular flow; (e) Dispersed flow.

In figure 1.3, the possible flow structure has been articulated for the two phase Liquid-Liquid (water-oil flow), additional flow types could arise depend on either the continuous phase is water or oil.

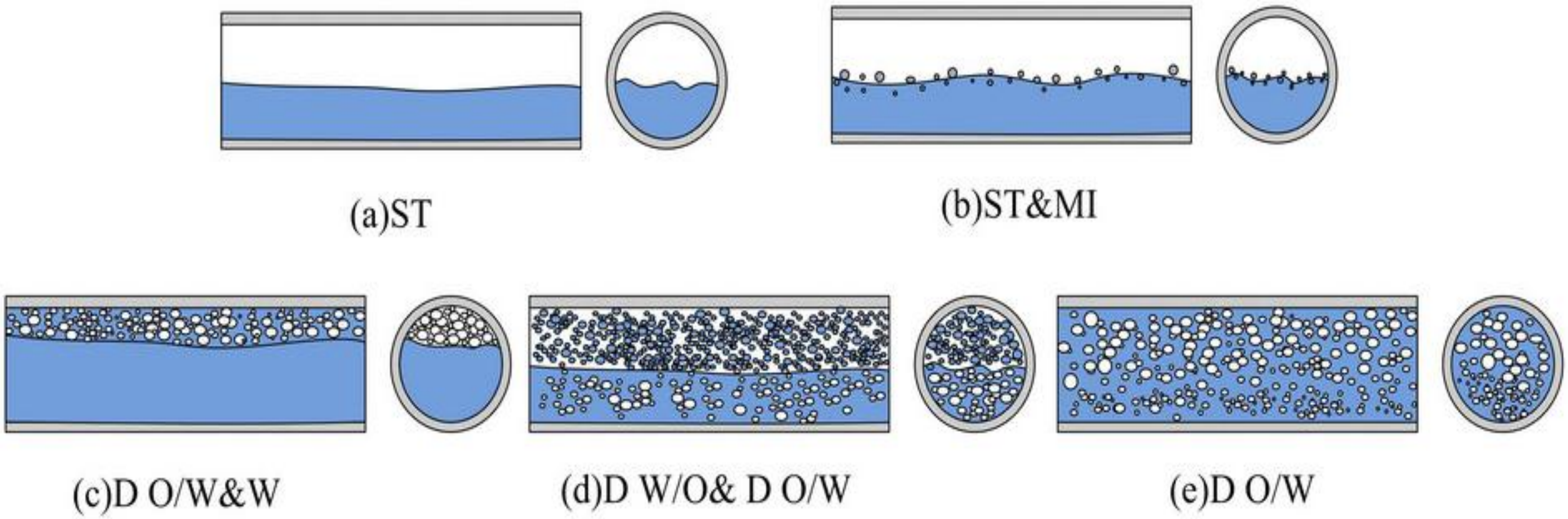

Figure 1.3: Oil-water flow regimes in horizontal configuration.(Gao et al.[3])

(a) Stratified flow (ST); (b) Stratified flow with mixing at an interface (ST&MI); (c) Dispersion of oil in water and water flow (D O/W&W); (d) Dispersion of water in oil and oil in water flow (D W/O& D O/W); (e) Dispersion of oil in water flow (D O/W).

To study the behavior of flow patterns in the multiphase flow there are several techniques have been reported and many researcher in this field continued developing different models to predict the detailed behavior of those flows by offering an explanation for the existing phenomena.

The available models in which such flow types and it's behavior are explored can be obtained through three different ways categorized as; (1) Experimental modeling in which laboratory-sized arranged with appropriate instrumentation used to get at the end an empirical models (2) Theoretical modeling where using a mathematical equations and models for the flow with the assist of an existing experimental data and (3) Computational modeling, utilizing power and size modern computers to address the complexity of the flow, however still in some applications the need for full-scale laboratory models are possible candidate. But, in many cases, the designing of the laboratory models must have different scale than the prototype for the seek of having realistic theoretical and computational models. Furthermore there are some cases in which a laboratory model cannot be establish to gain the needed data then the computational techniques could offer an effective solution.

An early investigation of the flow patterns for two phase gas-liquid flow in horizontal pipes has been done by Mandhane et al.[4] They have used a huge data bank with numerous conditions to eliminate large discrepancies that been reported in their previous works. Based on this data bank the computational modeling has been performed and they were able to generate a comprehensive flow pattern map with transitional flow regimes boundaries as shown in figure 3.4. Refer to other studies , they also made a comparison study and it was clearly indicated that their work provided an extension for Aziz et al.[5]

Since they enhanced the technique of the prediction significantly taking into account the effect of physical properties of the flowing fluids.

Moreover adding the effects of pipe diameter could also improve the prediction of the patterns and this has been shown in the research of Weisman et al. [6] when they were varying the line sizes from 1.2 to 5 cm, the reliability of the previous models was increased in identifying the flow regimes and it's ranges.

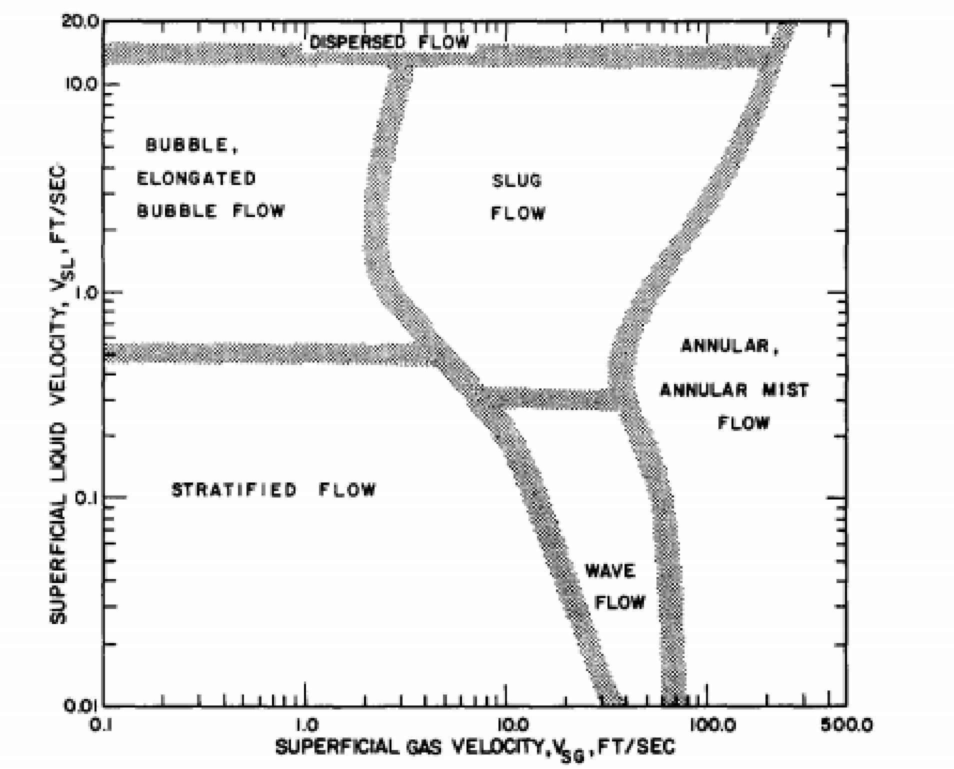

Figure 1.4: Proposed flow pattern map.(Mandhane et al. [4]).

1.2 Drag Reduction by Polymers

Drag reducer chemicals are high molecular weight polymers (greater than 2×10^6). Typical species include Polyacrylamides, natural and Xanthan gums. Their mode of action is believed to be by reducing turbulent eddies and extending the laminar boundary layer at the pipe wall and they considered to be effective under turbulent conditions.

During the transportation of the multiphase (oil-water-air) in pipelines industry several flow regimes might be form leading to a large pressure gradient. To reduce the frictional pressure drop different techniques have been proposed in the literature. Addition of a few parts per million (ppm) of polymers liquid in the pipe, is one way to achieve the drag reduction and reduce the frictional pressure losses.

The additives used for drag reduction are divided into three main groups; polymers, surfactants and fibers, the mechanism of the Surfactants is to reduce the surface tension of a liquid - more suitable for closed circulating fluid systems such as district heating pipelines and heat exchangers - while Fibers (long cylinder- like objects with high length to width ratio) reduces drag when they oriented in the main direction of the flow Mowla et al.[7]. The basic understanding of the polymers effects is by reducing Reynolds shear stresses and the wall normal velocity fluctuations Warholic et al.[8], another common principle is that the turbulent eddies tend to be dumped when they interact with the viscous polymer resulting in an overall reduction of the turbulent momentum transfer.

Adding high molecular weight long-chain polymers into a single-phase liquid flow was first published by Toms [9] and known as Tom's phenomenon when high reduction was observed on the frictional resistance at the pipe wall which finally leads to the possibility of increasing the pipeline capacities and flow rates.

This technique was economically applied in the real industry by Trans Alaska Pipeline System (TAPS - 800 miles) using an oil soluble polymers, the flow rate has been increased by 32,000 m^3 per day using polymer concentration of 10 ppm (weight basis) Burger et al.[10]. Approximately 200,000 bbl/day of this throughput was a directly due to injection of a drag reducing additive. Wahl et al. [11]. Significant advantages supported by an experimental evidence have been reported in the literature such as the reduction in the operation costs of pumping since the frictional pressure drop decreased (without mechanical modifications), the capital cost will also be reduced since pipe diameter and pumping facilities have been reduced and finally enhancing the refinery handling. Moreover the production will increase while maintaining high flow rates and low pressure drop. Furthermore they reported that the effectiveness of the DRP will increase when it existed just after the pumping stations; because the high shear forces which created by the pumps will disappear.

1.3 Objectives

The scope of this research is to perform a comprehensive experimental study for investigating the effects of Drag Reducing Polymers (co-polymer of polyacrylamide) on the frictional pressure drop; through well established experimental setup uses a pipe inside diameter of 0.4 inch and carrying two phase water-air flow. Moreover the effects of the DRP on two phase flow with more emphasis on the following factors:

1. Superficial velocities of the two components:

   The effects of varying water and air superficial velocity for a wide range taking into account different flow patterns and it's transition when the polymeric additives added.

2. Polymer concentration:

   One of the important parameter is to reveal the effect of different DRP concentration with more attention to the effectiveness of DRP at low concentrations.

3. Reynolds number:

   Accomplishing experimental study to demonstrate the effectiveness of those polymers in a wide range of Reynolds number, this range could directly broaden the picture by covering different flow types and behavior, and then it can permit reliable generalization when needed, and also it will be very useful for understanding the mechanism of the Drag Reduction.

Furthermore, the above parameters can be utilized to generate enough experimental data for developing different correlations which needed to allow better understanding for the Drag Reduction mechanism. These correlations are quite useful in the two phase water-air applications; since it can provide a quick and reliable estimation for factors that affects achieving a desired reduction.

1.4 Thesis map

This thesis is divided into five chapters. The introductory part is given in chapter one and the remaining chapters can be described as follows:

Chapter two: Represents the literature part by giving an overview of the research that has been conducted to study the influence of the Drag Reducing Polymers (DRP) in single phase, two phase oil-water flow and finally two phase air water mixture.

Chapter three: This chapter explains the whole experimental setup and the procedures that been used to perform experiments for testing the DRP effectiveness.

Chapters four and five: The experimental results are presented with detailed analysis and discussions. Based on our findings, conclusions and recommendations are presented in chapter five.

CHAPTER 2

LITERATURE REVIEW

This section is presented to provide an overview of the current and future research. The literature review is organized into three parts in order to shift the focus into the research area that has not been investigated or need more research.

2.1 Drag reduction in single phase flow

As a result of high crude oil viscosity at normal field temperature the transportation will become very difficult, heaters are used to heat the crude to reduce the viscosity, and also one of the techniques that has been used to enhance the flowability by diluting the crude oil using about 30% of Kerosene additive into the viscous crude oil. The operation cost of such heaters and extra pumps will add a new cost to the crude oil pipeline transportation facilities. Drag reducers chemicals can be able to reduce such costs and increase the total amount of oil produced.

The drag reducers were not that effective in heavy oil pipelines (crude oil) since the flow is usually laminar while the drag reducers use to dampen the turbulent fluctuations near wall region when it operate on clear turbulent flows. [12]

Mckeon et al.[12] investigated the influence of adding 1-pentanol and kerosene on the Kern River crude oil at 77 F, they claimed that the effect of the 1-pentanol are much more effective than the kerosene in reducing the viscosity. They also observed that the drag reducers itself increase the pressure gradient but when adding 5% of a 1-pentanol to 0.1% drag reducer, the pressure will expected to be reduced accordingly. Finally they suggested that the effect of adding just 55 of 1-pentanol can play the role of reducing the pressure drop in crude oil pipeline.

Swaiti et al.[13] conducted an experiment on large scale crude oil pipelines to show the drag reduction by introducing new chemicals additives. Also they studied the concentration of the additives and it's effects in drag reduction when changing the pipes diameter. The maximum drag reported was 63% using 9 –ppm solvent in 4 inch pipeline.

The experiment procedure was established by changing the solvent ppm on four different pipe diameters 1, 2, 3 and 4 inch. They found that as the pipe diameter increases more drag reduction will be obtained and the optimum solvent concentration was 9-ppm.

Moreover a good indication was observed when the drag reduction shows an increase with the increase of Reynolds number which means an increase in the oil flow rate.

Vejahati et al.[14] examined different types of polymeric drag reducing agents in light/medium and heavy crude oil. They realized that at high Reynolds number and low viscosity the drag reducers are more effective, they provided the factors that the effectiveness of these agents depends on, such as crude properties, flow rate, polymer concentration, molecular interactions between the polymers and crude, the turbulent fluctuation intensity and finally the polymer molecular size.

A correlation that relate the polymer concentration and Reynolds number to predict the drag reduction percentage has been examined at different conditions and various crude types, the drag reduction showed a noticeable effectiveness within the range of 5 – 50 ppm and above this range very small reduction percentage has been observed.

Recently Karami et al.[15] developed a model to predict the drag reduction effectiveness in crude oil pipelines. They validated the proposed correlation with experimental data points of 648 at different operation parameters, temperature, flow rate, pipe diameter and roughness by introducing three types of drag reducing agents DRA1, DRA2 and DRA3. The comparative study has been established based on the fanning friction factor plotted with the solvent Reynolds number. At the same conditions the best solvent found was DRA1 because of it's higher boiling temperature, higher molecular weight, more solubility in crude oil and higher resistance to degradation.

Strelnik et al.[16] proposed a mathematical model of viscous liquid motion in pipeline using drag reducing agents. They observed that DRA shows reduction in the efficiency when it moves down the pipeline, this phenomenon was because of the mechanical breakup of the polymer chains. They examined three pipelines to show the dependency of the travelled distance in the pipeline to the efficiency of the DRA, moreover the dependence of the hydraulic resistance coefficient an distance travelled by DRA in the pipe line has been studied.

Culter et al. [17] investigated the effect of the polymer additives on crude oil 8 inch pipeline of 28 miles long. They examined the effect of different flow velocities on the drag reductions of 300, 600 and 1000 ppm, they realized that the drag reduction increases as the flow velocity increases, drag reductions of 16, 21 and 25 percent has been reported by changing the polymers concentration in the pipe flow.

They noted that the effectiveness of the DRA did not diminish since all the tests have been done in turbulent fluid flow. An empirical correlation that used to relate the experimental data points with the flow velocity and polymer concentration has been proposed, this correlation was found to give a good prediction of the production that can be gained for a given concentration of drag reducing polymer.

Sultan et al. [18] examined the choice of enhancing the capacity of an existing pipeline by using the drag reducers. They reported a drag reduction of 55% using 16 ppm and about 68% when using chemical concentration of 34 ppm on the crude oil (viscosity of 7.8cst at 80F) flow test. After the experiments have been performed they claimed that the DRA showed significant success in reducing the frictional pressure drop, from data points obtained the results illustrated that as the DRA concentration increase, more drag reduction will be gained in the range of flow rate from 220,000 to 660,000 bpd.

Beaty et al. [19] performed an experimental work on drag reduction on four different oil pipeline diameters 8, 12 and 48 inch by changing the velocity on each test section. The needs of their experiments were to find an effective drag reducing agent that can reduce pressure losses at very low concentrations, in addition to the ability of reducing the cost by minimizing the pumping facilities especially in remote areas such as offshore production operations when the handling of these requirements has a great problem.

The major conclusion that they mentioned on their research that the improvement on the drag reducing polymers has become attractive method within pipe diameter range of 8, 12 and 48 inch.

Karami et al.[20] studied the effect of various parameters on the crude oil pipeline pressure drop reduction when the drag reducing additives introduced into the flow. The parameters that they investigated extensively were the temperature, pipe diameter and roughness, crude oil flow rate, type of the drag reducing agent and it's concentration.

In order to have a high drag reduction the definition of an effective DRA and it's characteristics have been listed as follows: U.Ibrahim et al. [21]

- High molecular weight.
- Quick solubility in the pipeline fluid.
- Chemical and mechanical degradation resistance.
- Don't affect hydrocarbon liquids.
- Effective at low concentrations.

The experimental work showed that as the temperature increases the percentage of drag reduction increases accordingly and this was because the DRA will become more soluble at elevated temperature. Also within the concentration range of their study (25 – 200 ppm) the drag reduction increases with the additives concentration.

Mansour et al.[22] conducted an experiment to test the new reducing chemical additives and the effects of reducing the skin friction in turbulent crude oil, large scale pipeline has been investigated using different DRA concentrations and pipe diameter of 2, 3 and 4 inch pipes were used. The maximum reduction in the frictional pressure drop obtained was 63% by adding 9-ppm of additives.

2.2 Drag reduction in Liquid-Liquid Two phase flow

Two phase liquid-liquid flow is broadly classified into two main flow patterns: stratified (or segregated), and mixed flow. Stratified flow consists of two distinct liquid phases separated by an interface. In general, stratified flow is encountered at low liquid velocities. Mixed flow is observed at higher liquid velocities, where the two liquid phases flow fully dispersed as a homogeneous phase, with no real change in concentration within the pipeline Robert et al.[23].

Sifferman et al.[24] studied drag reduction of three polymers (carboxymethyl cellulose, polyethylene oxide, and guar gum) using three different fluid systems: single-phase dilute polymer-water solutions, two phase liquid-solid, and three- phase immiscible liquid-liquid-solid solutions. The drag reduction percentage has been observed for all three the cases. At Reynolds numbers exceeding 10^5 drag reduction of up to 80% was obtained for the dilute polymer system at concentrations of 0.3 wt% DRA. A high drag reduction of 95-98% was achieved for the liquid-solid system, indicating an additive drag reduction effect for polymer solutions with suspended solid particles.

Al-Wahaibi et al.[25] Studied the influence of the drag reducing polymers on two-phase oil-water in small pipe diameter of 14 mm. They observed that by adding a co-polymer of polyacrylamide and sodium acrylate the region of the stratified has been extended while the slug flow formation been delayed. However using this polymer the reduction of the waves intensity has been realized.

The visual observation of the flow patterns has been reported with adding the drag reducing polymer. For all cases the annular flow changed to stratified flow, in contrast the slug flow regime for most the cases shifted to a stratified configuration and for those cases where the bubble still appear, the oil slugs and bubbles flowed near to each other compare with the one without using the drag reducing polymer.

The effect of the polymer on the pressure drop reduction also has been presented in their study, and as the polymer concentration increases the reduction on the pressure drop become more realized. The maximum drag reduction reported was about 50%.

Recently Al-Yaari et al.[26] Performed an experimental study to measure the drag reduction in oil-water flow using 1 inch ID. The polymer of Magnafloc 1011 (anionic polyacrylamide) with different molecular weight has been used to see the effects on the flow regime and the drag reduction effectiveness. Simple visualization technique used to detect the changes on the flow regime, They offered an explanation of how the drag reducing polymer can changes the flow pattern from water continuous dispersed flow to stratified flow which due to reduction of turbulent mixing forces. The pressure gradient found to be reduced by adding 50 ppm polymer concentration and this reduction may affected by the water fraction, mixture velocity, polymer molecular weight and concentration. The maximum drag reduction obtained was 65% by adding only 10-15 ppm.

2.3 Drag reduction in Gas-Liquid Two phase flow

Gas-liquid flow in pipes has been experimentally investigated and the effect of the drag reducing polymers on the existing system has been published. Oliver et al.[27] Were the first who investigated the effect of drag reducing polymers in gas-liquid flows using 1.3%

polyethylene (PEO) aqueous solution and air. They reported that the liquid in the slug flow where the wave was absorbed to give smooth liquid film.

Drag reducing polymers in gas-liquid flow was investigated by Greskovich et al.[28] ,they observed that by adding 50 ppm of a viscoelastic polymers on the flow loop contained air-water in acrylic pipe with inside diameter of 0.038 m .The maximum pressure drop reduction obtained was 50%. The experiment has been done with the presence of different air and water flow rates for the slug flow regime.

Al-Sarkhi et al.[29] Studied the drag reducing polymers on air-water flow in horizontal pipes, they found that the DRA destroys the turbulent waves which affect the flow rates and the pressure of the system .The maximum drag reduction obtained was about 48% for annular flow configuration. The discussion has been carried out about the effectiveness of the drag reduction agent which is depend on the way of DRA been introduced into the regime , they suggested an injection of a well mixed master solution to the film in order to have good distribution along the pipe circumference.

Soleimani et al.[30] Examined the influence of adding polymers on the pseudo slug flow and the transition to slug flow patterns for the air-water two phase configuration using pipe diameter of 2.54 cm. They studied the effect of the polymer concentration on the pressure gradient for different superficial liquid velocities (U_{sl}) and they also noted that the decrease in the pressure gradient is not monotonic with the polymer ppm because the polymers will enlarge the liquid holdup while decreasing the interfacial friction which have an opposite affects on the pressure drop, therefore an increase or decrease could be realize.

Stratified flow configuration and it's transition to slug flow in small pipes may exhibits some complicity than the one flows in large diameters since the interface between gas and the liquid is hidden by the large waves which touch the pipe top wall. Baik et al. [31] investigated the effect of the drag reducing polymers on these waves at high and low superficial gas velocity, they reported that the wave amplitude decreased dramatically using the polymer solution and drag reduction of about 42% was noted.

The effect of Drag Reducing Polymers on the interfacial shear stress has been studied in the work of Al-Sarkhi et al. [32], the experimental works revealed that as DRP of a 50 ppm added to the flow both interfacial shear stress and wall liquid shear stress have been decreased. They also reported that addition of DRP could affect the flow behavior; for example at a very low gas superficial velocity the annular flow regime has been changed to stratified annular flow, Moreover The DRP found to be very effective to damp slug frequency that appear in the slug flow pattern.

Fernandes et al. [33] conducted an experimental study using high molecular weight poly-alpha-olefin polymers on two phase flow(gas-condensate flow) that operate in annular flow regime, they developed a mechanistic model and comparative study by applying the DRA on similar experimental loop of Al-Sarkhi et al. [29] to show the applicability of their model and it's limitation. The error between the model and the experimental data was 5%, Finally they concluded that as the pipe diameter increases the drag reduction increases due to the reduction of the entrainment.

Mowla et al.[7] carried out an experimental study to see how the polymeric drag reducers addition can affect the slug two phase regime (air and crude oil).The maximum pressure drop reduction reported was 40%, they observed that at small pipe diameter the more drag reduction will be gained for the reason of higher turbulence that appears and justifies better effect of DRA. Unlike the previous studies they claim that the main role of the DRA is to reduce the fluctuation height which is going to reduce the pressure drop in the flow direction.

The drag reducing polymers in inclined 0.0127 m pipe diameter has been studied by A.Al-Sarkhi et al.[34], the flow regime was annular air-water flow and the highest reduction recorded was 71% using 100 ppm polymer concentration. Different pipe inclination angles were examined and the maximum drag reduction percentage has been reported accordingly. They realized that the flow pattern changes with the upward inclination angle, the maximum reduction was obtained at pipe angle of 1.28.

The effect of the drag reducing polymers in a vertical two phase flow has been investigated by Nieuwenhuys [35] and Fernandes et al.[36] . An experimental set-up has been made to examine different flow patterns occurs with changing void fractions and see the effect of adding polymers to it. Visual realizations while adding the DRP were reported such as bubbles size and the transition to slug flow configuration by lowering gas superficial velocities. They also offered a good explanation of how the degradation on vertical two phase flow can affect the flow void fraction and it’s reflection to the hydrostatic and frictional pressure drop.

The drag reduction prediction of the polymeric additives has been simulated using different turbulence models and techniques. Mehrabadi et al. [37] improved the available models in the literature by adjusting two calibration parameters based on an experimental data for some polymers. Adding these parameters they have been studied the choice of a well-known turbulence model called ‘‘Launder–Sharma” to show it’s possibility for predicting the huge drag reduction which has been observed for different polymer solutions.

The effect of oil viscosity on the performance of the DRP has been addressed in the experimental investigation of Daas et al. [38], two oil viscosities of 0.0025 Pa .s and 0.05 Pa.s has been examined using Carbon dioxide gas phase to form slug flow regime. A clear observation from their work is that as the oil viscosity increases the total pressure drop increases accordingly for all values of superficial gas velocity, and the DRP effectiveness increase as the oil phase become less viscous.

Many Researcher in the literature continued delivering numerous empirical correlations that help in evaluating the pressure drop occurs within multiphase flows, with respect to various operational conditions those models have been developed. Pressburg et al. [39] investigated the vertical upward pipe carrying gas-liquid flows, they provided a correlation to estimate liquid holdup and frictional two-phase pressure drop utilizing six different liquids to include the effect of density and viscosity. The correlation generated has less discrepancy compared with other studies.

J. Hart et al. [40] generated different correlations for calculating the liquid holdup and pressure drop accumulated in gas-liquid systems covering a small values of liquid hold-up (from 0 to 0.06) which includes stratified, wavy and annular flow regimes. From their model a simple equation stated below was based on the assumptions that the gas phase is isothermal and steady-state gas-liquid flow through horizontal pipes. (Neglecting the interfacial velocity)

$$\Delta P_{TP} = 4 f_{TP} \left(\frac{L}{D} \right) \frac{1}{2} \rho_G v_G{}^2 \qquad (2.1)$$

$$v_G = \frac{u_G}{(1-\varepsilon_L)} \tag{2.2}$$

Where f_{TP} is the friction factor of the two-phase, v_G represents average axial velocity of the gas phase, u_G is the gas superficial velocity and ε_L is the Liquid holdup.

Considerable efforts to evaluate the liquid holdup more accurately through utilizing a wide data bank of experimental data have been reported in the literature, one of the comprehensive studies for predicting the liquid holdup in gas liquid flows is indicted in the work of Fernandes et al.[33]. Their model concluded 2276 gas liquid experimental data point to cover a wide range of Reynolds number from 2000 up to 2670000 including all the possible flow patterns could be existed in a horizontal flow configuration.

The work of Fernandes et al. [33] is further extended to develop and improve correlations for predicting the liquid holdup and also they went for producing another correlation to predict the friction factor using flow parameters.

The more accurate friction factor correlation compare with the previous studies in this area has been established by Fernandes et al. [36], this model was done based on 2560 gas–liquid flow experiments for horizontal pipes to calculate mixture friction factor with respect to the mixture Reynolds number, the experimental data has been classified according to liquid holdup ranges and for each range the flow pattern is clearly identified. Moreover according to the experimental data under the study, the correlation showed the best performance in predicting the pressure gradient followed by Lockhart et al. [41] correlations.

Recently Al-sarkhi et al.[42] developed two correlations for the friction factor (based on the asymptotic value of drag reduction) for a wide range of pipe diameter from 0.019 to 0.0953m and using the results of the published data of air–liquid annular flows and liquid–liquid flows to see the capability of the prediction for any flow pattern with the presence of DRP in pipes.

The comparison between measured friction factor and the calculated values for gas–liquid annular flow has been reported in this study for the range of mixture Reynolds Number varied from 2.4×10^5 to 4×10^6. Most the data have been predicted within ± 20%. The same comparison done for oil– water flows and the proposed equation effectively correlated the experimental results within ± 20%. Most of the scattered points were for the case close to the inversion point. Their correlations have shown a great potential in predicting the drag reduction in multiphase flow systems with drag-reducing polymers in oil and gas for petrochemical industries.

CHAPTER 3

EXPERIMENTAL SETUP AND PROCEDURE

3.1 Flow loop

The experiments for single phase water and two phase flow of air-water have been conducted to study the influence of Drag Reducing Polymers (DRP) on the pressure drop and flow pattern transition (when it's possible) in a horizontal pipe. The characteristics of the flow before and after injecting the DRP were reported.

Figure 3.1 depicts the experimental flow loop setup which designed to investigate the influence of these additives on the flow behavior of water, oil and air mixture. The loop comprises two 200 liter barrels for water and oil respectively and an instrument air connection for the air supply. The flow rate of the feed streams is measured and can be adjusted using regulating valves .The additive is added to the flow system via a nozzle into the mixed fluid stream.

The feed pumps for the liquids (oil and water) are rotary pumps equipped with axial face sealings. Water, air and oil can be separated in the separator or using cyclone and separator which are connected to the outlet of the test section.

The test section is made of stainless steel tube with an outer diameter of 0.5 inch and an inner diameter of 0.4 inch. it's total length is approximately 5 m divided into two straight horizontal sections separated by elbows (90 degree elbow). The horizontal sections are equipped with differential pressure transducer to measure the pressure drop inside the test section. At the end of the test section an acrylic section of 20 cm allows the visible inspection of the flow behavior. After having passed the test section, the fluid can be directed to the phase separator where water and oil can be separated by gravity or alternatively to the cyclone whose outlet is connected to the phase separator.

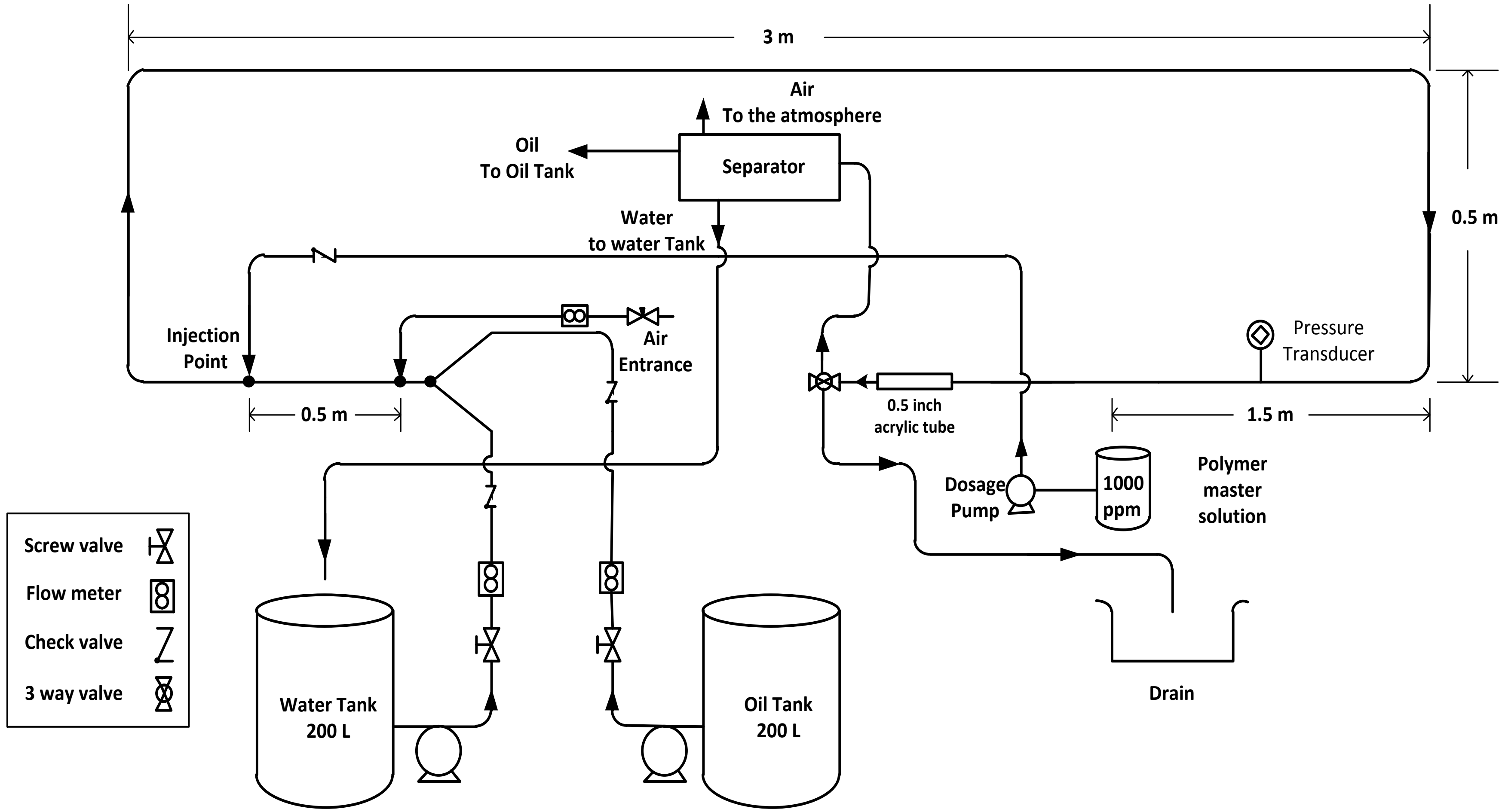

Figure 3.1: Sketch of the system Layout

Figure 3.2: Layout of the experimental system.

Figure 3.3: Acrylic section for visual flow investigation and temperature sensor.

3.2 Experimental procedure

3.2.1 Calibration of the flow loop

The frictional pressure drop calculated using Blasius equation, figure 3.4 presents a comparison between calculated and measured pressure gradient at various water flow rates using an accurate pressure transducer along to 1.5m just before the visualization test section. The plot shows a good agreement between the calculated and the measured one.

The Blasius friction factor calculated by:

$$f = \frac{0.3164}{\mathrm{Re}^{0.25}} \tag{3.1}$$

$$\mathrm{Re} = \frac{\rho D V}{\mu} \tag{3.2}$$

And the frictional pressure drop calculated using:

$$\Delta P = \frac{f\ \rho V^2}{2D} \tag{3.3}$$

Where:

f is friction factor.

Re is Reynolds number.

ρ is liquid density.

V is average liquid velocity.

D is inside diameter of the pipeline.

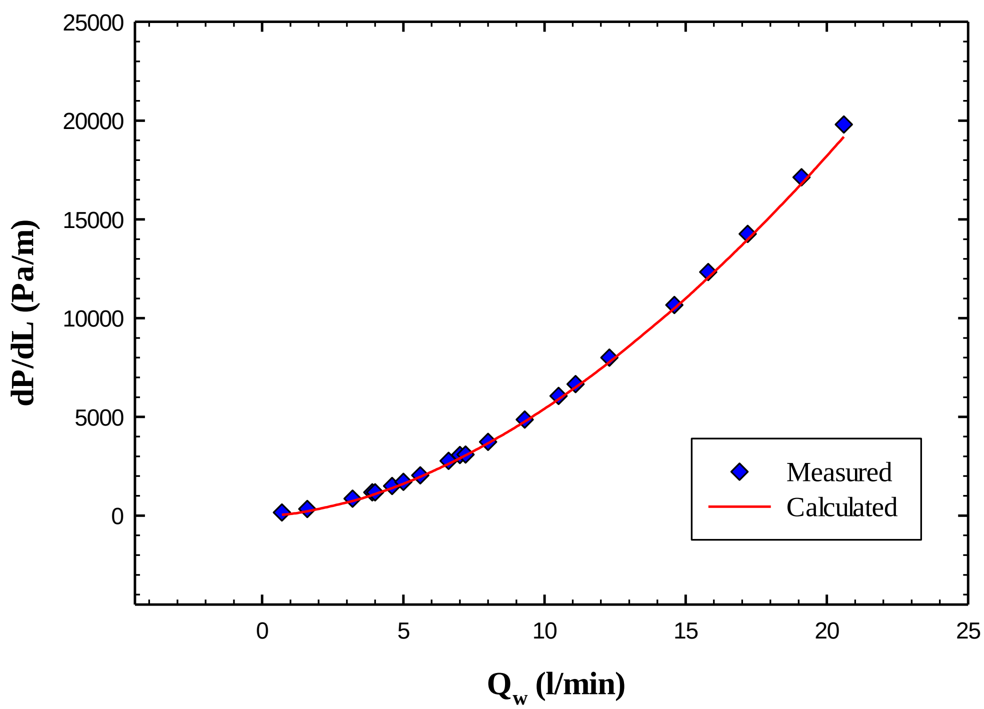

Figure 3.4: Variation of the pressure drop versus flow rate for the water single phase.

3.2.2 Preparation of the Polymer solution

The Polymer in a powder format is mixed with water in rotating magnetic mixer at low speed in order to avoid polymer shear degradation. Then rotation is stopped when the mixture completely dissolved in the water and having a conglomerated consistency. The mixing process may take several hours and sometimes a heat addition up to 50℃ was used to accelerate the solubility. Water and polymer specifications are given in Table 3.1 and 3.2.

Table 3-1: Fluids standard properties.

Water Density	1000 $\frac{kg}{m^3}$
Water viscosity	0.000891 Pa s
Ph	7-8
Gas Density	1.28 $\frac{kg}{m^3}$
Gas viscosity	0.0000185 Pa s

Table 3-2: polymer technical properties from manufacturer.

Product Name	Coopolymer of acrylamide and quaternized cationic monomer		
Product type	Powder		
physical form	off-white granular solid		
cationic charge	Medium-high		
Molecular weight	very high		
specific gravity	0.75		
Bulk density	46.8 lb/ft^3		
Ph 1% solution	4-6		
Apparent Viscosity/(cP) @25 ℃			
Concentration	0.0025	0.005	0.01
Viscosity	650	1200	3000

After this stage the master solution of 1000 ppm concentration is ready to be injected to the flow loop. Al-Sarkhi et al [29],[43] reported that the polymer solution concentration is very sensitive in order to obtain high Drag Reduction; hence a master solution of 1000 ppm was found the optimum in their studies. Moreover A. Al-Sarkhi et al. [44] suggested two techniques for injecting the prepared solution into the test section, the first one is by adding the solution just before water-air contact (Entrance injection), the second one which is more effective method when the solution is injected after the water and air get mixed (downstream injection).

All these considerations have been taken into account for our experiments since the master solution of 1000 ppm concentration is the one that used and it is injected just after 0.5m from the water air mixing section (Figure 3.1).

However to avoid polymer degradation a new technique has been introduced by using a diaphragm pump to inject the master solution into the flow loop. Figure 3.5 shows the arrangement used to inject the polymer solution. The dosage pump has different flow speeds (up to 1380 rpm) manually adjustable stroke length by which various solution concentrations could be added to the system.

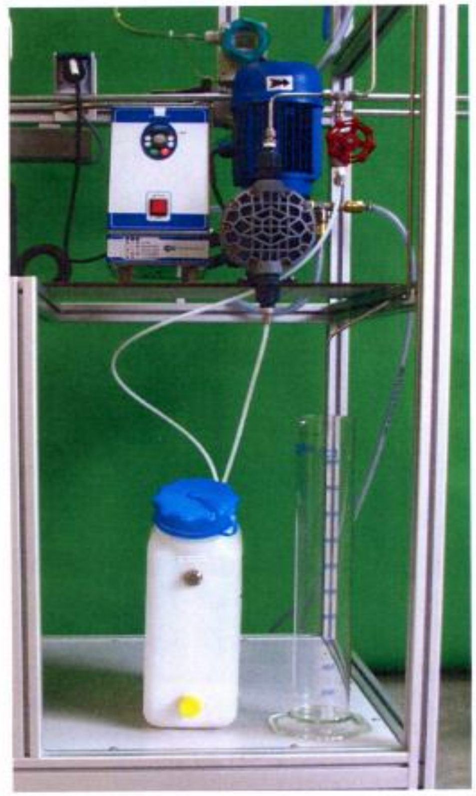

Figure 3.5: Additives injection system.

3.2.3 Operation of the system

The generated air-water two phase flow is circulated through the flow loop using a vertical centrifugal pump that can provide a maximum flow rate of 40 l/min of water. On the other hand the air is introduced to the system (from the laboratory main source) using a pressure regulator (with a maximum 16 bar inlet pressure and maximum 10 bar outlet pressure) connected at the inlet of the compressed air. A thermal mass flow rate in figure 3.6 measures the air flow in range from (0 – 150) Sl/min.

Figure 3.6: Air flow rate measuring device.

The flow rate of the water is measured using an electromagnetic flow meter for flow range up to 40 l/min, a check valve is connected after the flow meter to prevent back flow of water. Figure 3.7 exhibits the water flow rate measuring device.

Figure 3.7: Water flow rate measuring device.

An accurate pressure transducer presented in Figure 3.8 (SITRANS P DSIII HART series Pressure Transmitter) is used to measure the differential pressure drop over 1.5 m long and mounted about 3.5 m downstream the mixing section.

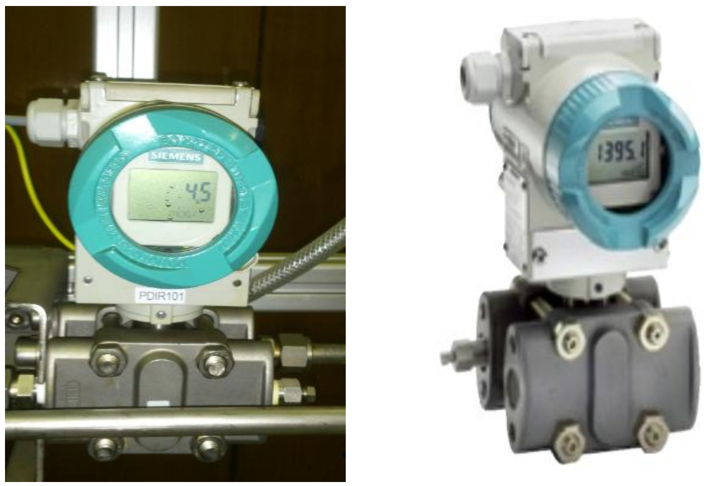

Figure 3.8: Differential pressure measurement device.

The hydrodynamic fully developed region has been estimated for single flow of water using equation (3.4, 3.5) for laminar and turbulent flows respectively. At low Reynolds number of 1,091 occurred at 0.5 l/min flow rate of water, the fully developed length is given by equation (3.4) was 0.55 m. However at maximum flow rate (40 l/min) Reynolds number is about 87,300 and the fully developed length calculated was 0.3 m. Therefore the pressure transducer is connected at 3.5m to confirm that all the measurements are within the fully developed region.

$$\frac{Le}{D} = 0.06\,\mathrm{Re} \quad (\text{for Re<2300}) \tag{3.4}$$

$$\frac{Le}{D} = 4.4\,\mathrm{Re}^{\frac{1}{6}} \text{ (for Re>4000)} \tag{3.5}$$

The data acquisition procedure is carried out for better and more accurate data gathering. A multi channel recorder illustrated in Figure 3.9 has been utilized for display, record, and archiving the data for further analysis.

The recorder is able to cope with 6 different input signals at the same time. Moreover this data acquisition has been connected to the computer using USP interface- integrated with software package- to collect the data from the flow meter and pressure transducer is in a second basis.

Figure 3.9: multi channel recorder.

3.3 Uncertainty Analysis

The purpose of a measurement is to determine the value for a quantity of interest. However there is an error associated with every measurement, therefore in this section Uncertainty analysis is performed to estimate the limits of these errors in order to improve measurement quality.

Measurement errors can be classified into two main types; Random errors and systematic errors. According to Dieck [45] , Random errors defined as a component of measurement error that in replicate measurements varies in an unpredictable manner. Based on the standard deviation this type of errors can be written mathematically as follow:

$$S_x = \sqrt{\frac{\sum (X - \overline{X})^2}{N - 1}} \quad (3.6)$$

The standard deviation for N samples:

$$S_x - = \frac{S_x}{N} \quad (3.7)$$

Where $S_x -$ is the random uncertainty, the coverage factor K is used to estimate this error within 95% confidence level.

$$S_x - = K\left(\frac{S_x}{N}\right) \quad (3.8)$$

Systematic Uncertainty (B); refer to a component of measurement error that in replicate measurements remains constant or varies in a predictable manner. This error usually occurs due to the experimental conditions and physical effects. In our experiments systematic errors mainly comes from calibration errors.

The combination of these errors (Random and systematic) is known as the combined uncertainty (U) which can be stated as follows:

$$U = K\left[\sqrt{\left(\frac{B}{2}\right)^2 + (S_x -)^2}\right] \tag{3.9}$$

The uncertainty results for liquid and gas flow meters, and for the pressure transmitter are summarized in Table 3.3.

Table 3-3: Uncertainty Analysis Results.

Parameter	**Instrument**	**Supplier**	**Random Uncertainty**	**Systematic Uncertainty**	**Combined Uncertainty**
Liquid flow rate	Magnetic flow meter (SDI series)	EGE	0.51%	0.02%	1.02%
Gas flow rate	Thermal mass flow meter (red-y compact series)	red-y	0.38%	0.01%	0.76%
Pressure drop	SITRANS P (DS III HART series)	SIEMENS	0.57%	0.04%	1.14%

CHAPTER 4

RESULTS AND DISCUSSION

Experiments were conducted for single phase water and two-phase air-water flows with and without injecting Drag Reducing Polymers (DRP). The need for understanding the flow behavior with the presence of DRP could possibly be gained through a comprehensive experimental study at various flow parameters and conditions to conclude several flow regimes and corresponding frictional pressure losses which are mainly changes due to the variation in phases flow rates.

The drag reduction percentage associated with the addition of such polymers need to be determined in a wide range of operational conditions. In this work a neat selected matrix through well established experimental set-up has been developed such that to provide a wide range of water and air superficial velocities which can broaden the gap of a various flow patterns that probably be existed (this range is presented in figure 4.11). Moreover the range examined with the presence of the DRP can assist in designing real operating systems by giving estimation for frictional pressure drop reduction and the additional throughput that accordingly be obtained.

4.1 Single phase water flow

Figure 4.1 shows the pressure gradient variation with water flow rate. It can be seen clearly that the pressure gradient increases with the flow rate and the value is less in the case when the DRP added to the system. This figure illustrates a simple example to understand the basic effect of the DRP on frictional pressure drop. In these experiments - as discussed in chapter three - the master solution of a water soluble polymer has been prepared to form 1000 ppm, and then with the assist of the diaphragm pump the polymers were added in different concentration to show DRP effectiveness. Table 4.1 presents the effect of various DRP concentrations on the pressure gradient using different operating speeds of the polymer dosage pump.

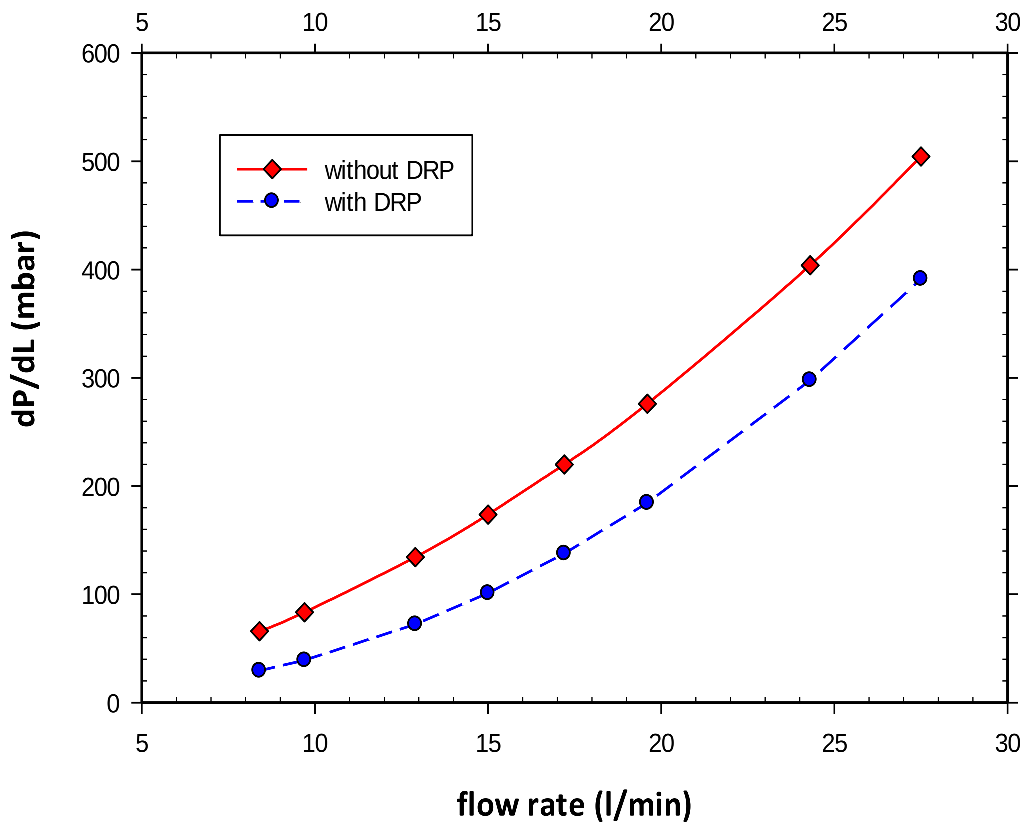

Figure 4.1: Variation of the pressure gradient versus the flow rate with and without DRP for water single phase.

Table 4-1: Experimental data of the pressure drop for a water single phase flow with and without DRP.

rpm	$ppm\ in\ pipe$	$\frac{dP}{dL}\left(\frac{kPa}{m}\right)$ *Without DRA*	$\frac{dP}{dL}\left(\frac{kPa}{m}\right)$ *With DRA*	$DR\%$
1380	50.00	8	4.4	45
1000	33.33	8	4.5	43.8
800	21.67	8	4.7	41.25
600	16.67	8	5	37.5
400	10.00	8	6	25
200	4.17	8	8	3.8

Figure 4.2 exhibits the variation of the drag Reduction effectiveness DR% with the concentration of polymer injected in ppm, this figure reveals that as the concentration increases the corresponding drag reduction increases rapidly up to about 22 ppm, then the reduction remains constant for more than 33.33 ppm injection. However at fixed polymer solution flow rate ($Q_{DRP} =$ 0.6 l/min) the drag reduction percentage reduces dramatically as water flow rates increase and this is clearly illustrated in figure 4.3. Moreover it can be seen that DRP concentration at each flow rate has been presented to figure out how much drag reduction could be obtained for specific flow rate at a given ppm.

The drag reduction percentage is determined by measuring the frictional pressure drop with and without adding the polymer for the same flow rate, equation (4.1) used to calculate the effectiveness of the drag reducing polymer:

$$DR\% = \left(\frac{\frac{dP}{dL}\Big|_{without\ DRP} - \frac{dP}{dL}\Big|_{with\ DRP}}{\frac{dP}{dL}\Big|_{without\ DRP}} \right) x100 \qquad (4.1)$$

Where $\frac{dP}{dL}\Big|_{without\ DRP}$ and $\frac{dP}{dL}\Big|_{with\ DRP}$ are the frictional pressure gradient measured without and with the presence of the drag reducing polymer respectively.

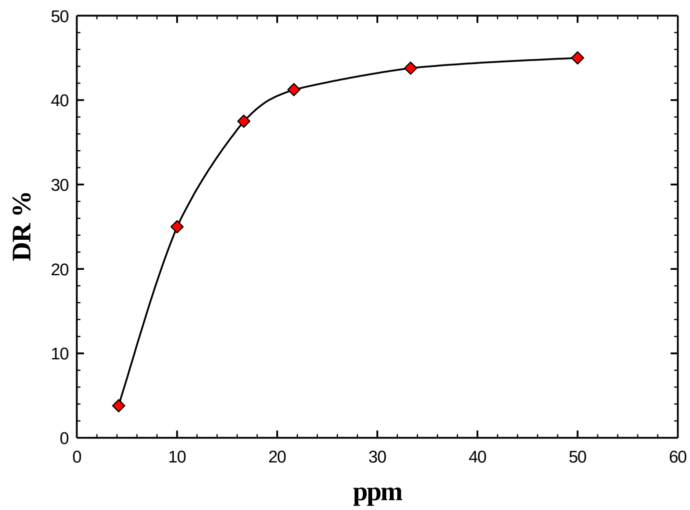

Figure 4.2: Variation of the Drag reduction percentage at different Polymer concentrations.

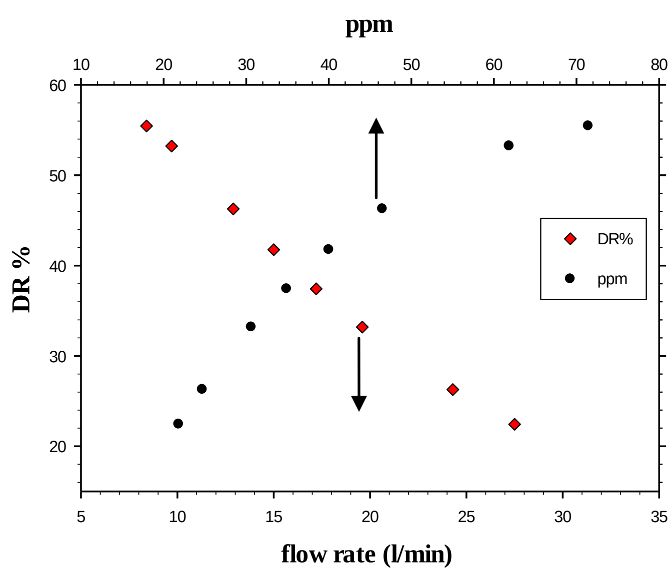

Figure 4.3: Variation of the Drag reduction percentage with various water flow rate and the corresponding polymer concentration in ppm.

4.2 Two phase gas-liquid flow

4.2.1 Effect of DRP on frictional pressure drop

Experimental investigations were carried out to test the Drag Reducing Polymers (DRP) effectiveness in two phase water-air flow in a small pipe.

To study the effect of adding the DRP on frictional pressure gradient for air-water mixture, the experimental work has been performed for a wide range of liquid and gas flow rates, the liquid flow rate starts from 3 to 25 l/min while gas flow is up to 70 l/min. The corresponding pressure drop has been recorded for the entire range with and without the DRP.

Figures (4.4 - 4.8) illustrate the results of the frictional pressure drop variation with liquid superficial velocity at a constant gas superficial velocity of 1.03, 2.06, 3.08, 4.11 and 5.14 m/s, respectively.

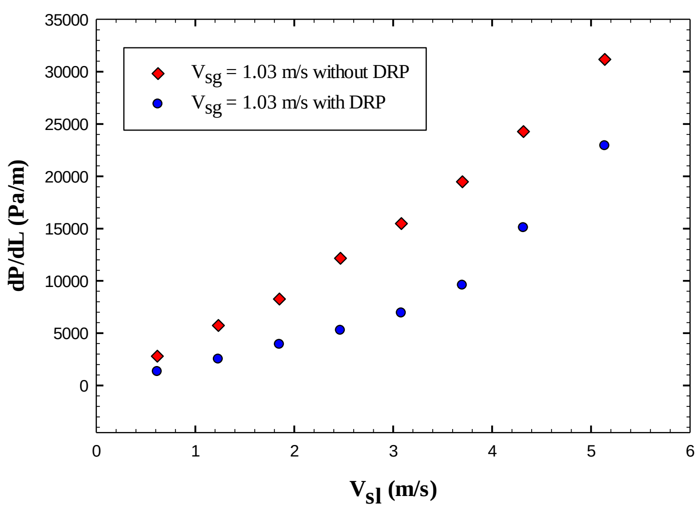

Figure 4.4: Variation of the frictional pressure drop with various liquid superficial velocities at constant gas superficial velocity of 1.03 m/s.

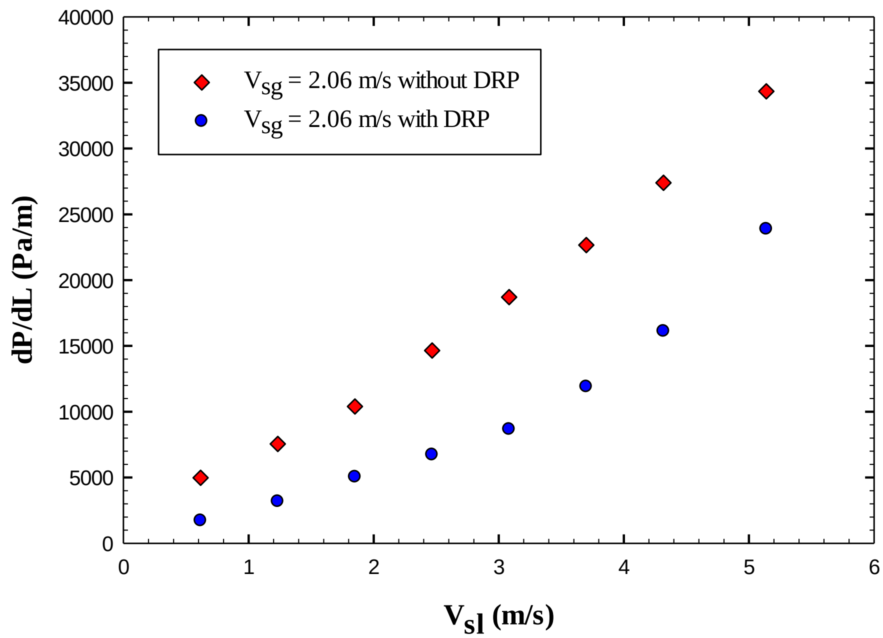

Figure 4.5: Variation of the frictional pressure drop with various liquid superficial velocities at constant gas superficial velocity of 2.06 m/s.

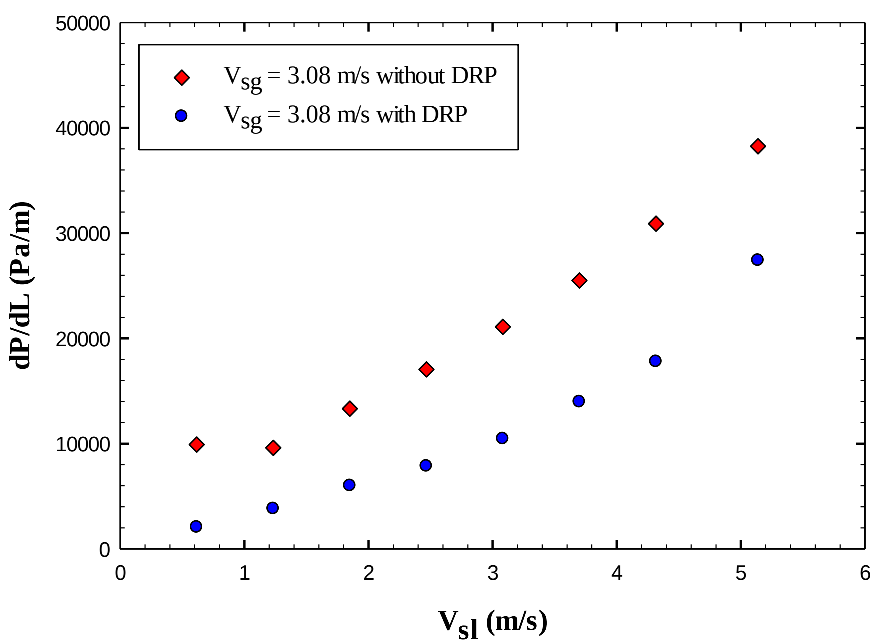

Figure 4.6: Variation of the frictional pressure drop with various liquid superficial velocities at constant gas superficial velocity of 3.08 m/s.

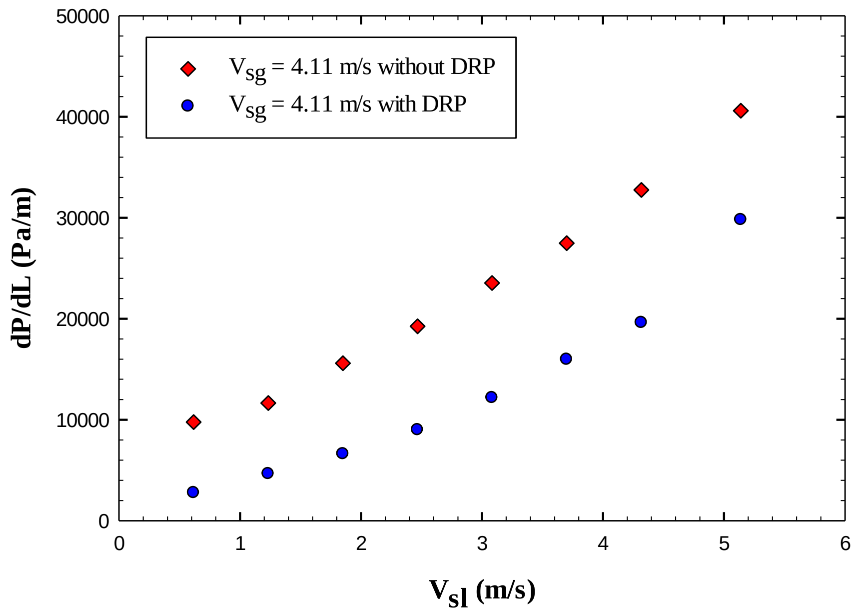

Figure 4.7: Variation of the frictional pressure drop with various liquid superficial velocities at constant gas superficial velocity of 4.11 m/s.

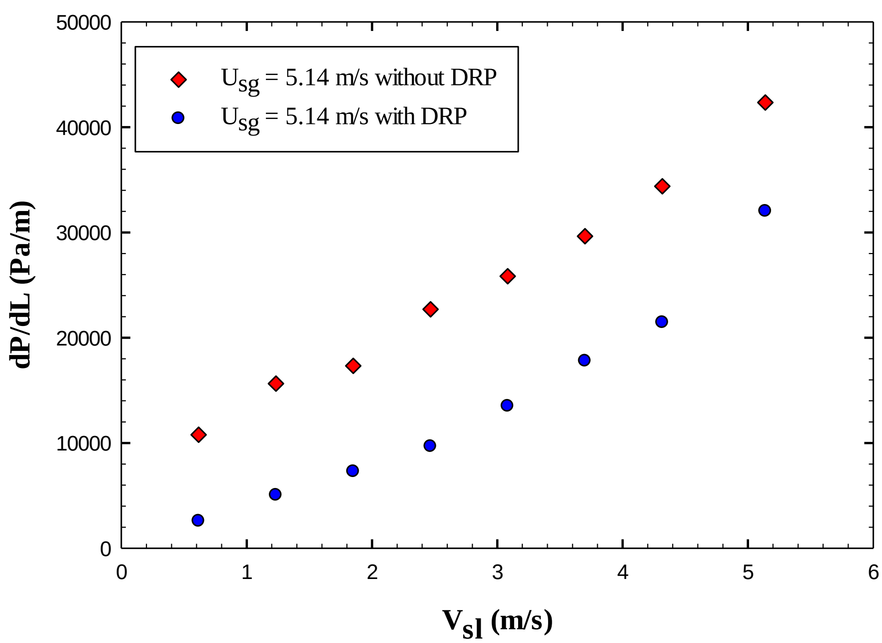

Figure 4.8: Variation of the frictional pressure drop with various liquid superficial velocities at constant gas superficial velocity of 5.14 m/s.

These results show that the pressure drop increases with the increase of liquid superficial velocity. Figure 4.9 provides a clear comparison for the frictional pressure drop reported with different liquid superficial velocities. It is also indicated that from this figure as the gas superficial velocity increases from 2.6 to 4.11 m/s the pressure drop increases accordingly, one possible justification for this behavior is that once the gas velocity increases an additional pressure losses in the mixture of the two phase flow appear due to the disturbance in the liquid flow caused by the gas.

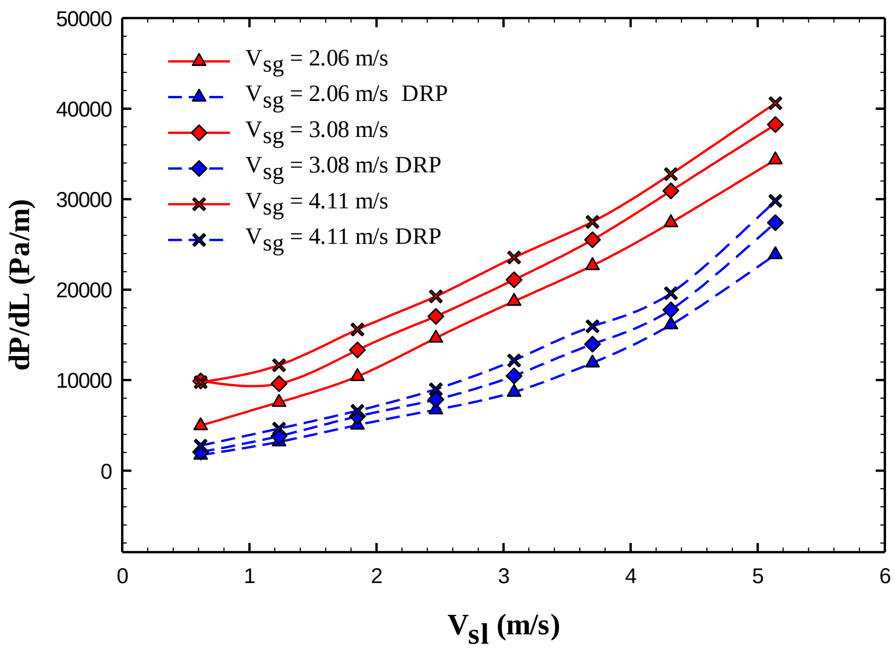

Figure 4.9: Comparison of the frictional pressure drop variation with respect to liquid superficial velocity at different gas superficial velocities of 2.06, 3.08 and 4.11 m/s.

Figure 4.10 presents the relation of the drag reduction ratio as a function of the normalized superficial velocity, the drag reducing polymer found to be effective at low gas and liquid superficial velocities.

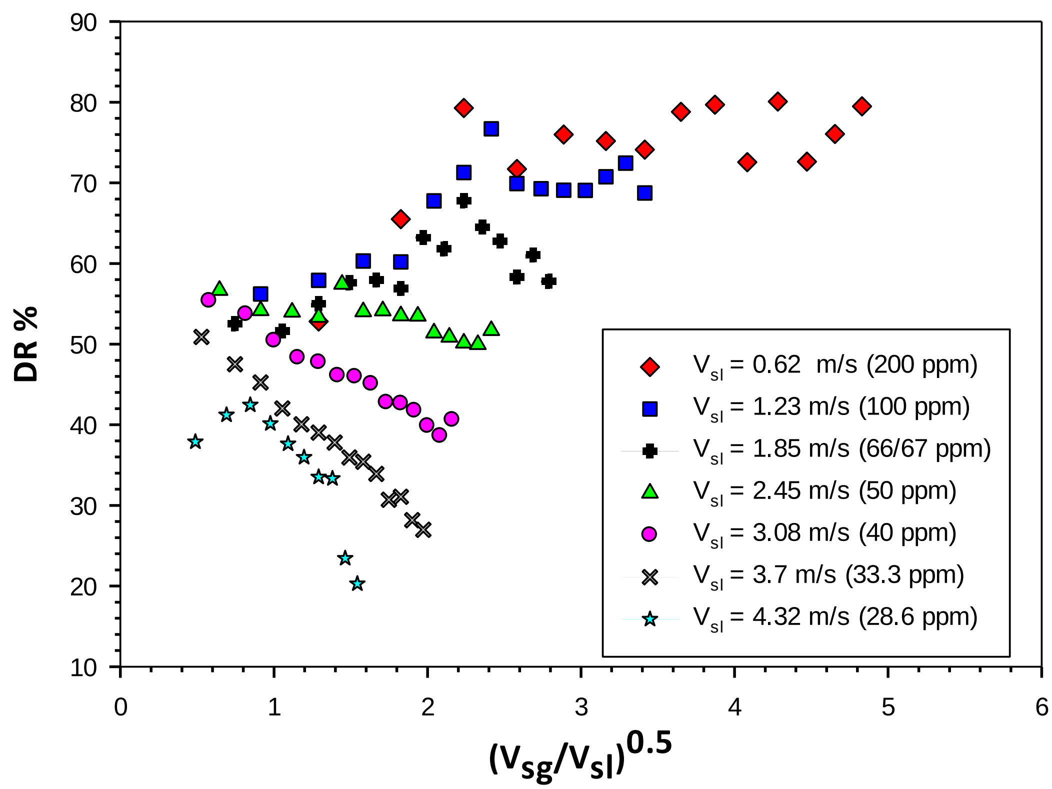

Figure 4.10: Drag reduction percentage versus normalized superficial velocity at various liquid superficial velocities.

As can be seen in Figure 4.10, as the value of liquid superficial velocity increases from 0.62 m/s to 4.32 m/s the drag reduction ratio decreases accordingly, and this was done for different gas superficial velocities V_{sg} . Furthermore the drag reduction associated with addition of the Drag Reducing Polymer is increased slightly and this is limited just for the range of liquid superficial velocities up to 1.85 m/s where the slug or Pseudo slug regimes appeared. An opposite trend has been observed as presented in Figure 4.10 when the liquid superficial velocity increased from 2.45 up to 4.32 m/s; at which the flow started to shift to a Dispersed flow pattern. The transition from Slug flow to Dispersed flow regime is clearly indicated in Barnea Model. (see Figure 4.11). The trend could not be the same as indicated In the previous studies of Hanratty and co-workers [29,43], In which a clear increase in the Drag reduction percentage has been observed with an increase in V_{sl}. That means the increase in (DR %) associated with the increasing of V_{sl} is not always the case and this may confirm the observation of Fernandes et al [36].

Also one possible explanation is that the increasing in liquid superficial velocity could augment the entrainment rate of liquid droplets getting into the gas core which can add more disturbances for the two phase water-air mixture then the friction factor increases consequently.

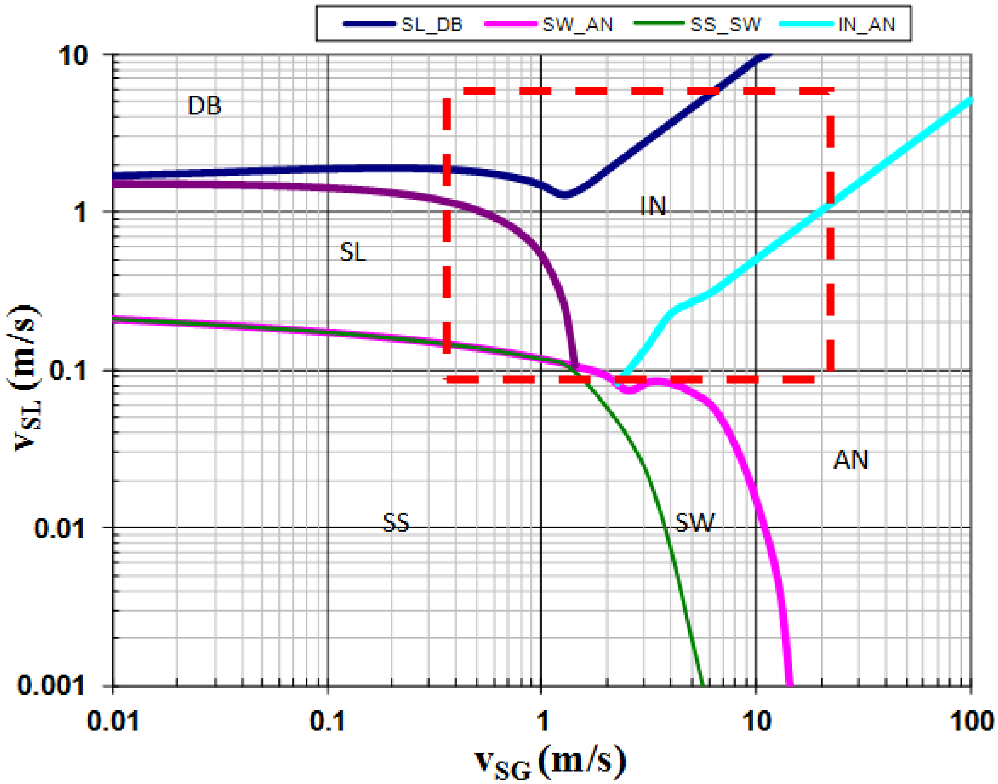

Figure 4.11: Air-water flow pattern map using Barnea [46] Model in a 0.4 inch pipe.

(Dashed box is the present work flow conditions)

Where:

DB: dispersed bubble

SL: Slug

IN: Intermittent

SS: Smooth Stratified

SW: Stratified Wavy

AN: Annular

4.2.2 Effect of DRP in two-phase flow transition

4.2.2.1 Stratified and Stratified wavy flow regimes:

The reductions in the role waves and ripples have been realized and the flow becomes more stable. Furthermore the range of the smooth stratified flow pattern increased primarily at the transition region between slug and Stratified wavy flows.

As seen from figure 4.12 that the frictional pressure gradient increases significantly as the dimensionless superficial velocity increases which is mainly due to the increase in gas superficial velocity that adds more disturbance to the gas liquid interface.

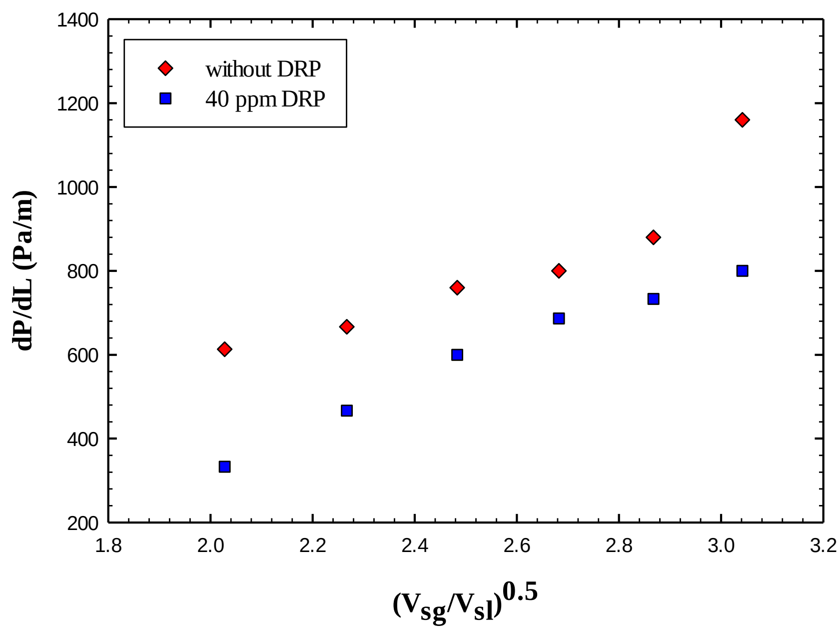

Figure 4.12: Effect of Drag Reducing Polymer on Stratified flow regime.

Adding only 40 ppm polymer concentration has been found to reduce the frictional pressure drop within the stratified flow regime and the maximum Drag Reduction reported was about 35% at the lowest gas superficial velocity of 0.4 m/s.

Minimal effect of DRP has been noted for the stratified regime due to uniform and quite stable interface between gas and liquid (air-water), also there is no clear transition effects from Wavy stratified to stratified flow pattern; however the role waves and its intensity have been damped further with the presence of DRP. Also as emphasized by Baik et al. [31] that the DRP effectively reduced the wave amplitude and delayed transition to slug flow regime. Figures 4.13, 4.14 depict the Stratified and Wavy Stratified flows before and after adding the DRP.

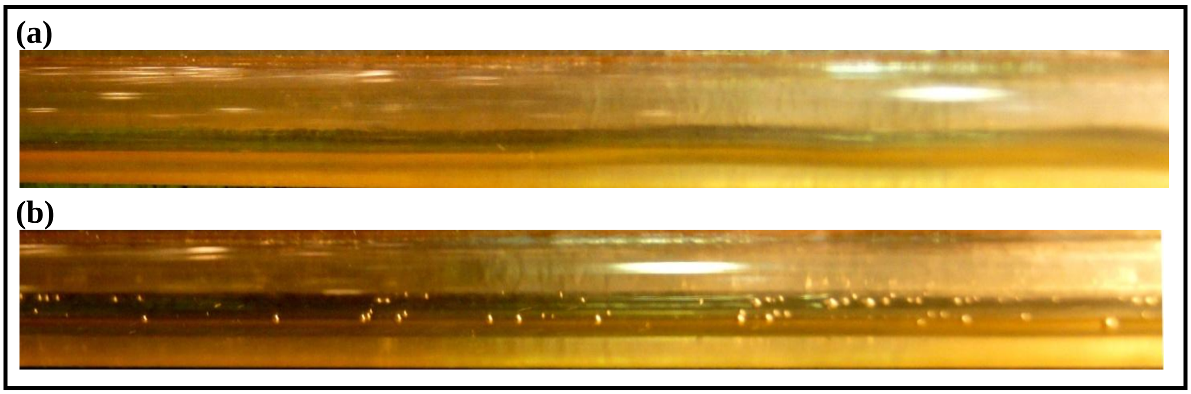

Figure 4.13: (a) Stratified flow without DRP (V_sl=0.1 m/s, V_sg=0.41 m/s) (b) Stratified flow with adding 40 ppm DRP.

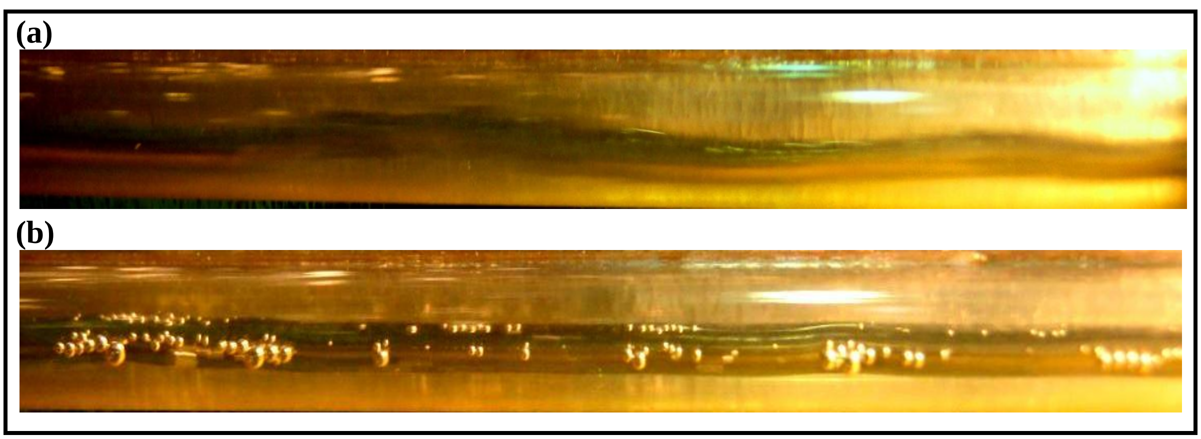

Figure 4.14: (a) Stratified Wavy flow without DRP (V_sl=0.1 m/s, V_sg=2.88 m/s) (b) Stratified Wavy flow with the addition of 40 ppm DRP.

Table 4-2: Frictional pressure drop and flow pattern with and without 40 ppm DRP.

run	$V_{sl}\left(\frac{m}{s}\right)$	$V_{sg}\left(\frac{m}{s}\right)$	$\frac{dP}{dL}\left(\frac{Pa}{m}\right)$ without DRP	*Flow pattern*	$\frac{dP}{dL}\left(\frac{Pa}{m}\right)$ 40 ppm DRP	*Flow pattern*	DR%
1	0.1	0.41	613	St	400	St	35
2	0.1	0.51	667	St	467	St	30
3	0.1	0.62	760	St	600	St	21
4	0.1	0.72	800	St	687	St	14
5	0.1	0.82	880	St	733	St	17
6	0.1	0.93	1160	St - Slug	800	St Wavy	31
7	0.1	1.03	1200	St - Slug	933	St Wavy	22
8	0.1	1.64	1800	Slug	667	St Wavy	63
9	0.1	2.06	1933	Slug	800	St Wavy	59
10	0.1	2.47	2467	Slug	1000	St Wavy	59
11	0.1	2.88	3000	St Wavy	1067	St Wavy	64
12	0.1	3.70	1467	St Wavy	667	St Wavy	55
13	0.1	4.11	1667	St Wavy	733	St Wavy	56
14	0.1	4.52	1800	An	867	St Wavy	52
15	0.1	4.93	1867	An	867	St Wavy	54
16	0.1	5.34	2000	An	1000	St Wavy	50
17	0.1	7.20	1467	An	773	St Wavy	47
18	0.1	7.81	1533	An	800	St Wavy	48
19	0.1	8.43	1600	An	867	St Wavy	46
20	0.1	9.05	1800	An	1000	St Wavy	44
21	0.1	9.66	1867	W An	1133	St Wavy	39
22	0.1	10.28	2000	W An	1267	St Wavy	37
23	0.1	10.90	2067	W An	1400	St Wavy	32
24	0.1	11.51	2133	W An	1467	St Wavy	31
25	0.1	12.13	2400	W An	1640	W An	32
26	0.1	12.75	2667	W An	1713	W An	36
27	3.08	1.03	15480	DB	6905	Pseudo Slug	55
28	3.08	2.06	18713	DB	8659	Pseudo Slug	54
29	3.08	3.08	21100	DB	10456	Pseudo Slug	50
30	3.08	4.11	23553	DB	12171	Pseudo Slug	48
31	3.08	5.14	25847	DB	13500	Pseudo Slug	48
32	3.08	6.17	27920	DB	15050	DB	46
33	3.08	7.20	29287	DB	15823	DB	46
34	3.08	8.22	31280	DB	17172	DB	45
35	3.08	9.25	32067	DB	18359	DB	43
36	3.08	10.28	33680	DB	19323	DB	43

4.2.2.2 Annular and Wavy annular flow patterns

Annular and Wavy annular flow pattern have been studied to show the effectiveness of adding a small concentration of Drag Reducing Polymer. Figure 4.15 illustrates how the DRP can reduce the pressure drop at various gas superficial velocities. It can be seen clearly that the DRP was able to suppress the waves at the bottom of annular film for all gas flow rates been studied. Thus a Drag Reduction has been observed.

Moreover the transition from Wavy Annular regime to Stratified Wavy occurred with the addition of only 40 ppm of DRP. Table 4.2 summarizes the ranges at which these transitions have been observed and the maximum drag reduction obtained for the Annular and Wavy annular region was 48%, this effectiveness decreases as more waves propagate at the annular liquid film.

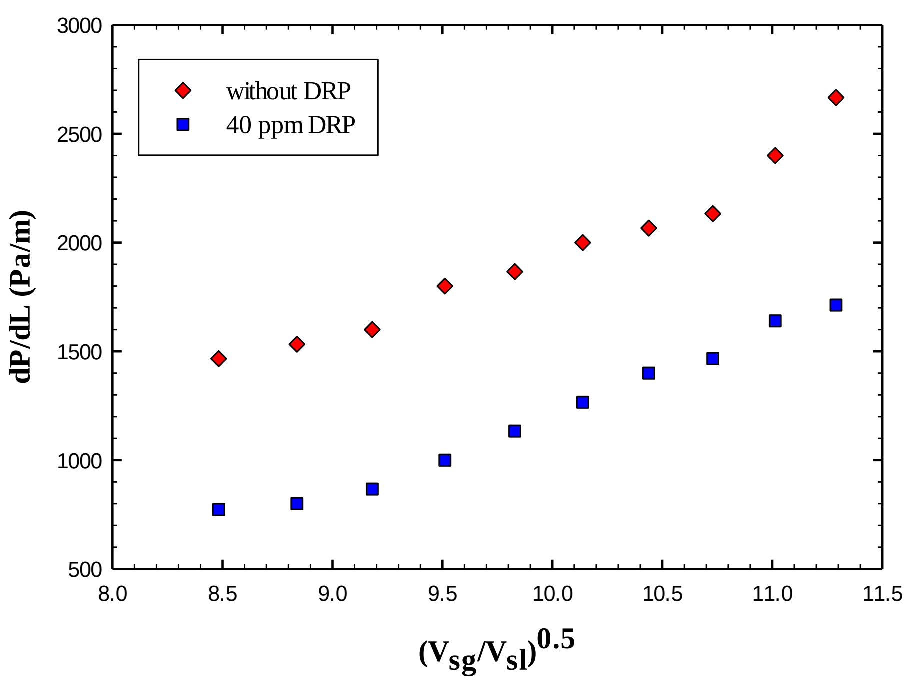

Figure 4.15: Effect of Drag Reducing Polymer on Annular flow regime.

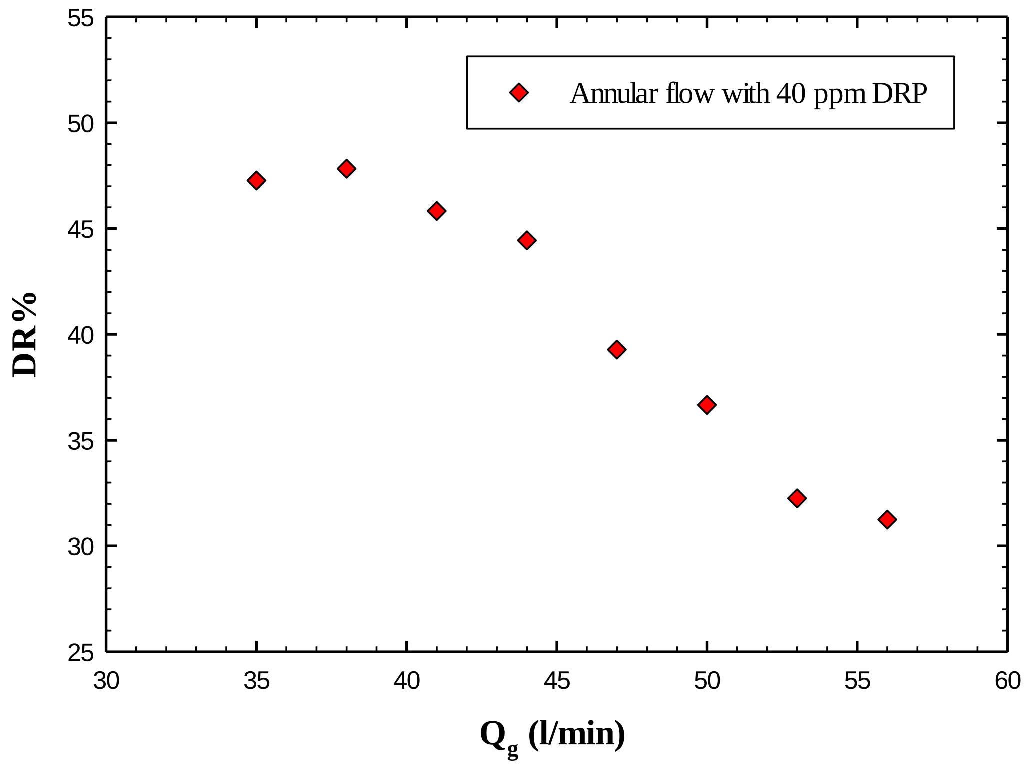

Figure 4.16: Variation of DRP effectiveness with gas flow rates at constant liquid flow rate of 0.5 l/min.

Taylor et al.[47] divided the annular flow regime into three distinct regions according to liquid film disturbance, first region in which the wave starts to form then augments more in region two, and finally the wave oscillations go down in third region. The overall frequency of the interfacial waves decreases as far as it move downstream Zhao et al.[48]. The energy associated with forming these waves always results in reduction in the total pressure, thus using DRP to damp and delay these oscillations lead to a reduction in pressure drop. Figure 4.17 and 4.18 represent typical features of Annular and Wavy annular flow regimes.

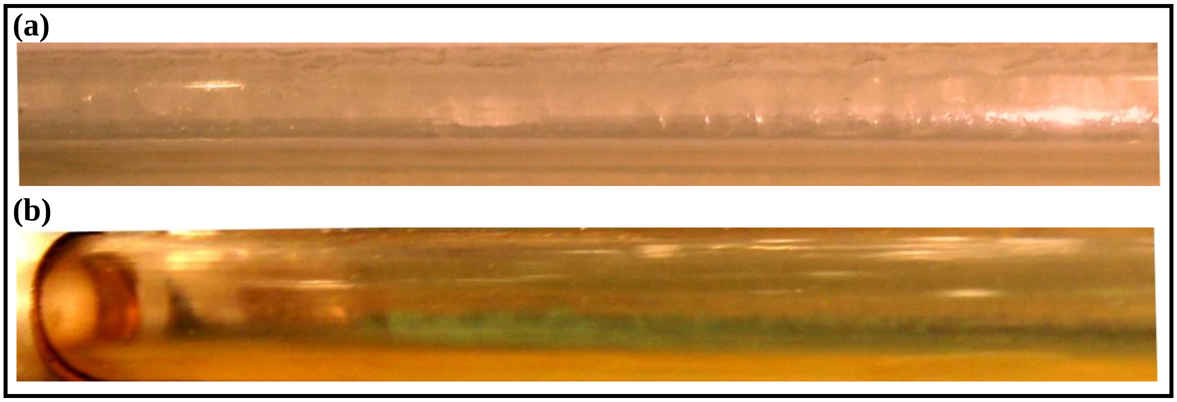

Figure 4.17: (a) Annular flow regime without DRP.(at V_sl=0.1 m/s, V_sg=9.05 m/s) (b) Annular flow regime with 40 ppm of DRP.

Figure 4.18: Annular wavy flow pattern.(at V_sl=0.1 m/s, V_sg=12.75 m/s).

The effectiveness of the Drag Reducing Polymers is very sensitive to the way that been introduced to the system (Al-Sarkhi et al.[29]), in the present study a diaphragm pump has been utilized to inject the polymer into liquid film of the annular flow to avoid polymer molecules breakup. Figure 4.17 and 4.18 indicated that the Wavy annular flow shifted slightly to Stratified wavy regime as DRP injected.

It should be noted that Drag Reducing Polymers acting to stabilize the liquid film by damping disturbance waves at the gas liquid interface, thus a reduction in pressure drop occurs and also an increase in the mean liquid thickness could be observed, this realization in a good agreement with Spedding et al. [49] and Thwaites et al. [50] findings for Annular flow regime. However as the gas flow rates increases the mean film thickness reduces and also the effectiveness of the DRP reduces accordingly as shown in Figure 4.16.

4.2.2.3 Dispersed Bubbly flow regime

As the liquid superficial velocity further increases the dispersed Bubbly regime would be a possible candidate and generally this flow pattern characterized by small bubbles introduced as a discrete particles in the liquid continuous phase. Figure 4.19(a) shows the typical behavior of the Bubbly flow. The performance of the DRP has been examined for this type of flow; figure 4.20 exhibits the variation of the pressure drop with the dimensionless superficial velocity with and without the DRP. From Table 4.2 it can be seen that the maximum drag reduction percentage occurred was about 55% and the flow changed slightly to Pseudo slug flow regime, these changes were limited up to 5 m/s of gas superficial velocity.

The onset of transition to Pseudo slug flow is clearly indicated in figure 4.19(b) with the presence of 40 ppm DRP. The mechanism of the transition is that; with these polymers the separated bubbles tends to coalesce together forming gas Pseudo slugs, due to the decrease in the level of turbulence which contribute in keeping the air bubble dispersed in the liquid.

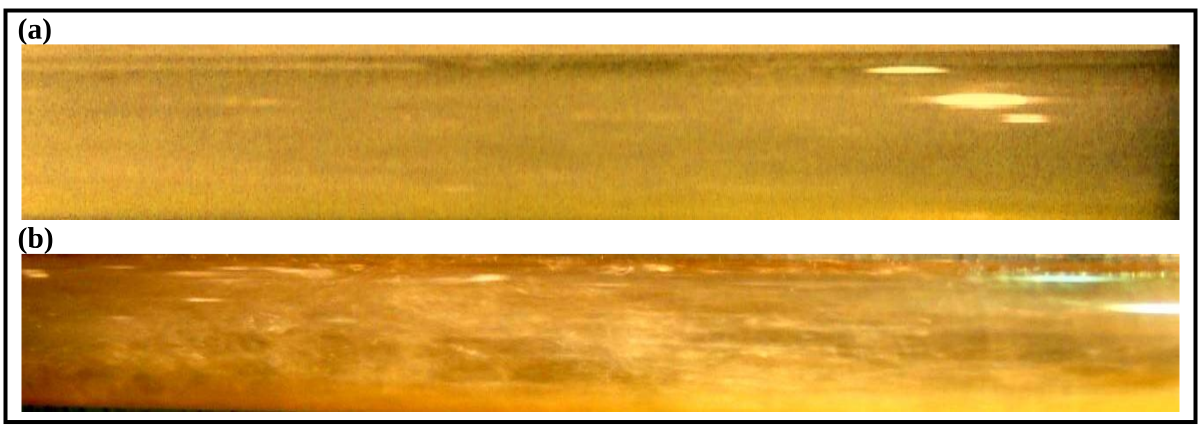

Figure 4.19: (a) Typical feature of a Dispersed Bubbly flow pattern.(at V_sl=3.08 m/s, V_sg=1.03 m/s) (b) Transition from Dispersed Bubbly to Pseudo slug flow regime with 40 ppm DRP.

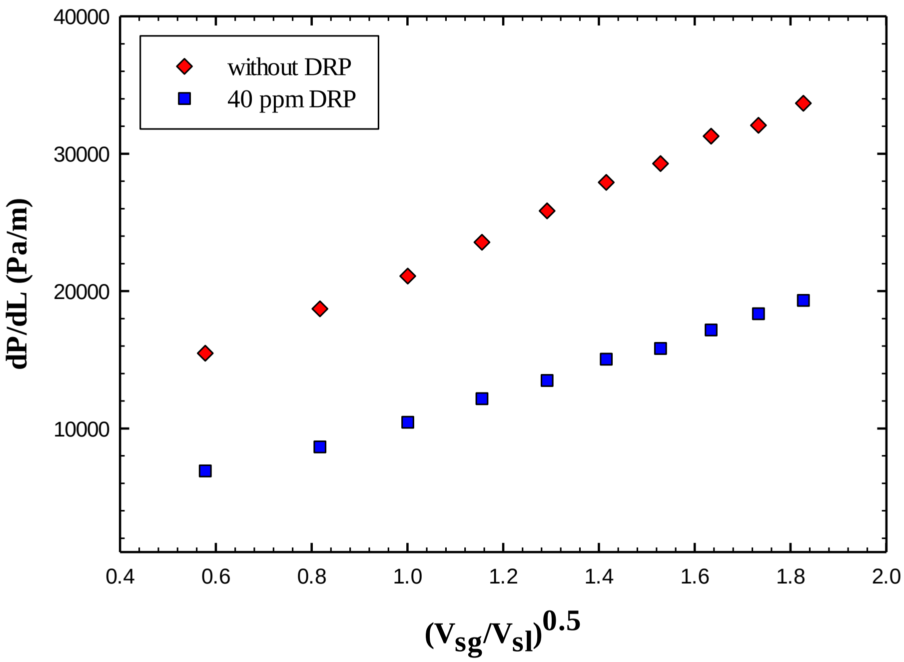

Figure 4.20: Effect of Drag Reducing Polymer on Dispersed Bubbly flow regime.

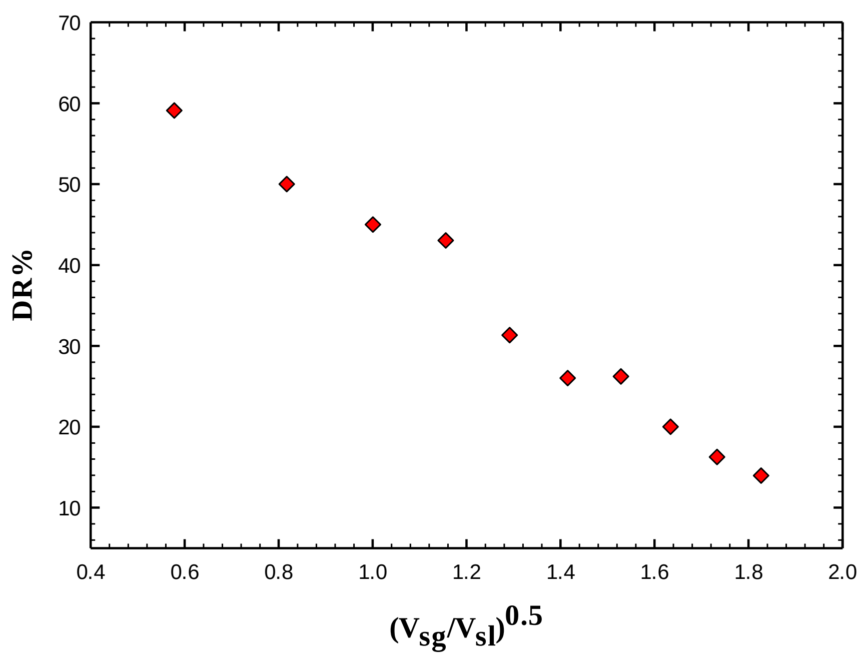

Figure 4.21: Drag Reduction percentage versus normalized superficial velocity for Dispersed Bubbly flow.

4.2.2.4 Slug and Pseudo slug flow regimes

A distinctive study has been carried out to examine the effect of the DRP on the characteristics of Slug and Pseudo slug flows utilizing two polymer concentrations namely 40 and 100 ppm; to show the effectiveness of the DRP in changing the flow patterns at low and relatively high concentrations.

Tables 4.3 and 4.4 articulate the frictional pressure gradient with and without adding DRP of 40 and 100 ppm respectively. It is noted that adding 40 ppm DRP could results in a decrease of turbulence wave's intensity and slug frequency with no clear transition from Slug to Stratified wavy regime. The inception of this transition is illustrated with the presence of adding 100 ppm (Figure 4.24). As seen from Figure 4.22 that the pressure drop reduced more in the case of 100 ppm and the maximum Drag Reduction effectiveness reported in the case of 40 ppm was 53%, and 66% for a situation where 100 ppm added to the flow.

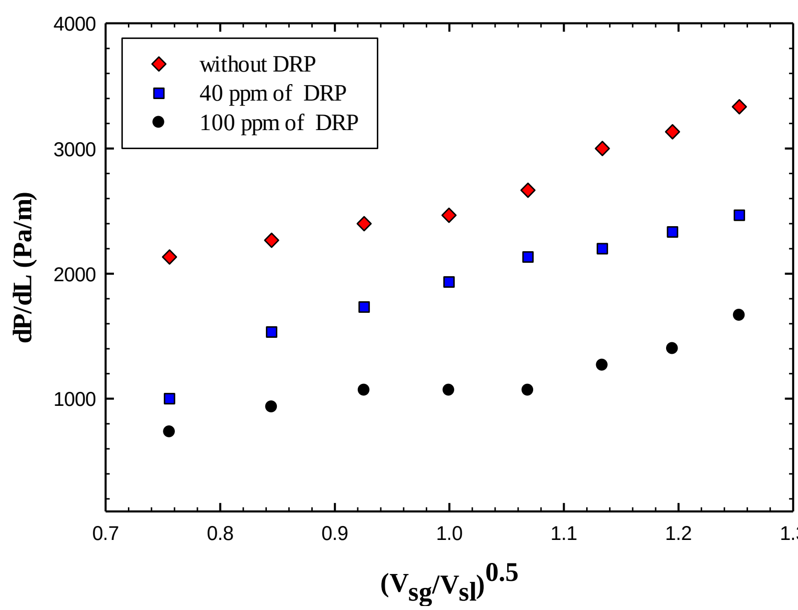

Figure 4.22: Effect of Drag Reducing Polymer on Slug flow regime using a concentration of 40 and 100ppm.

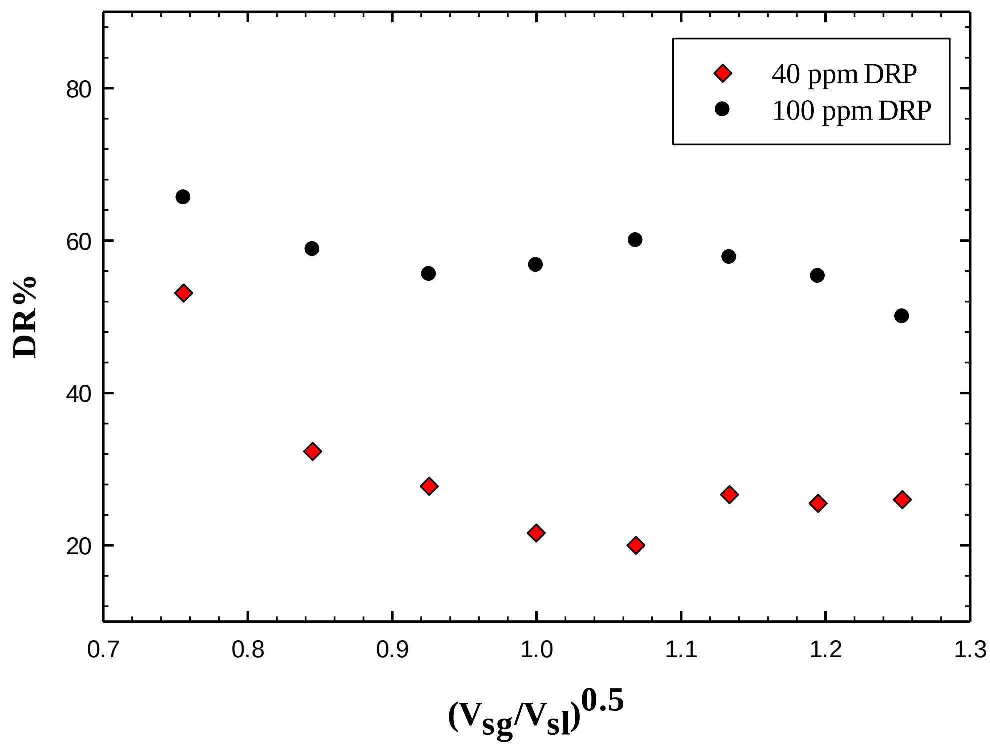

Figure 4.23: Drag Reduction percentage versus normalized superficial velocity for Slug flow regime.

Table 4-3: Frictional pressure drop associated with the Slug flow regime and Drag Reduction effectiveness using 40 ppm DRP.

run	$V_{sl}\left(\frac{m}{s}\right)$	$V_{sg}\left(\frac{m}{s}\right)$	$\frac{dP}{dL}\left(\frac{Pa}{m}\right)$ without DRP	Flow pattern	$\frac{dP}{dL}\left(\frac{Pa}{m}\right)$ 40 ppm DRP	Flow pattern	DR%
1	0.72	0.41	2133	Slug	1000	Slug	53
2	0.72	0.51	2267	Slug	1533	Slug	32
3	0.72	0.62	2400	Slug	1733	Slug	28
4	0.72	0.72	2467	Slug	1933	Slug	22
5	0.72	0.82	2667	Slug	2133	Slug	20
6	0.72	0.93	3000	Slug	2200	Slug	27
7	0.72	1.03	3133	Slug	2333	Slug	26
8	0.72	1.13	3333	Slug	2467	Slug	26

Table 4-4: Frictional pressure drop and transition of the Slug flow regime using 100 ppm DRP.

run	$V_{sl}\left(\frac{m}{s}\right)$	$V_{sg}\left(\frac{m}{s}\right)$	$\frac{dP}{dL}\left(\frac{Pa}{m}\right)$ without DRP	Flow pattern	$\frac{dP}{dL}\left(\frac{Pa}{m}\right)$ 100 ppm DRP	Flow pattern	DR%
1	0.72	0.41	2133	Slug	733	St Wavy	66
2	0.72	0.51	2267	Slug	933	St Wavy	59
3	0.72	0.62	2400	Slug	1067	St Wavy	56
4	0.72	0.72	2467	Slug	1067	St Wavy	57
5	0.72	0.82	2667	Slug	1067	St Wavy	60
6	0.72	0.93	3000	Slug	1267	St Wavy	58
7	0.72	1.03	3133	Slug	1400	St Wavy	55
8	0.72	1.13	3333	Slug	1667	St Wavy	50

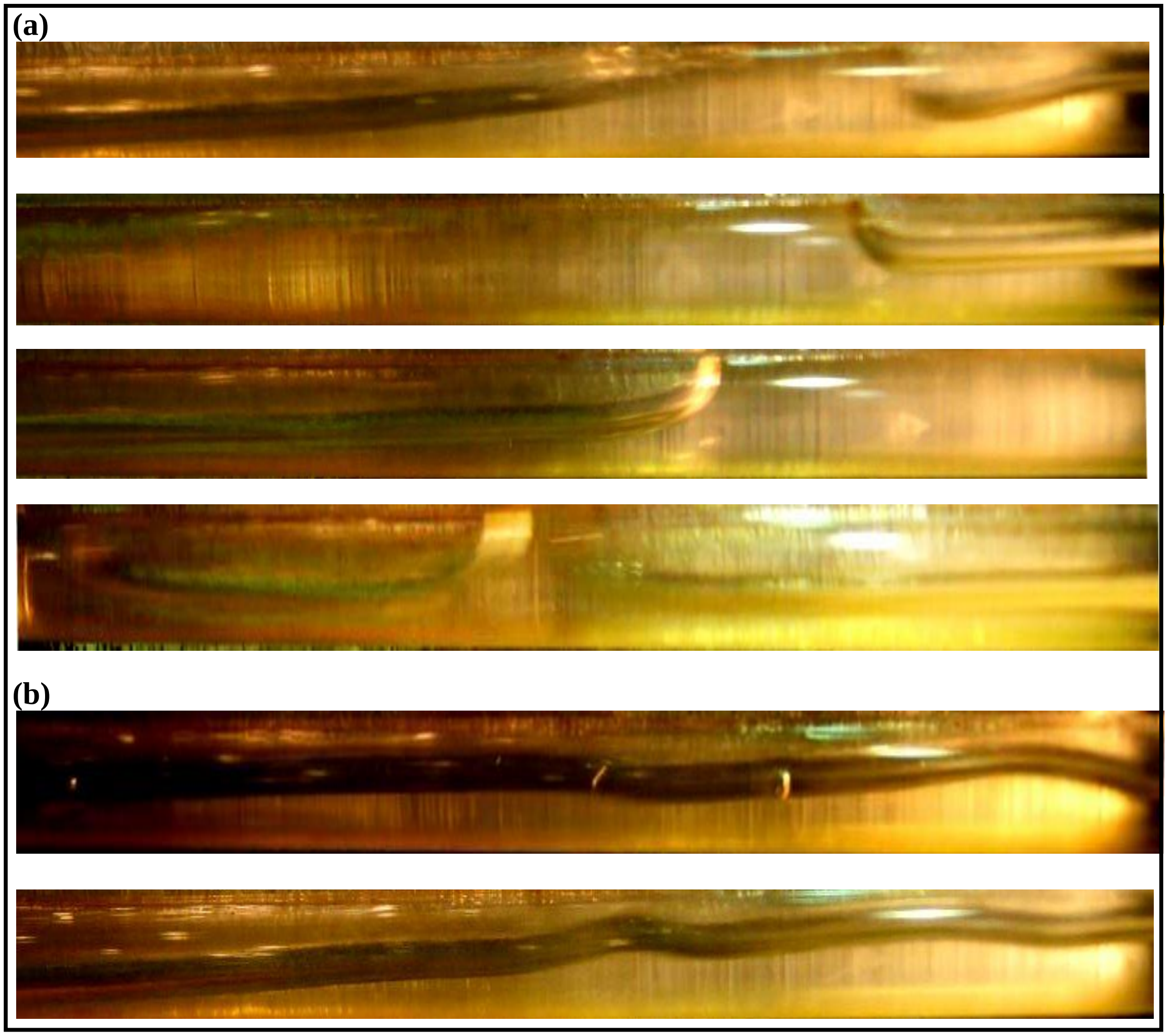

Figure 4.24: (a) Slug flow regime without DRP.(at V_sl=0.72 m/s, V_sg=0.41 m/s) (b) Transition from Slug to Stratified Wavy flow using 100 ppm DRP.

It should be noted that the transition from Slug to Stratified wavy flow has been observed for all the range studied with addition of 100 ppm concentration unlike the case where no transition noted with utilizing only 40 ppm.

The effectiveness of DRP on Pseudo slug regime is exhibited in Table 4.5 and 4.6. Here, the possible transition to Wavy annular flow started earlier when 40 ppm has been added. Also it has been realized that more disturbance appears as the gas flow rate increases, and there is no changes in the characteristics of Pseudo regime have been observed, though the DRP only acts to decrease the turbulence intensity at the gas liquid interface which is totally support the claims of More et al.[50]

Increasing the DRP concentration even more up to 100 ppm enhanced the transition to Wavy annular for the whole superficial gas velocity range (1.03 – 6.17 m/s) and this could justify why the drag reduction has been increased. Figure 4.25 depicts this transition clearly.

Table 4-5: Frictional pressure gradient and transition of Pseudo Slug flow regime using 40 ppm DRP.

run	$V_{sl}\left(\frac{m}{s}\right)$	$V_{sg}\left(\frac{m}{s}\right)$	$\frac{dP}{dL}\left(\frac{Pa}{m}\right)$ *without DRP*	*Flow pattern*	$\frac{dP}{dL}\left(\frac{Pa}{m}\right)$ 40 *ppm DRP*	*Flow pattern*	*DR%*
1	1.03	1.03	4000	Pseudo Slug	2667	W An	33
2	1.03	2.06	5667	Pseudo Slug	3333	W An	41
3	1.03	3.08	7333	Pseudo Slug	4333	W An	41
4	1.03	4.11	8467	Pseudo Slug	6400	Pseudo Slug	24
5	1.03	5.14	9800	Pseudo Slug	7067	Pseudo Slug	28
6	1.03	6.17	10800	Pseudo Slug	8000	Pseudo Slug	26

Table 4-6: Frictional pressure gradient and transition of Pseudo Slug flow regime using 100 ppm DRP.

run	$V_{sl}\left(\frac{m}{s}\right)$	$V_{sg}\left(\frac{m}{s}\right)$	$\frac{dP}{dL}\left(\frac{Pa}{m}\right)$ *without DRP*	*Flow pattern*	$\frac{dP}{dL}\left(\frac{Pa}{m}\right)$ 100 *ppm DRP*	*Flow pattern*	*DR%*
1	1.03	1.03	4000	Pseudo Slug	1600	W An	60
2	1.03	2.06	5667	Pseudo Slug	2333	W An	59
3	1.03	3.08	7333	Pseudo Slug	2667	W An	64
4	1.03	4.11	8467	Pseudo Slug	3600	W An	57
5	1.03	5.14	9800	Pseudo Slug	4467	W An	54
6	1.03	6.17	10800	Pseudo Slug	5800	W An	46

The maximum effectiveness reported was about 41% and 64% for the case of 40 and 100 ppm respectively, figures 4.26 shows the variation of pressure drop with the dimensionless superficial velocity, it is clearly indicated that the pressure drop has been reduced further more in case of adding 100 ppm DRP concentration for both Slug and Pseudo slug regimes.

The formulation of Slug flow pattern always accompanied by a formation of two components, gas pocket and liquid film (figure 4.28). As it can be seen from figure 4.25(a) that the gas pocket (at gas liquid interface) penetrates in the stratified liquid film causing an increase in turbulence intensity. Adding the Drag Reducing Polymer is believed to reduce these penetrations, suppresses turbulence patches and also enlarges the stratified liquid film region (figure 4.25(b)). Daas et al.[38] pointed out similar explanation for drag reduction mechanism in Slug flow regimes.

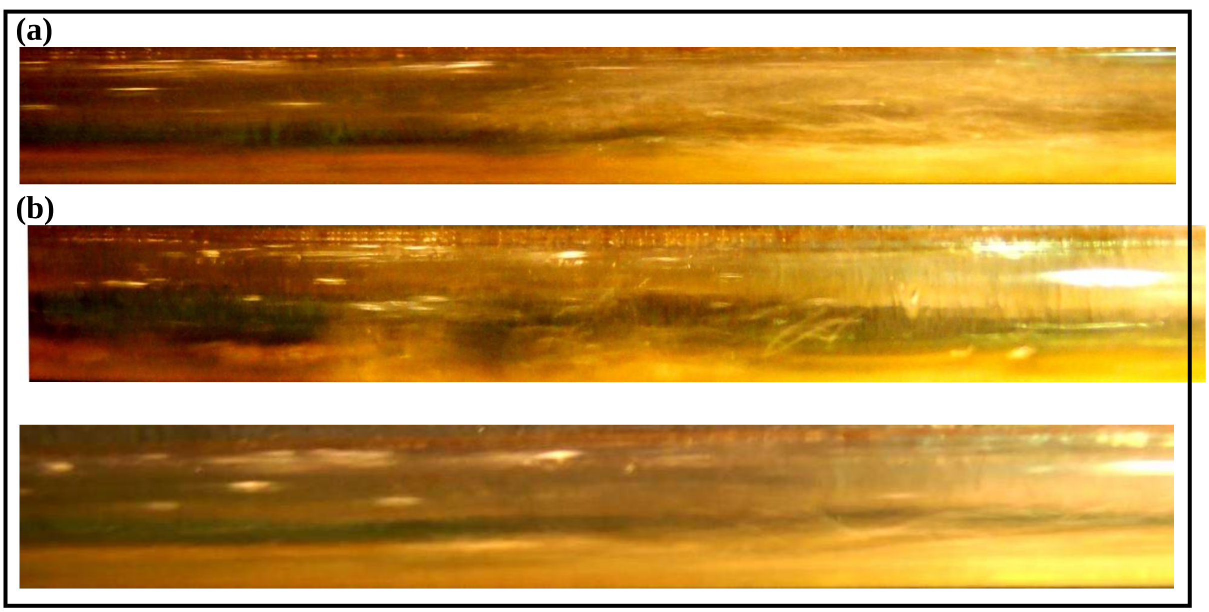

Figure 4.25: (a) Pseudo Slug flow without DRP.(at V_sl=1.03 m/s, V_sg=3.08 m/s). (b) Transition from Pseudo Slug to Wavy Annular flow regime.

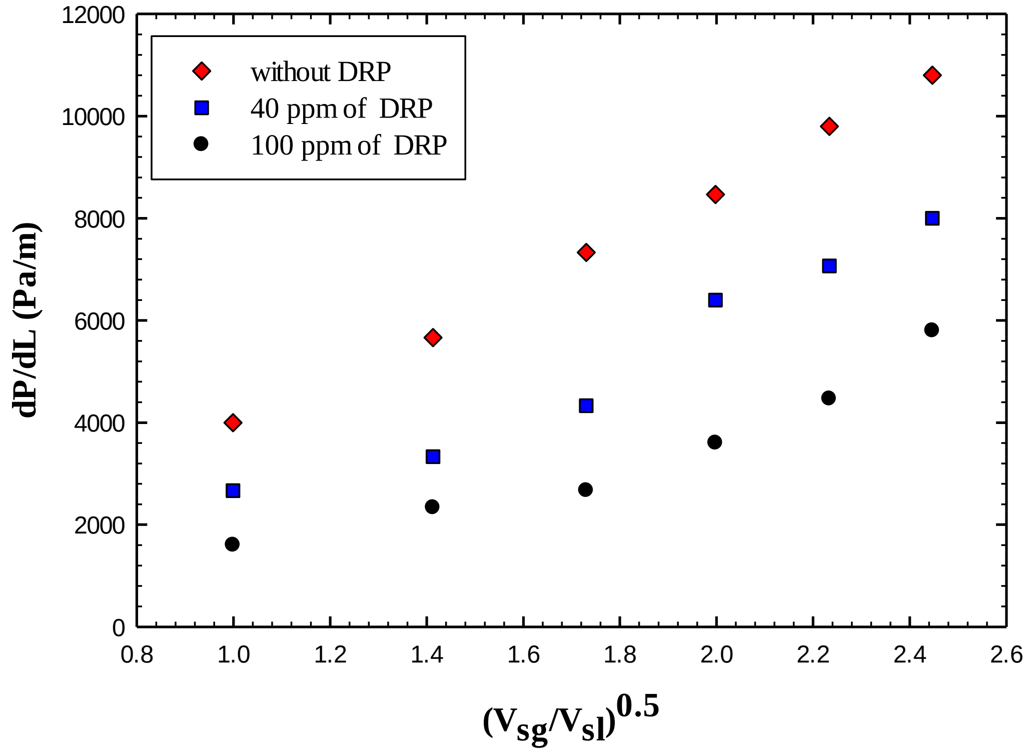

Figure 4.26: Effect of Drag Reducing Polymer on Pseudo Slug flow regime using a concentration of 40 and 100ppm.

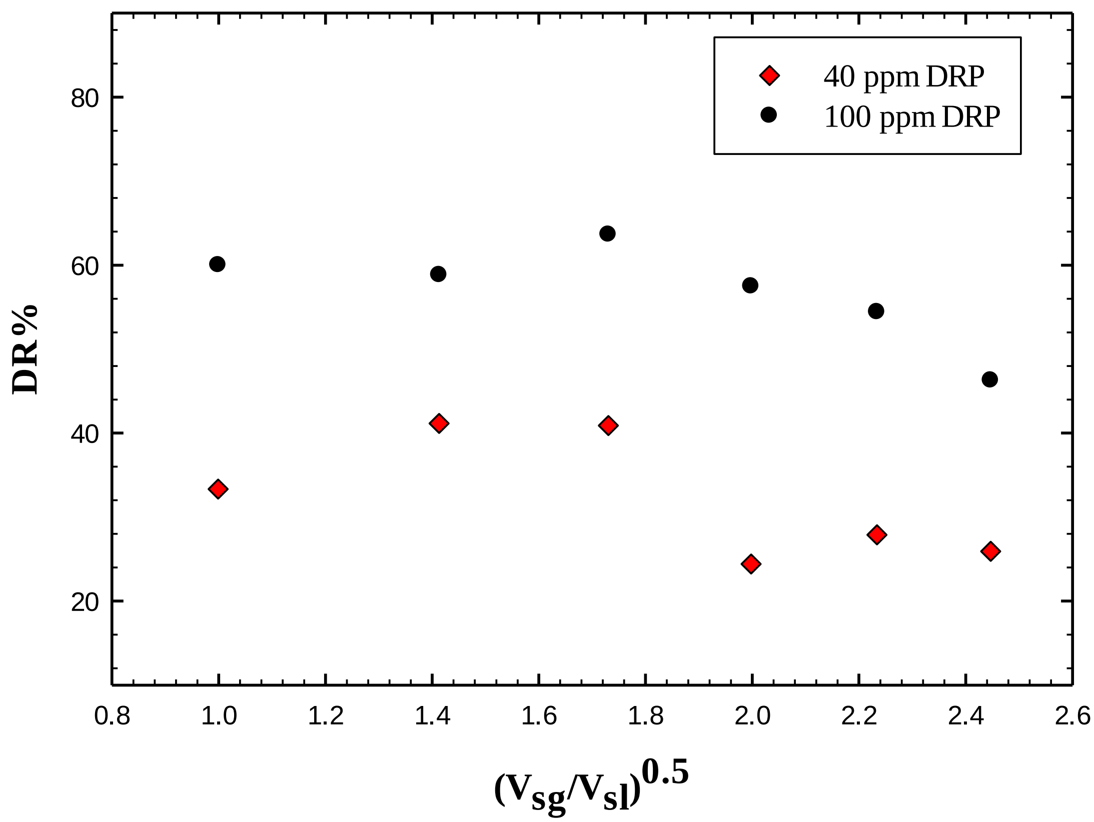

Figure 4.27: Effect of Drag Reducing Polymer on Pseudo Slug flow regime using a concentration of 40 and 100ppm.

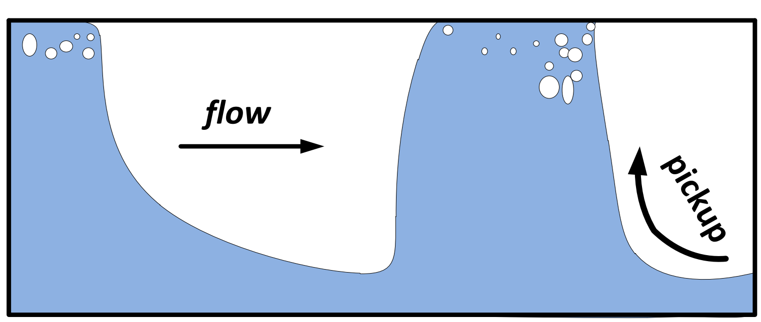

Figure 4.28: Sketch of the slug unit.

4.2.3 Effect of Reynolds number on the DRP effectiveness

Superficial gas Reynolds number is calculated using equation (4.2) and the trend with the Drag Reduction effectiveness has been noticed as can be seen from figures 4.29 and 4.30. Reynolds number can offer a realistic dimensionless parameter because it comprises of the gas phase properties and superficial velocity. Also it should be noted that when the liquid superficial velocity increased less drag reduction has been realized.

$$\mathrm{Re}_{sg} = \frac{\rho_g V_{sg} D}{\mu_g} \tag{4.2}$$

Plot 4.29 shows the variation of the gas superficial Reynolds number with polymer effectiveness, there is no obvious increase or decrease in the effectiveness with Reynolds number reported within the range of superficial liquid velocity up to 1.85 m/s, which indicated that the superficial Reynolds number has no direct effects on drag reduction percentage in this range. On the other hand the trend decreases dramatically as Reynolds number increases for liquid superficial velocity of 2.47, 3.08 and 3.7 m/s as shown in Figure 4.30.

As emphasized by Hamouda et al. [52] the influence of the polymer on turbulent flow is related to the elongation of polymer molecules in the flow leading to a high extensional viscosity which could affect the turbulence structure by eddies damping mechanism and finally causing drag reduction. But at relatively high liquid superficial velocity (more than 1.85) where the possible flow pattern is a Dispersed Bubbly flow; the polymer aggregates would break up causing loss in polymer effectiveness. The effectiveness could be reduced consequently with gas superficial Reynolds number as shown in Figure 4.30.

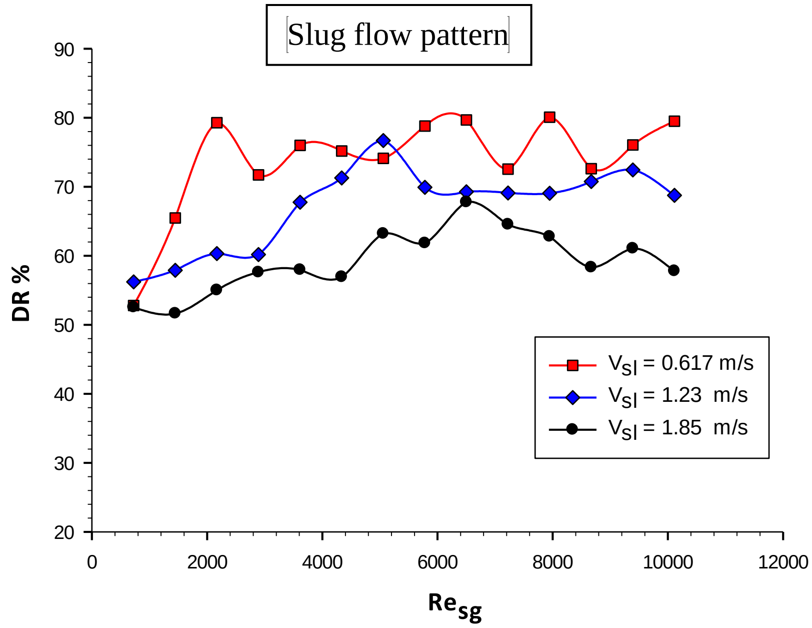

Figure 4.29: Effects of the gas superficial Reynolds number on the drag reduction ratio for various superficial liquid velocities 0.617, 1.23 and 1.85 m/s.

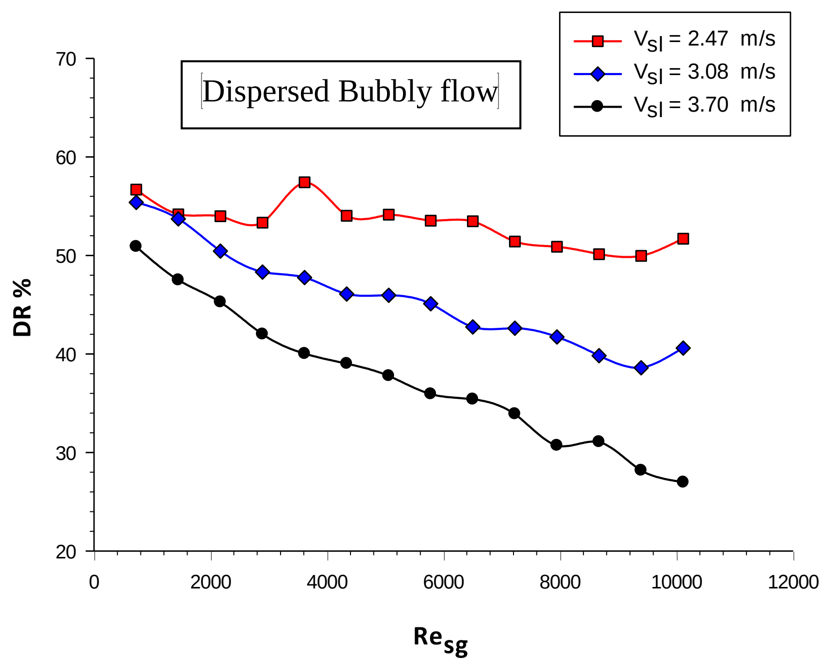

Figure 4.30: Effects of the gas superficial Reynolds number on the drag reduction ratio for various superficial liquid velocities 2.47, 3.08 and 3.70 m/s.

4.2.4 Effect of Air superficial velocity on DRP performance

Figures (4.31-4.36) exhibit the performance of the DRP on the frictional pressure drop at different gas superficial velocities from (1.03 – 14.39) m/s . all these results obtained at fixed liquid superficial velocities of 0.617, 1.23, 1.85, 2.47, 3.08 and 3.7 m/s respectively. As it can be seen that the increase in the gas superficial velocity was associated with an increase in the pressure drop for the whole range of the liquid superficial velocities.

For a superficial liquid velocity of 0.617 m/s the frictional pressure drop range is from 2800 - 20840 Pa/m, without adding the polymer. It is clearly seen from figure 4.31 that with the increase of gas superficial velocity from 1.03 to 14.39 m/s the pressure drop increases accordingly. Furthermore the figure shows that as the gas superficial velocity increased more fluctuation will occur due to the increase in the slug frequency, However the pressure drop goes up and down depends on either the slugs is decaying or propagating.

The physical interpretation of this phenomena which has been addressed in the work of Daas et al. [38]. That when the gas superficial velocity increased the gas tends to push the liquid around it's circumference which results in increasing the contact area between liquid and the pipe inner wall, thus the pressure drop will progress more at the top of the liquid film.

The DRP is very effective in reducing the frictional pressure gradient by up to 80% for this particular value of liquid superficial velocity, Furthermore at the presence of the DRP the turbulence intensity has been successfully tumbled and the transition from intermittent flow regime to a Wavy annular regime has been noticed for the range of more than 7 m/s V_{sg} as seen in figure 4.31. Also an increase in the DRP effectiveness is observed as the gas superficial velocity increases.

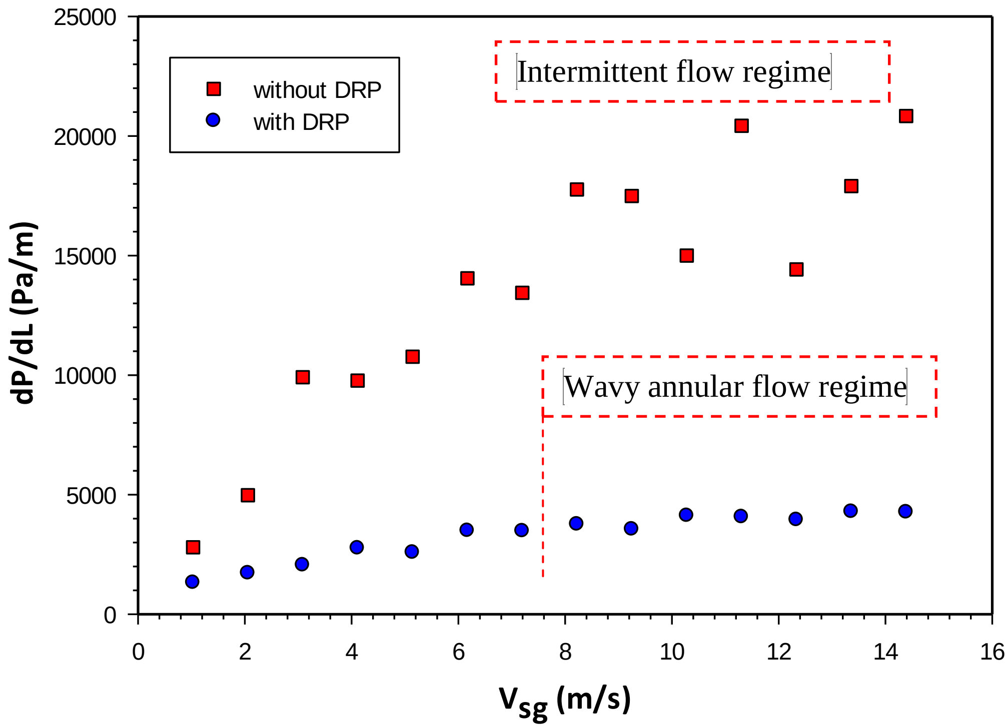

Figure 4.31: Variation of frictional pressure gradient with gas superficial velocity at fixed liquid superficial velocity of 0.62 m/s. (200 ppm of DRP)

Figure 4.32 shows the results obtained for constant liquid superficial velocity of 1.23 m/s with the same range of gas velocities. As it can be seen that the pressure gradient within the range of 5700 – 32000 Pa/m and the pressure drop correspond to these values when the drag reducing polymer is added are about 2500 -9900 Pa/m respectively.

The effect of the DRP for this range of pressure drop is investigated and the maximum drag reduction realized was about 72 %. Same trend of the DRP effectiveness with respect to the increase in the gas superficial velocity also been observed as shown in figure 4.29.

Before injecting the DRP, Slug flow and intermittent flow patterns were observed. With addition of DRP the slug intensity has been reduced and the flow shifted to a low frequency slug flow regime.

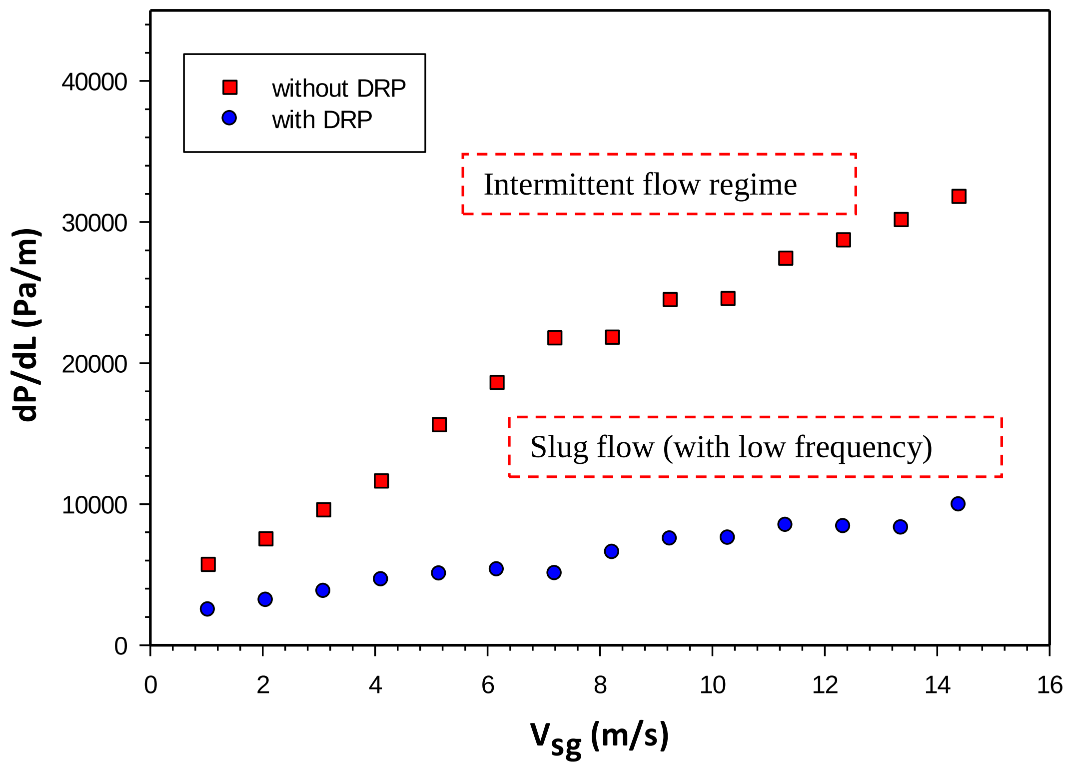

Figure 4.32: Variation of frictional pressure gradient with gas superficial velocity at fixed liquid superficial velocity of 1.23 m/s. (100 ppm of DRP)

Figure 4.33 presents an equivalent result of a liquid superficial velocity of 1.85 m/s. The pressure drop range for this velocity increased slightly to 8200 Pa/m for low gas superficial velocity (1.03 m/s) and 32000 Pa/m at highest value of 14.39 m/s gas velocity at which a highly intermittent flow appears.

The maximum drag reduction noticed was 67.8% at gas superficial velocity of about 9.25 m/s when the highly waves that appeared in the intermittent flow is suppressed to form a Slug flow with low frequency; As can be seen from the plot the slugs appearance delayed further compared with the previous graphs where the slugs came to the picture at gas superficial velocity of about 3.08 and 6.2 m/s for liquid superficial velocity of 0.617 and 1.23 m/s respectively. Moreover it should be noted that there is subsequent reduction in the Slug intensity at this velocity as the DRP introduced to the system, on explanation could be for this reduction that because of the possible transition of the flow from Slug or Pseudo slug to Wavy annular flow regime which is more stable.

The drag reduction percentage has been plotted as a function of the gas superficial velocity for three different liquid superficial velocities namely 0.617, 1.23, 1.85 m/s to show the how the drag reduction dramatically with the increase in the gas superficial velocity (for the range of liquid superficial velocity below 2 m/s). This enhancement in the reduction ratio could be due to the possible change of the flow regime from Stratified wavy to Slug (Pseudo slug) where high fluctuation and turbulence intensity appears; hence the DRP will perform more effectively to reduce those fluctuations and damping high intensities.

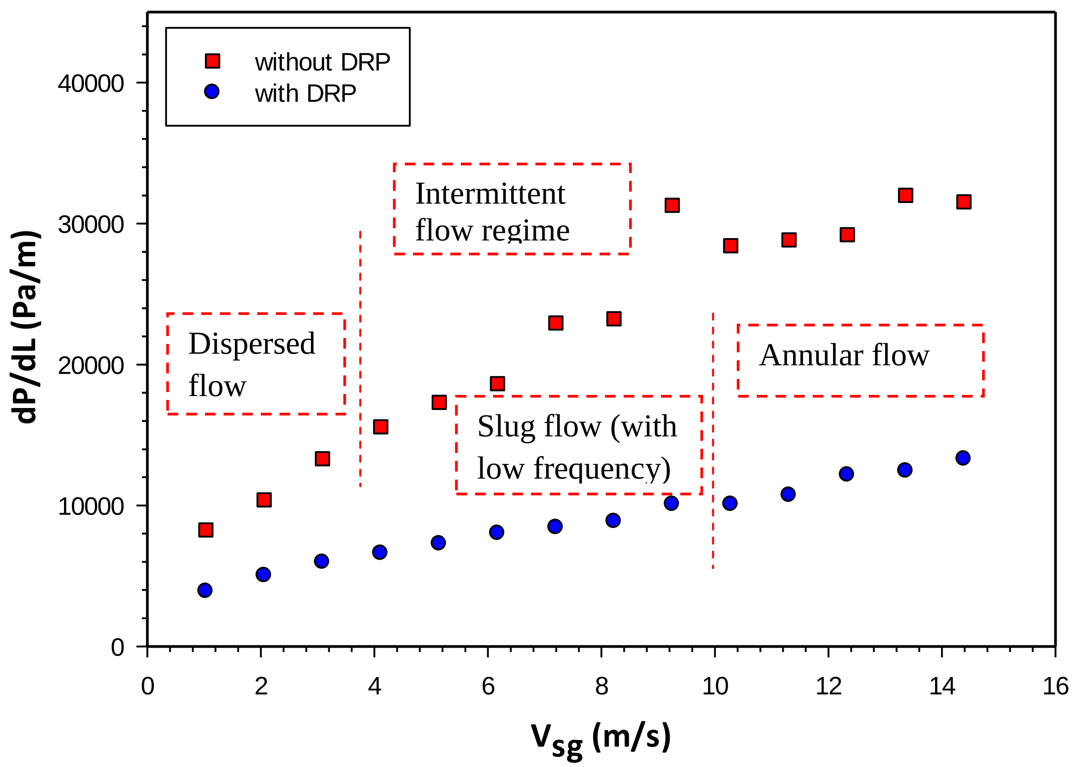

Figure 4.33: Variation of frictional pressure gradient with gas superficial velocity at fixed liquid superficial velocity of 1.85 m/s. (66.67 ppm of DRP)

The results of 2.47 m/s superficial liquid velocity and the pressure drop experiments are presented in figure 4.34. The maximum pressure drop has been increased significantly up to 37,700 Pa/m and the maximum drag percentage reported was 57.5%. It can be seen that the pressure drop increased correspondingly with the superficial gas velocity, in addition to that as the liquid velocity increased the transition to Annular flow regime could be the possible candidate as seen obviously from the test section that the gas phase particles start to orient it selves on the pipe core then push the liquid to cover the area around the gas and wetting the pipe wall. The pressure drop increased significantly with no higher slug frequency.

The anomalous trend compared with the previous liquid superficial velocities shown in figure 4.30; which indicated that the effectiveness of the drag reducing polymer reduced while increasing gas superficial velocity and this is in complete agreement with the results reported by Alsarkhi et al.[34],[29] for the annular flow studied using gas-water two phase.

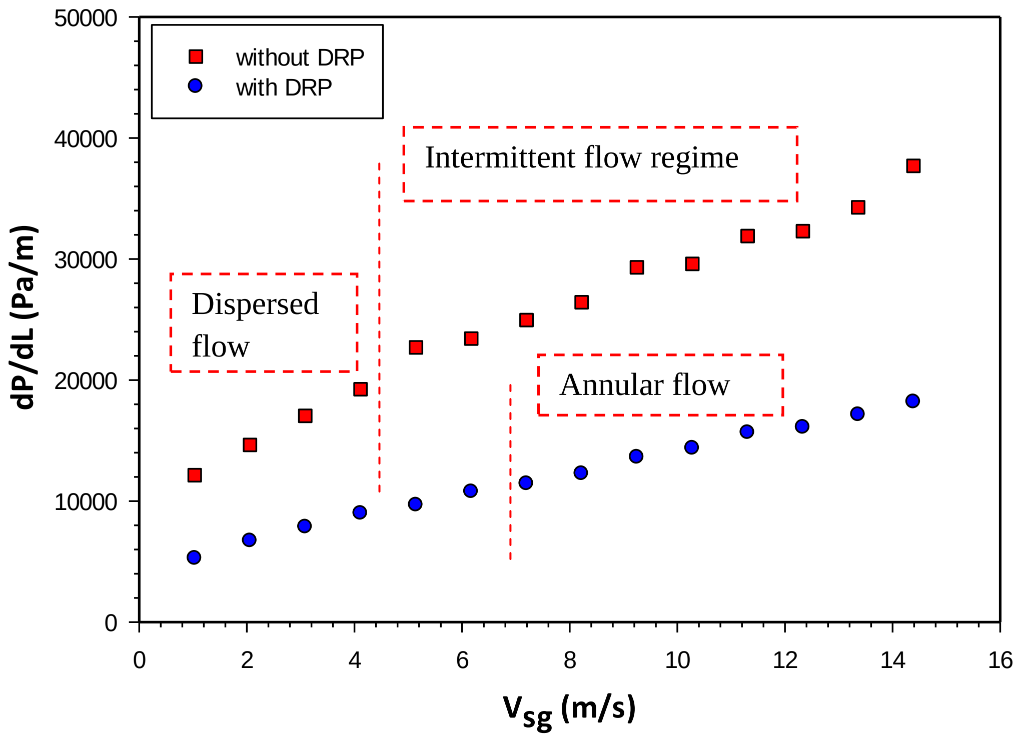

Figure 4.34: Variation of frictional pressure gradient with gas superficial velocity at fixed liquid superficial velocity of 2.47 m/s. (50 ppm of DRP)

Similar trend could be realized in this range as we are increasing the liquid velocity more, the augmentation in the pressure drop that accomplished with this velocity also reported (from 15,500 – 41,200 Pa/m), figure 4.35 shows the variation of the frictional pressure drop with increasing the gas superficial velocity. As indicated that the as the liquid superficial velocity increases (more than 3 l/min) the disturbance waves reduce dramatically due to the formation of the Dispersed flow regime. On the other hand the frictional pressure drop increases more due to the fact that the frictional resistance arose from liquid phase flow.

The maximum percentage of drag reduction reported in this range was 55.4% which is less than those occurred on the previous sets of liquid velocities.

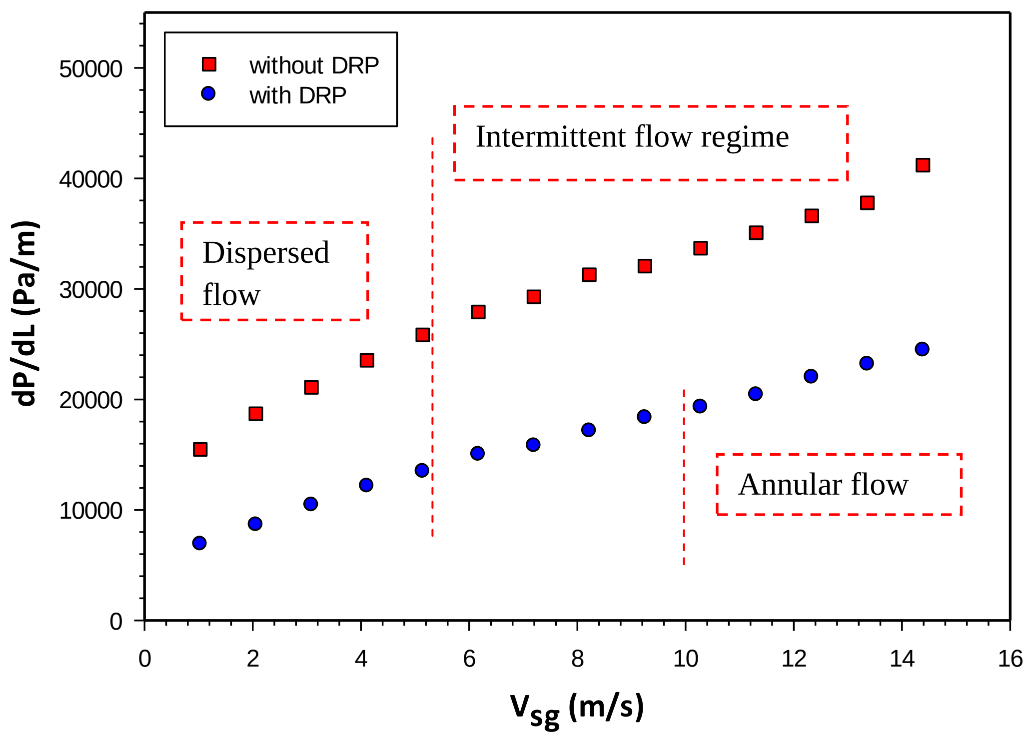

Figure 4.35: variation of frictional pressure gradient with gas superficial velocity at fixed liquid superficial velocity of 3.08 m/s. (40 ppm of DRP)

Increasing the liquid superficial velocity further to 3.7 m/s lead to an increase in the pressure drop within the band of 19,500 and 44,700 Pa/m as a result of increasing the liquid superficial velocity, the formation of discrete bubbles would be appear at the liquid film forming Dispersed Bubbly regime. This flow pattern is covering most of range (up to 10 m/sV_{sg}), by adding the DRP these Bubbles connected together inside the liquid continuous phase leading to form Wavy annular flow regime. The highest value of drag reduction ratio recorded was 51%.

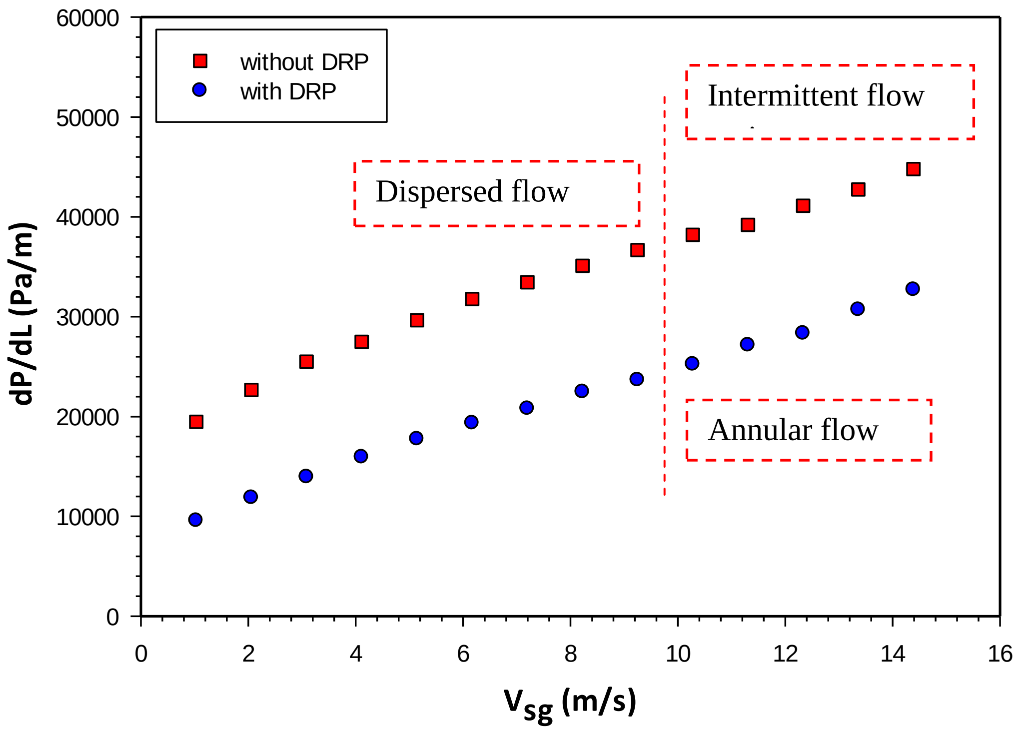

Figure 4.36: variation of frictional pressure gradient with gas superficial velocity at fixed liquid superficial velocity of 3.7 m/s. (33.33 ppm of DRP)

4.2.5 Effect of water fraction on frictional pressure drop reduction

The experimental results of the effect of input water fraction (at different gas superficial velocities) on DRP have been shown in this section in order to give more understanding on how the DRP can perform. The input water volume fraction can be defined based on gas and liquid superficial velocities as follows:

$$Input\ water\ volume\ fraction = \frac{V_{sl}}{V_{sl} + V_{sg}} \tag{4.3}$$

As it can be seen from Figure (4.37 through 4.41) as water fraction increases the corresponding pressure drop increases and the maximum pressure drop reported was about 42,000 Pa/m in case of 5.14 m/s gas superficial velocity.

Figure 4.37 illustrates that the Drag Reduction is very sensitive to the input water fraction and this was clearly observed when a dramatic reduction in the frictional pressure drop obtained with slightly change in the input water fraction from 0.7 to 0.8.

In general, with all gas superficial velocities (1.03, 2.06, 3.08, 4.11 and 5.14) these Figures show that the pressure gradient of simultaneous flow of air-water in pipe is increased with increasing of input water fraction (0.2 up to 0.8).This is due to the fact that the height of the liquid film increases with increasing water fraction also due to the increasing of frictional force between liquid film and the wall. However for all water fractions the DRP was able to reduce the frictional pressure effectively.

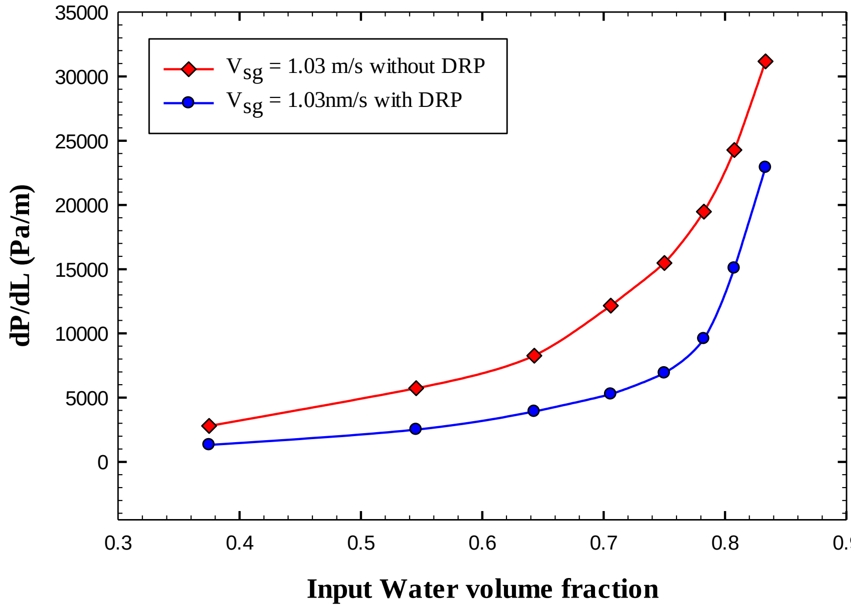

Figure 4.37: Frictional pressure drop variation (with and without DRP) with input water fraction at fixed gas superficial velocity of 1.03 m/s.

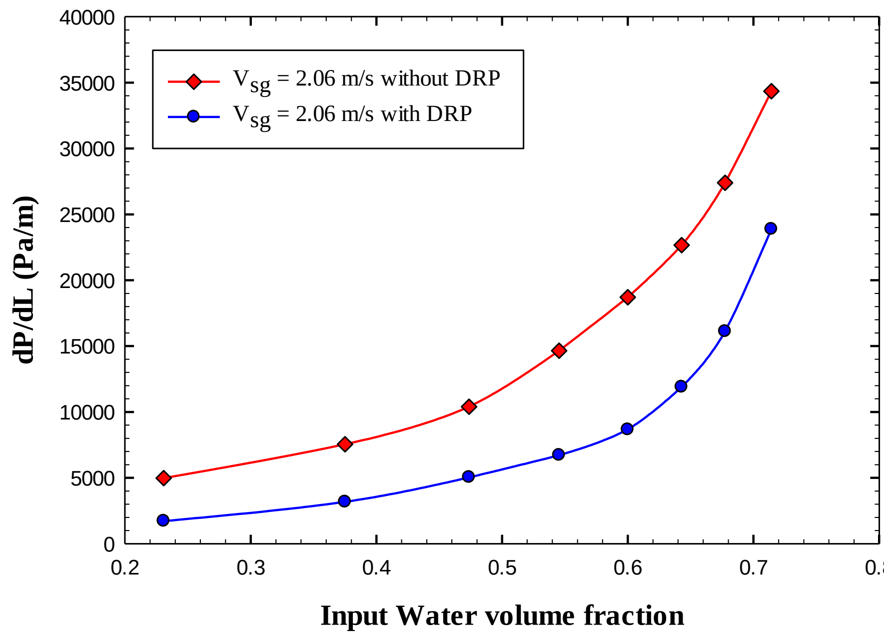

Figure 4.38: Frictional pressure drop variation (with and without DRP) with input water fraction at fixed gas superficial velocity of 2.06 m/s.

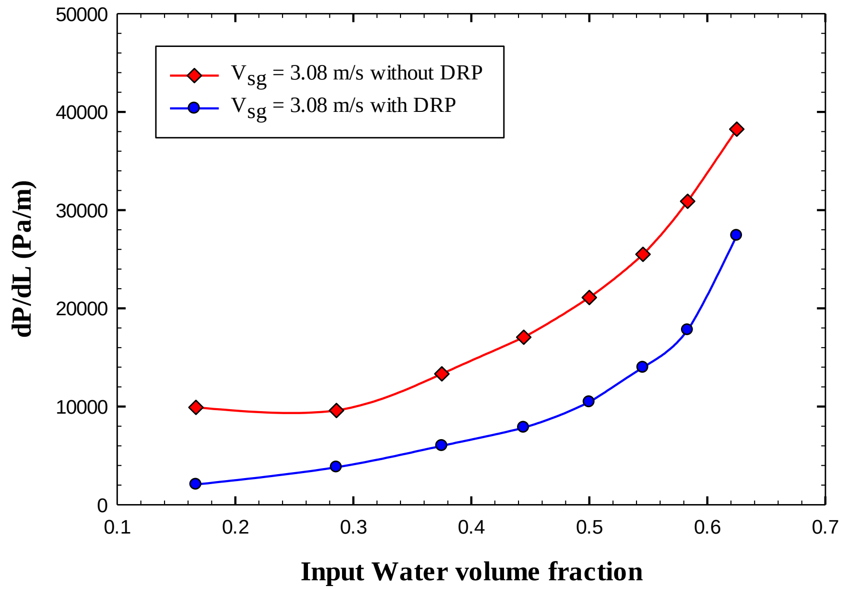

Figure 4.39: Frictional pressure drop variation (with and without DRP) with input water fraction at fixed gas superficial velocity of 3.08 m/s.

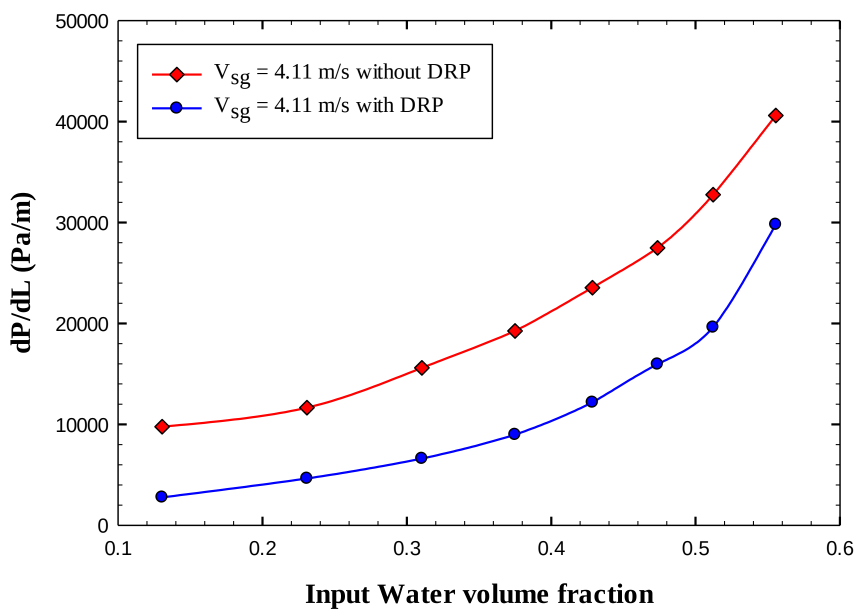

Figure 4.40: Frictional pressure drop variation (with and without DRP) with input water fraction at fixed gas superficial velocity of 4.11 m/s.

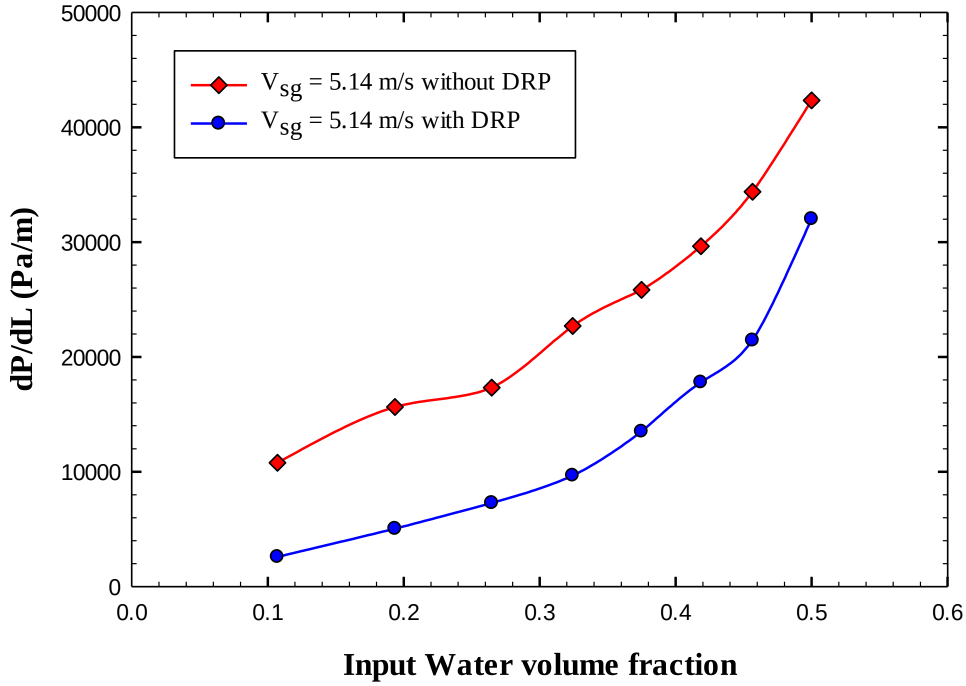

Figure 4.41: Frictional pressure drop variation (with and without DRP) with input water fraction at fixed gas superficial velocity of 5.14 m/s.

4.2.6 Effect of polymer concentration

Figure 4.42 show plot of the effectiveness variation with different concentration of polymers. The results indicated that Drag Reduction Ratio (DR%) increases as the polymer concentration increases due to an increase in the number of available polymer molecules within the two phase system. However, as the polymer concentration increases further, the solution viscosity drastically increases, leading to a decrease in the turbulent strength.

It should be noted that the maximum Drag Reduction reported was 65.5%, 71% and 76% for gas flow rates of 10 l/min, 20 l/min and 25 l/min respectively; which indicates that more frictional drag is observed when the gas flow rate increase from 10 l/min to 25 l/min and this is realized obviously at concentration of 60 ppm and so more.

Thus as it can be seen from figure 4.42, the Drag Reducing Polymers are very effective at high concentration for all cases, and if it is introduced into the air-water system of different gas flow rates it will be more effective at higher flow rate for the same ppm injected.

Also It is noted that the amount of Q_g can play a key role (Figures (4.43 – 4.45); since it increasing the mixture Reynolds number which affect the amount of drag reduction for a given polymer concentration. Furthermore the comparison in Figure 4.45 indicates that as liquid amount increases the frictional pressure drop increases accordingly due to the increasing in turbulency. Though based on our study it should be noticed that the role of DRP came into play with appearance of turbulency in the system and became more pronounced with increase of Reynolds number.

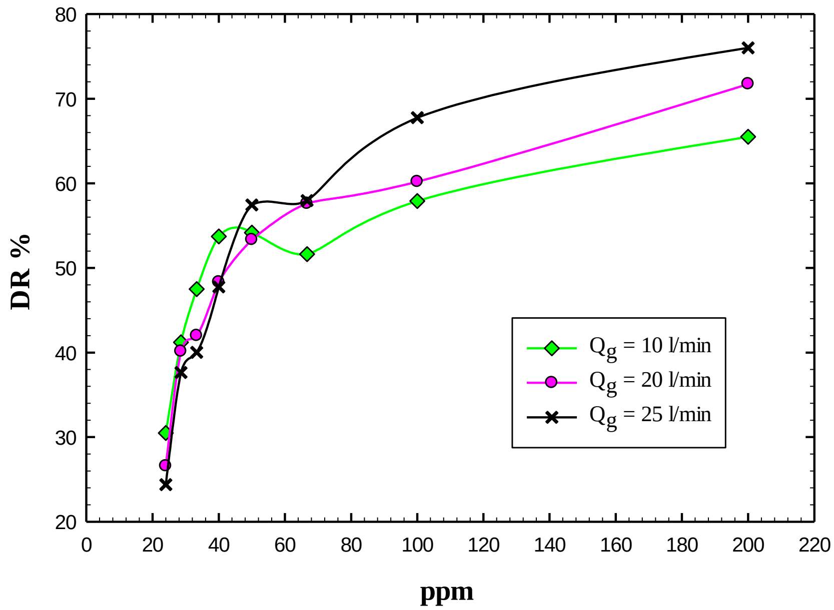

Figure 4.42: Variation of the Drag reduction ratio versus polymer concentration (ppm), at constant gas flow rates of 10, 20 and 25 l/min.

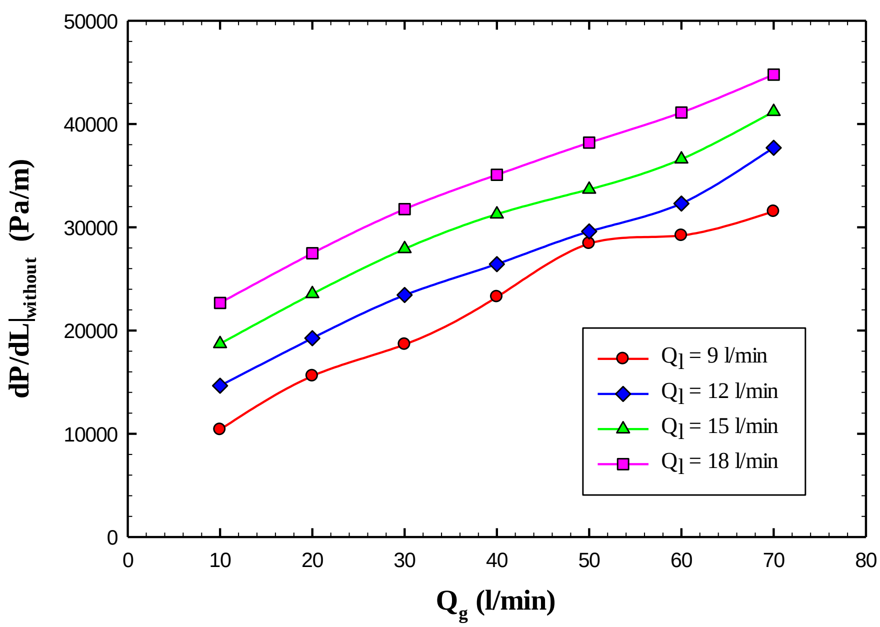

Figure 4.43: Measurement of the frictional pressure drop without DRP with changing the gas flow rate (at different liquid flow rates).

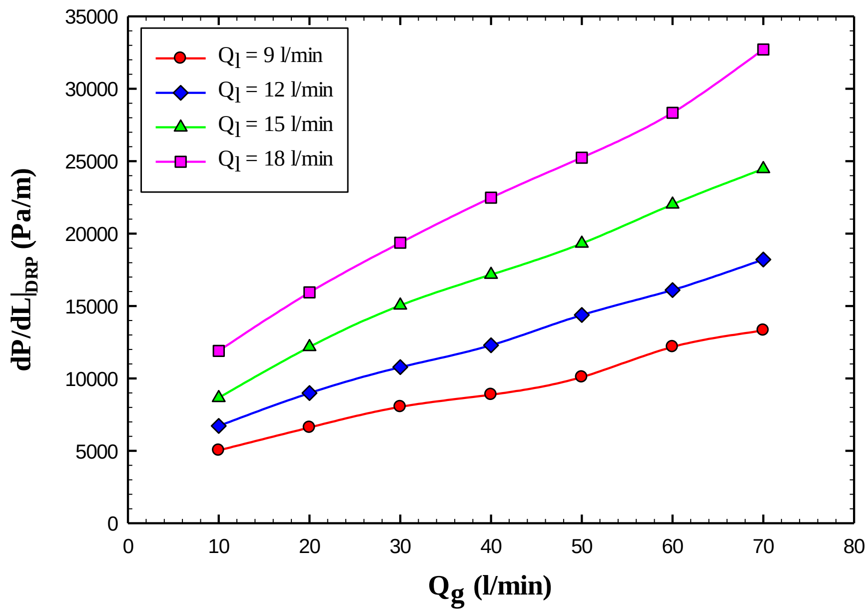

Figure 4.44: Measurement of the frictional pressure drop with DRP with changing the gas flow rate (at different liquid flow rate).

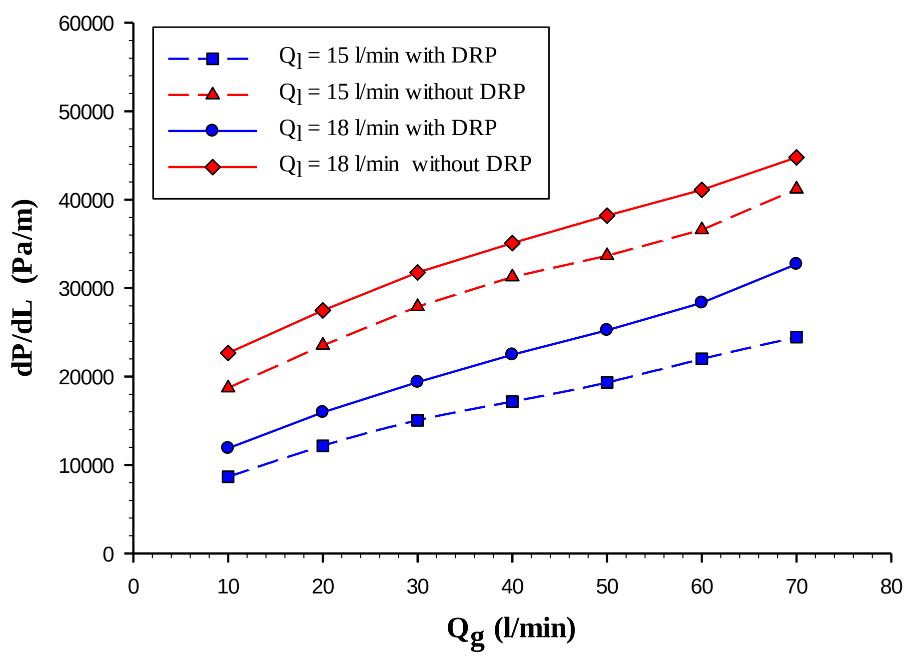

Figure 4.45: Comparison of the pressure gradient with and without Drag reducing polymer at liquid flow rate of 15 l/min and 18l/min.

4.3 Correlations

An experimental study has been carried out for a horizontal pipeline to examine the addition of water soluble polymer on the two phase water-air flow. The experimental data has been generated based on the two phase (air-water) map in figure 4.11.

In this section, correlations have been developed to allow further understanding of the drag reducing polymers in reducing the frictional pressure gradient and the parameters that could be affected by these additions also explained.

The mixture friction factor f_M and the mixture Reynolds number Re_M for the two phase water-air flow are playing a key role in developing such good relation that predict and represent the experimental data more properly. The definitions of the mixture friction factor and mixture Reynolds number has been illustrated in the studies of García et al. [53].

4.3.1 Correlation development

Usually the two phase water-air is very complex in nature and this complexity is more obviously when the detecting of a flow pattern that could be existed before and after adding the DRP is required. Therefore the need for developing a correlation that appropriately relate different flow parameters and characteristics receives high attention especially in predicting the pressure drop in pipelines without knowing the flow regime. Possible dimensionless parameter could be the one include various parameters such like the mixture Reynolds number Re_M which comprises pipe diameter, density, viscosity and mixture velocity in one dimensionless number.

Several studies has been performed to correlate the two phase using dimensionless groups, for example García et al. [53,54] developed a correlation of friction factor that covered a wide range of laminar and turbulent flow of gas-liquid regimes. The correlation that been produced was based on liquid holdup ranges to differentiate between the experimental data used in their analysis. But these correlations have been done without the addition of the Drag Reducing Polymers, hence different trends and correlations could be realized as the DRP added to the system.

Alsarkhi et al. [42] Studied the effectiveness of two correlations for predicting the effect of the drag reducing polymers on the mixture friction factor using the published experimental data of air-liquid and oil-water flows. This was the only attempt been found in the open literature at least for predicting the drag reduction in different pipe diameters namely from 0.019 to 0.0953 m.

In the present work an experimental investigation on water-air flow is conducted and several correlation has been developed based on various water superficial velocities using different dimensionless groups and parameters that used in Al-sarkhi et al.[42] and García et al.[53]

4.3.2 Dimensionless parameters

The mixture friction factor for water–air mixture without the addition of DRP $(f_{Mwithout\text{-}DRP})$ is expressed as follows:

$$f_{Mwithout\text{-}DRP} = \frac{2.D.\frac{dP}{dL}\big|_{withoutDRP}}{\rho_M . V_M^2} \tag{4.4}$$

Where D is the diameter of the pipe, and V_M is the mixture velocity which is defined as the summation of liquid and gas superficial velocities ($V_M = V_{sl} + V_{sg}$).

The superficial liquid and gas superficial velocities are calculated using the below equations:

$$V_{sl} = \frac{4Q_l}{\pi D^2} \tag{4.5}$$

$$V_{sg} = \frac{4Q_g}{\pi D^2} \tag{4.6}$$

Where Q_l, Q_g are the flow rate for the liquid and the gas respectively.

The mixture density (ρ_M) is defined as:

$$\rho_M = \rho_l \lambda_l + \rho_g (1 - \lambda_l) \tag{4.7}$$

Where: $\lambda_l = \frac{Q_l}{Q_l + Q_g}$ the volumetric flow rate fraction, then ρ_l, ρ_g are the densities of liquid and the gas respectively.

The mixture friction factor with adding the drag reducing polymer is formulated using the same parameters on equation (4.4) above with only changing the pressure drop to $\frac{dP}{dL}|_{DRP}$ which is the one with DRP added to the system.

$$f_{M\text{-}DRP} = \frac{2.D.\frac{dP}{dL}|_{DRP}}{\rho_M . V_M^2} \tag{4.8}$$

Reynolds number on this analysis is based on the liquid kinematic viscosity ν_L

$$Re_M = \frac{V_M.D}{\nu_L} \tag{4.9}$$

The regression analysis is conducted based on the experimental data obtained at different liquid superficial velocities ranged from 1.85 to 4.317 m/s forming around 100 data set points. As it can be seen from figure 4.46, that all the data points are following the same trend of the fitted curve.

The scatter data conclude a wide range of flow types and regimes of Slug (pseudo slug), Annular and Dispersed Bubbly flow regimes, this rang could enable better prediction of the correlation under the study.

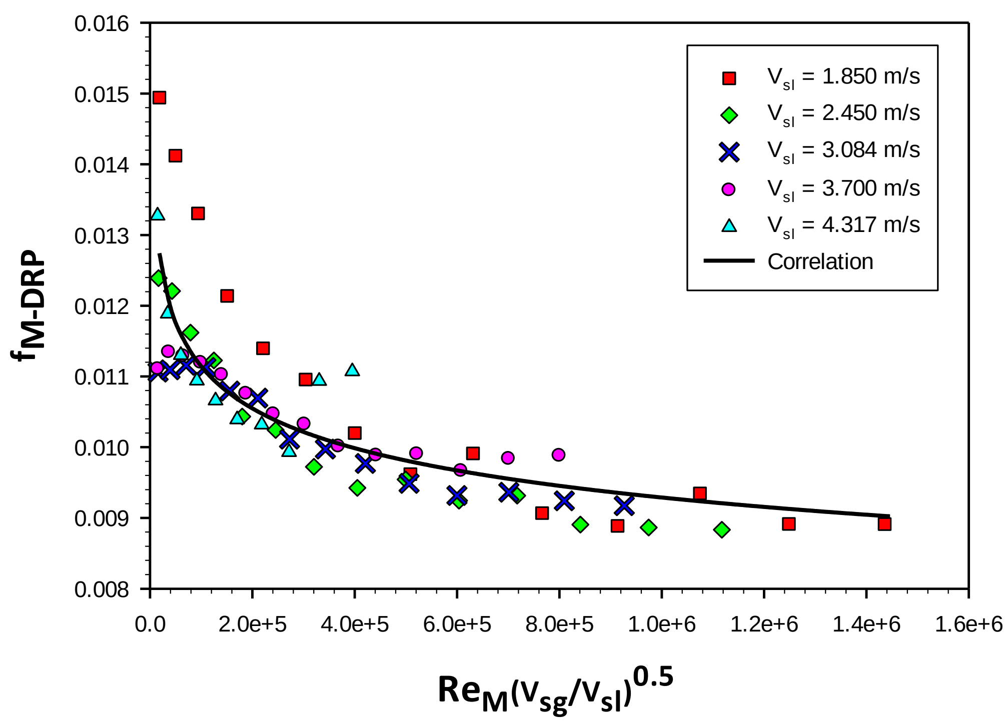

Figure 4.46: Friction factor variation with the mixture Reynolds number times the square root of the superficial velocities ratio for different liquid superficial velocities (1.85, 2.45, 3.08, 3.7 and 4.32 m/s)

Figure 4.47 exhibits the comparison between the measured values of friction factor and the predicted one, however as shown in the plot all scatter data has been predicted within band of $\pm$ 15%, and the correlation for the friction factor can be represented as:

$$f_{(M\text{-}DRP)} = 0.0276\left(\mathrm{Re}_M \left(\frac{V_{sg}}{V_{sl}} \right)^{(0.5)} \right)^{(-0.079)} \qquad (4.10)$$

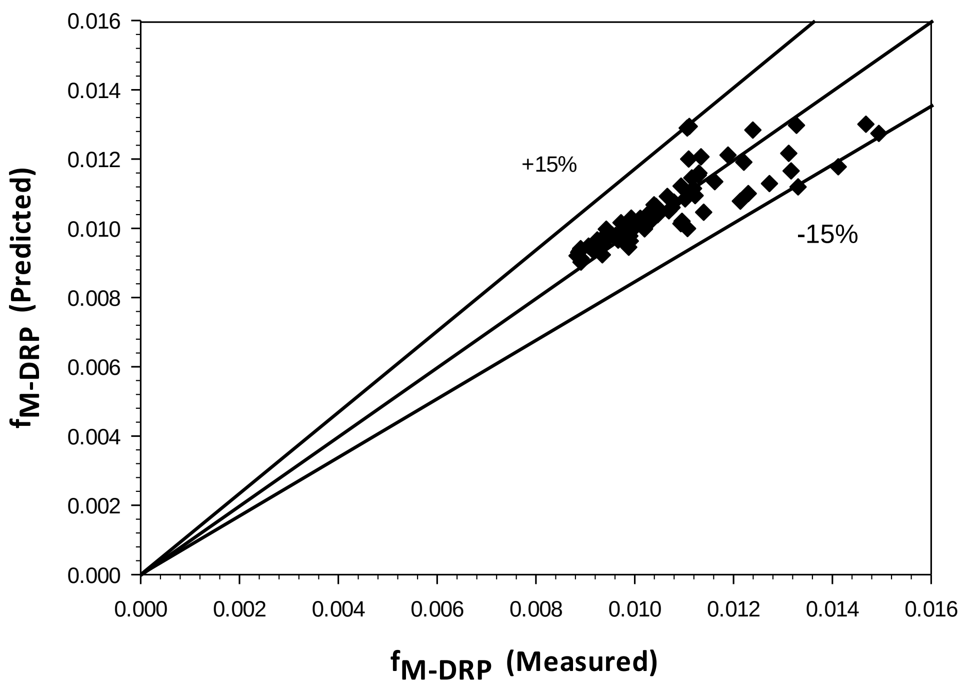

Figure 4.47: Comparison between measured friction factor and predicted by Eq.(4.10).

Using the experimental data we were able to generate another correlation that fits the data points exponentially. Since the frictional pressure drop will increase as more liquid flow rate added to the flow; then it could be more interesting to describe such dimensionless pressure drop that include the frictional pressure gradient when the flow assumed to be liquid only (P_{sl}) and the pressure drop with the addition of the drag reducing polymer (P_{DRP}).

Where P_{sl} defined as:

$$P_{sl} = \frac{f.\rho_l.V_{sl}^{\ 2}}{2D} \tag{4.11}$$

The friction factor (f) is calculated using the below equation:

$$f = 0.184\,\mathrm{Re}_{sl}^{\ -0.2} \tag{4.12}$$

And Re_{sl} is Reynolds number that can be expressed as:

$$\mathrm{Re}_{sl} = \frac{\rho_l.V_{sl}.D}{\mu_l} \tag{4.13}$$

Figure 4.48 presents the relation between the dimensionless pressure drop ratio $\frac{P_{DRP}}{P_{sl}}$ and the normalized superficial velocity $\frac{V_{sg}}{V_{sl}}$ As it can be seen that the superficial gas and liquid velocity are in great impact on the pressure drop ratio and could confirm that it is controlling the drag reduction.

The regression analysis is performed for the data points and as it is seen from figure 4.49 that all the scattered data are in between $\pm 10\%$ spread with correlation goodness of fit ($R^2 = 0.97$). The correlation can be expressed as:

$$\frac{P_{DRP}}{P_{sl}} = (0.5648)\exp\left(0.6456\left(\frac{V_{sg}}{V_{sl}}\right)^{0.5}\right) \tag{4.14}$$

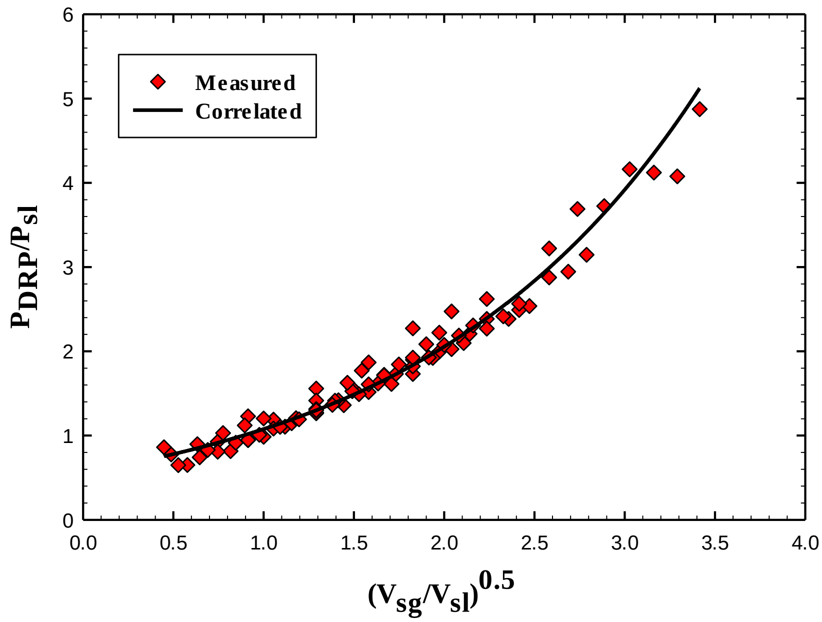

Figure 4.48: Dimensionless pressure drop ratio versus square root of the normalized superficial velocities.

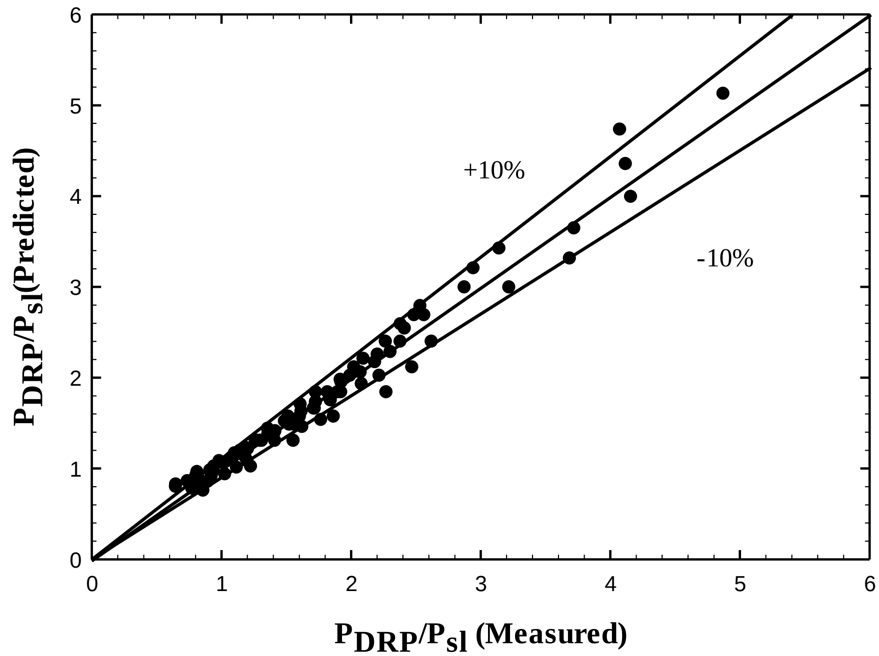

Figure 4.49: Comparison between measured Dimensionless pressure drop ratio and predicted by Eq.(4.14).

Adding the effect of different polymer concentrations injected in the pipeline could also help in predicting how much DRP needed in order to reduce the frictional pressure drop to a certain limit. The correlation which relate the pressure drop after the addition of the DRP ($\mathbf{P_{DRP}}$) with gas and liquid flow rates in addition to the concentration of these additives has been developed using commercial software (Eureqa® by Nutonian-Academic version) by varying the concentration from 28 to 200 ppm.

Figures 4.50-4.56 illustrate this relation at fixed polymer concentration of 200, 100, 66.67, 50, 40, 33.33 and 28.57 respectively, furthermore the comparison between the measured and predicted correlation is performed for the same concentration range. As it can be seen from these figures that the correlation could effectively predicted the pressure drop been measured for a wide range of gas and liquid flow rates.

The correlation formula could be presented as:

$$\frac{P_{DRP}}{P_{sl}} = \left(\frac{Q_g}{Q_l}\right)^{0.416} \left(ppm\right)^{0.000569\, ppm} \qquad (4.15)$$

The most interesting trend in figure 4.57, which sum up all the polymer concentration range in one plot to enable overall comparison of the correlation. It is clearly indicated that the correlation is very effective and useful in estimating the pressure drop that could possibly occurs when the DRP added within concentration range from 28 to 200 ppm.

This effectiveness presented more obviously in figure 4.58, where all the data have been correlated within $\pm 15\%$ and the error matrix can be expressed in the following table:

Mean Absolute Error	0.0947751
Mean square Error	0.0229213
R^2 (Goodness of fit)	0.973897
Correlation coefficient	0.987596
Rank correlation	0.96454
Maximum Error	0.0204
Median Error	0.0667164
Inter-quartile Absolute Error	0.0649
Signed difference Error	0.018
Hybrid correlation Error	0.137
Implicit Dervicative Error	0.763

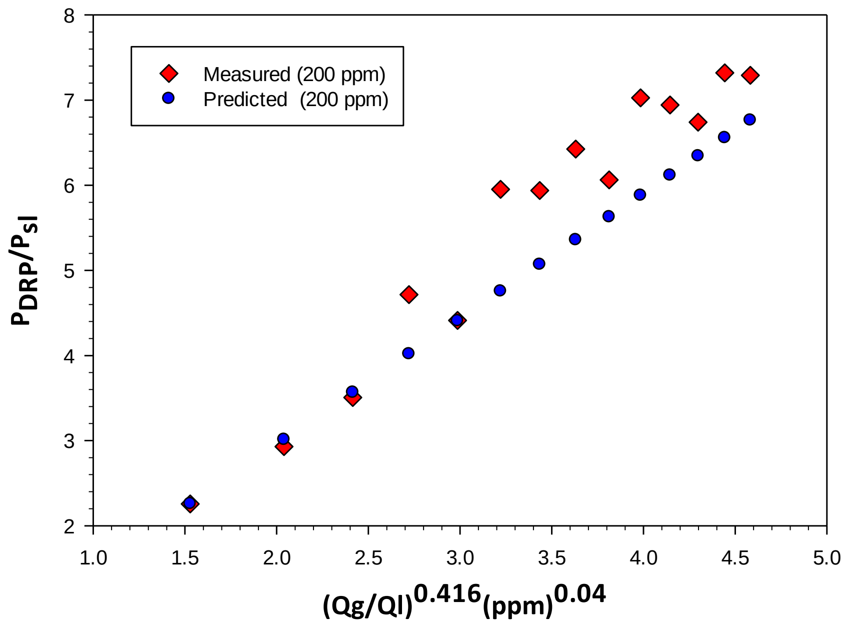

Figure 4.50: Variation of dimensionless pressure drop ratio with flow rate ratio times polymer concentration (ppm) at 200 ppm.

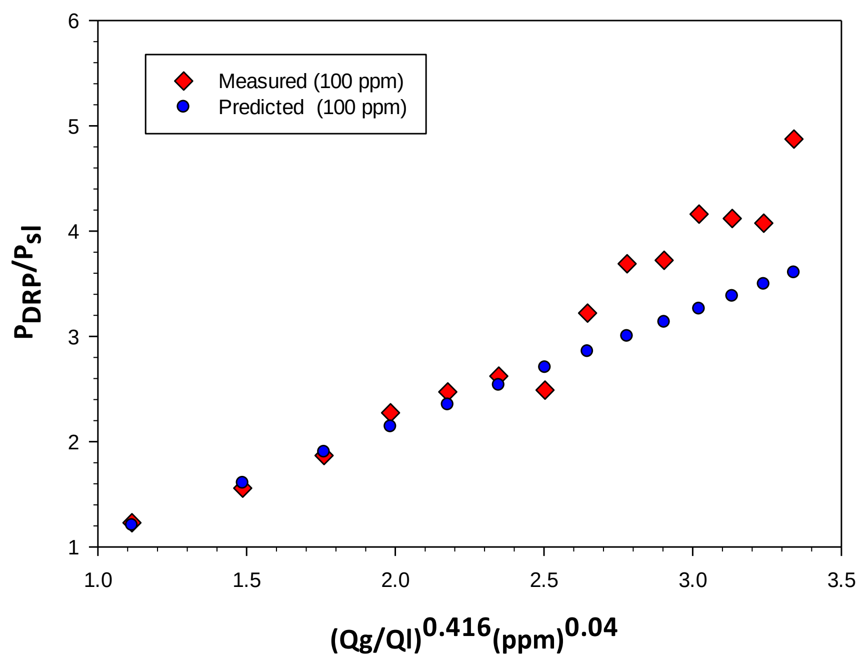

Figure 4.51: Variation of dimensionless pressure drop ratio with flow rate ratio times polymer concentration (ppm) at 100 ppm.

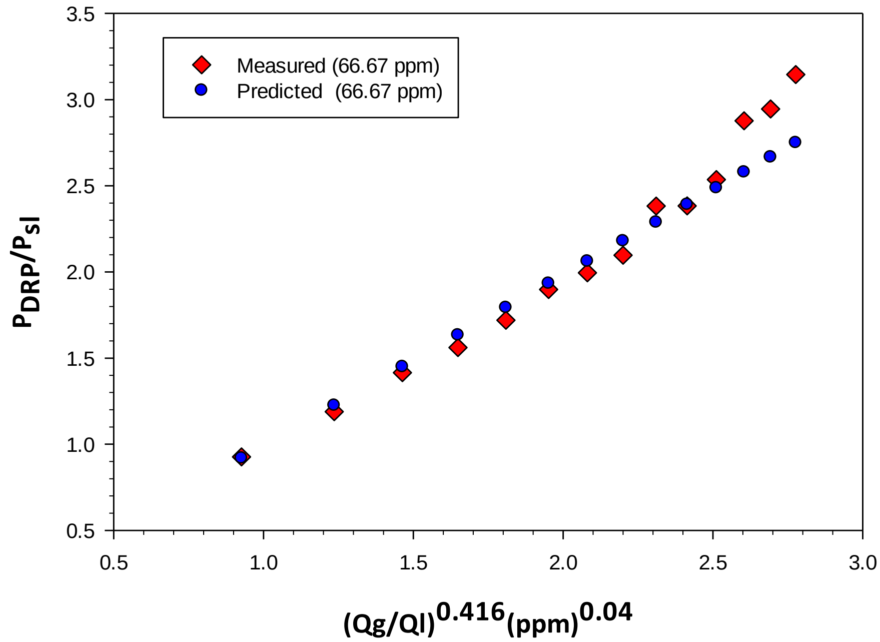

Figure 4.52: Variation of dimensionless pressure drop ratio with flow rate ratio times polymer concentration (ppm) at 66.67 ppm.

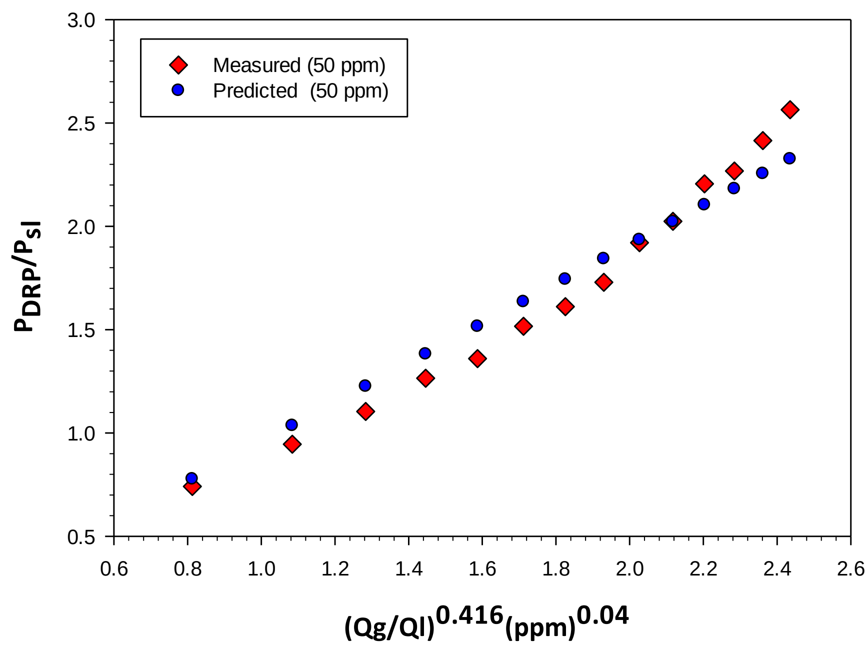

Figure 4.53: Variation of dimensionless pressure drop ratio with flow rate ratio times polymer concentration (ppm) at 50 ppm.

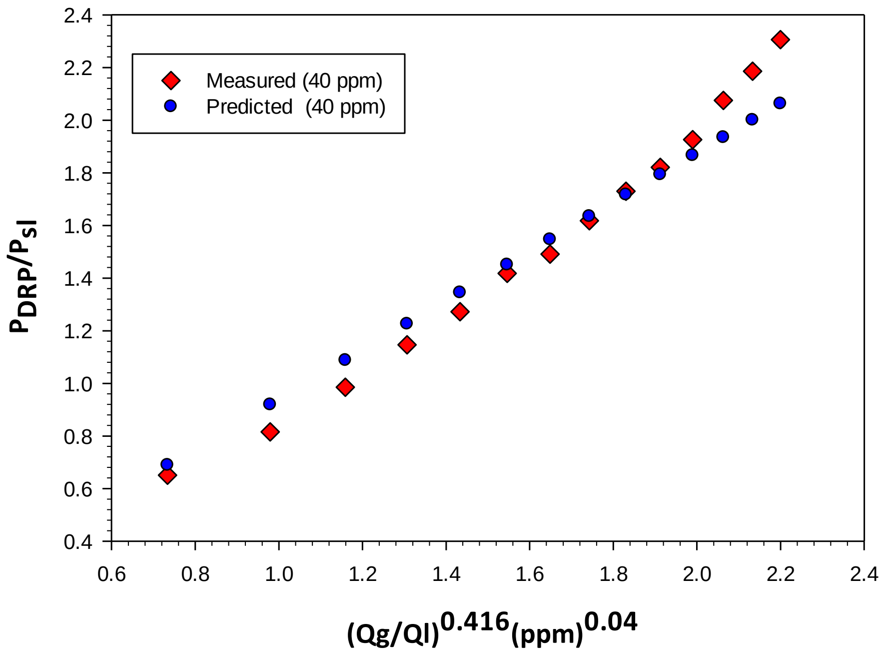

Figure 4.54: Variation of dimensionless pressure drop ratio with flow rate ratio times polymer concentration (ppm) at 40 ppm.

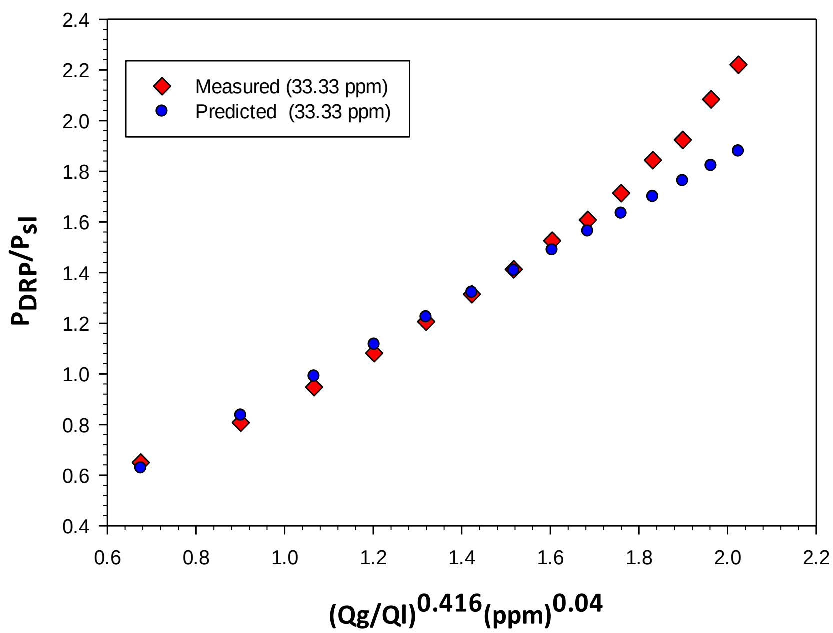

Figure 4.55: Figure 4.47: Variation of dimensionless pressure drop ratio with flow rate ratio times polymer concentration (ppm) at 33.33 ppm.

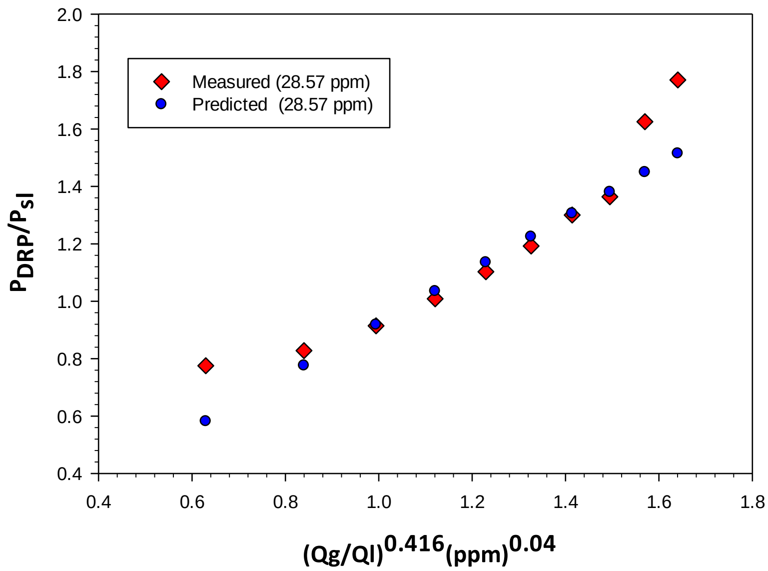

Figure 4.56: Variation of dimensionless pressure drop ratio with flow rate ratio times polymer concentration (ppm) at 28.57 ppm.

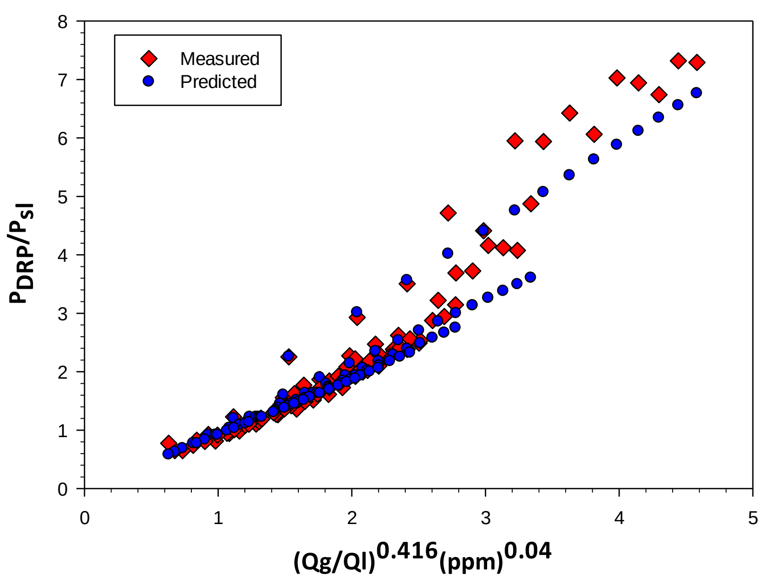

Figure 4.57: Variation of dimensionless pressure drop ratio with flow rate ratio times polymer concentration (ppm) for all concentrations.

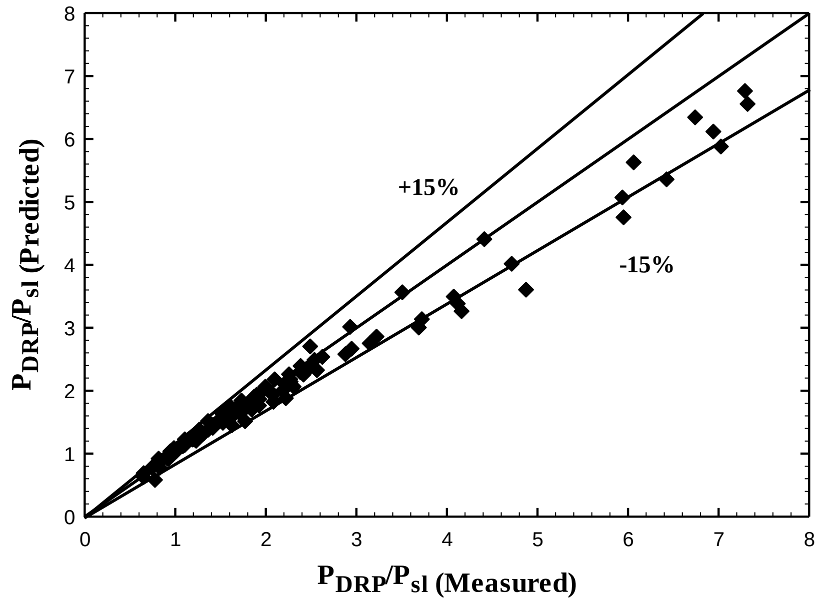

Figure 4.58: Comparison between measured Dimensionless pressure drop ratio and predicted by Eq.(4.15).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

In this chapter valuable findings are presented based on our experimental results and observations. Moreover recommendations for future work are articulated to extend the scope of the research. These conclusions can be displayed as follows:

5.1 Effect of DRP on frictional pressure drop

5.1.1 Single phase water flow

The frictional pressure drop in single flow of water has been reduced dramatically with the injection of Drag Reducing Polymers.

For a fixed flow rate of water as the DRP concentration increases the effectiveness increases accordingly. The maximum Drag Reduction percentage reported was about 45% using only 50 ppm.

5.1.2 Two phase air-water flow

From our observations we can conclude that the Drag Reduction in two phase of air-water mixture occurs at all liquid and gas flow rates. The mechanism is that the DRP lead to suppress the interfacial friction; the polymer solution stretched along the interface to increase laminar sub-layer thickness and result in more unidirectional free of eddies flow.

Utilizing the DRP with low concentrations attributed in pressure drop reduction for all cases been studied, the effectiveness of the DRP varied tremendously from 14% to 80% reported at Stratified and Intermettent flows respectively.

The ability of the Drag Reducing polymers in reducing the frictional pressure has been studied for a wide range of liquid and gas flow rates, the flow rates of the liquid are changed from 3 l/min up to 25 l/min, and for the gas it varied from 5 l/min to 70 l/min.

The DRP is effective in reducing the frictional pressure drop in the two phase air-water mixture, and the effectiveness reduces significantly as the gas flow rate increases for a given liquid flow rate.

5.2 Effect of DRP in flow regime transition

The DRP is more efficient in suppression of highly disturbed waves and found to be able to shift the flow from Slug and Pseudo slug to Stratified wavy and Wavy annular regimes respectively.

In order to produce high Drag Reduction the DRP should be able to damp turbulence intensity and fluctuations. The maximum Drag Reduction always occurs when the highly fluctuated waves were reduced effectively by DRP and accordingly phase transition appeared. For example DR% of 63% is reported when the Slug flow altered to Stratified wavy regime with the presence of only 40 ppm DRP.

5.3 Effect of DRP concentration

Drag Reducing Polymers are acting to stabilize the liquid film and reduce Slug frequency. The effectiveness of this DRP is increases as more ppm is injected and this was clearly observed in the Slug flow regime.

The maximum Drag Reduction reported with utilizing 40 ppm at ($V_{sl} = 0.72$ m/s, $V_{sg} = 0.41$ m/s) was 53% without transition to any different flow pattern. However increasing the concentration more (up to 100 ppm) for the same superficial velocities the maximum DR% increased to 63% and the flow is altered from Slug flow to Stratified wavy regime.

5.4 DRP injection technique

The injection mechanism of the DRP by using a diaphragm pump (gives DRP solution in dosages) has been found very effective without causing any polymer shear degradation. Moreover with an easy adjustable flow rate controller attached to the pump this method of injection can give a reliable way for industrial applications, since it can provide a wide range of flow rates with changeable speeds and torques by which the exact needed amount of polymer solution would be controlled more accurate.

5.5 Correlations

There is a need for generating more realistic empirical correlations for the two phase flow of air-water mixture. The importance of such correlation appears when the Drag Reducing polymers are added to the two phase system in order to broaden the understanding of the reduction mechanism by using general descriptive model.

In the present work the research is shifted towards developing three distinguish correlations that would be very useful in predicting flow parameters with the presence of DRP.

Friction factor correlation as a function of mixture Reynolds number obtained in this study is evaluated and it has been successfully covered a wide range of liquid and gas flow rates (including different flow regimes) and predicted the data effectively within $\pm 15\%$ when it is compared with the measured values.

The pressure drop after the addition of DRP(P_{DRP}) has been predicted using the experimental data, the correlation has been presented as a function of the superficial frictional pressure drop and normalized superficial velocity.

Regression analysis is conducted over a wide range of the experimental data, the correlation effectively predicted the data within $\pm 10\%$ spread with correlation goodness of fit ($R^2 = 0.97$).

The third empirical correlation is the most reliable one for predicting the pressure drop with addition of DRP. Such correlation is not available in the literature and it can estimate the pressure drop as function of polymer concentration added, in addition to liquid and gas flow rates.

The polymer dosage pump has been fixed at 0.6 l/min flow rate, the concentration of DRP is varied from 28 – 200 ppm depending on liquid flow variations (from 3 – 25 l/min).

Moreover correlation validity has been checked at every polymer concentration which shows less discrepancy compared with measured data, all the scatter points is predicted within band of $\pm 15\%$. the detailed statistical analysis is addressed in chapter four.

5.6 Recommendations

Based on the results presented in this study, the following recommendations are made to improve the quality of the data and to extend the scope of the research field:

Flow loop modifications:

a. Inhance the stability and Reducing the pressure fluctuations through well mounted piping flow loop to avoid pipe vibration at high flow rates.
b. The dosage pump gives pulsating flow. It is recommended to use pressurized air for steady fixed polymer flow rates.
c. Using a high speed video camera for better flow pattern identification.

Study the following:

a. Effect of temperature variation on the DRP performance.
b. Different type of DRP should be studied specially with different molecular weight. And the critical molecular weight that has positive effects.
c. Effects of water salinity on the overall performance of the DRP.
d. Effect of DRP on the heat transfer characteristics should be investigated.
e. The effect of the inclination angle on the DRP effectiveness and the possible phase transition with the addition of DRP.

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APPENDIX

V_{sl} (m/s)	V_{sg} (m/s)	dP/dL without (pa/m)	Flow pattern without	dP/dL with (pa/m)	Flow pattern with	ppm
0.62	1.03	2800	Intermittent	1321	Intermittent	200
0.62	2.06	4973	Intermittent	1716	Intermittent	200
0.62	3.08	9913	Intermittent	2053	Intermittent	200
0.62	4.11	9767	Intermittent	2762	Intermittent	200
0.62	5.14	10773	Intermittent	2585	Intermittent	200
0.62	6.17	14053	Intermittent	3486	Intermittent	200
0.62	7.20	13447	Intermittent	3478	Intermittent	200
0.62	8.22	17767	Intermittent	3764	Wavy annular	200
0.62	9.25	17493	Intermittent	3551	Wavy annular	200
0.62	10.28	15000	Intermittent	4115	Wavy annular	200
0.62	11.31	20433	Intermittent	4067	Wavy annular	200
0.62	12.33	14427	Intermittent	3948	Wavy annular	200
0.62	13.36	17913	Intermittent	4288	Wavy annular	200
0.62	14.39	20840	Intermittent	4271	Wavy annular	200

V_{sl} (m/s)	V_{sg} (m/s)	dP/dL without (pa/m)	Flow pattern without	dP/dL with (pa/m)	Flow pattern with	ppm
1.23	1.03	5727	Intermittent	2506	Pseudo slug (with low slug frequency)	100
1.23	2.06	7547	Intermittent	3176	Pseudo slug (with low slug frequency)	100
1.23	3.08	9600	Intermittent	3809	Pseudo slug (with low slug frequency)	100
1.23	4.11	11647	Intermittent	4636	Pseudo slug (with low slug frequency)	100
1.23	5.14	15640	Intermittent	5042	Pseudo slug (with low slug frequency)	100
1.23	6.17	18633	Intermittent	5348	Pseudo slug (with low slug frequency)	100
1.23	7.20	21793	Intermittent	5077	Pseudo slug (with low slug frequency)	100
1.23	8.22	21853	Intermittent	6571	Pseudo slug (with low slug frequency)	100
1.23	9.25	24507	Intermittent	7526	Pseudo slug (with low slug frequency)	100
1.23	10.28	24587	Intermittent	7595	Pseudo slug (with low slug frequency)	100
1.23	11.31	27447	Intermittent	8488	Pseudo slug (with low slug frequency)	100
1.23	12.33	28747	Intermittent	8405	Pseudo slug (with low slug frequency)	100
1.23	13.36	30187	Intermittent	8314	Pseudo slug (with low slug frequency)	100
1.23	14.39	31827	Intermittent	9943	Pseudo slug (with low slug frequency)	100

V_{sl} (m/s)	V_{sg} (m/s)	dP/dL without (pa/m)	Flow pattern without	dP/dL with (pa/m)	Flow pattern with	ppm
1.85	1.03	8260	Dispersed Bubbly	3919	Pseudo slug	67
1.85	2.06	10400	Dispersed Bubbly	5029	Pseudo slug	67
1.85	3.08	13320	Dispersed Bubbly	5990	Pseudo slug	67
1.85	4.11	15593	Intermittent	6609	Pseudo slug (with low slug frequency)	67
1.85	5.14	17320	Intermittent	7280	Pseudo slug (with low slug frequency)	67
1.85	6.17	18647	Intermittent	8033	Pseudo slug (with low slug frequency)	67
1.85	7.20	22953	Intermittent	8442	Pseudo slug (with low slug frequency)	67
1.85	8.22	23247	Intermittent	8873	Pseudo slug (with low slug frequency)	67
1.85	9.25	31307	Intermittent	10083	Pseudo slug (with low slug frequency)	67
1.85	10.28	28433	Intermittent	10085	Annular	67
1.85	11.31	28840	Intermittent	10731	Annular	67
1.85	12.33	29213	Intermittent	12174	Annular	67
1.85	13.36	32013	Intermittent	12464	Annular	67
1.85	14.39	31540	Intermittent	13311	Annular	67

V_{sl} (m/s)	V_{sg} (m/s)	dP/dL without (pa/m)	Flow pattern without	dP/dL with (pa/m)	Flow pattern with	ppm
2.47	1.03	12147	Dispersed Bubbly	5261	Pseudo slug	50
2.47	2.06	14647	Dispersed Bubbly	6711	Pseudo slug	50
2.47	3.08	17047	Dispersed Bubbly	7843	Pseudo slug	50
2.47	4.11	19253	Dispersed Bubbly	8984	Pseudo slug	50
2.47	5.14	22700	Intermittent	9661	Pseudo slug (with low slug frequency)	50
2.47	6.17	23433	Intermittent	10772	Pseudo slug (with low slug frequency)	50
2.47	7.20	24967	Intermittent	11447	Annular	50
2.47	8.22	26440	Intermittent	12284	Annular	50
2.47	9.25	29327	Intermittent	13643	Annular	50
2.47	10.28	29600	Intermittent	14381	Annular	50
2.47	11.31	31907	Intermittent	15669	Annular	50
2.47	12.33	32307	Intermittent	16108	Annular	50
2.47	13.36	34280	Intermittent	17154	Annular	50
2.47	14.39	37713	Intermittent	18213	Annular	50

V_{sl} (m/s)	V_{sg} (m/s)	dP/dL without (pa/m)	Flow pattern without	dP/dL with (pa/m)	Flow pattern with	ppm
3.08	1.03	15480	Dispersed Bubbly	6905	Pseudo slug	40
3.08	2.06	18713	Dispersed Bubbly	8659	Pseudo slug	40
3.08	3.08	21100	Dispersed Bubbly	10456	Pseudo slug	40
3.08	4.11	23553	Dispersed Bubbly	12171	Pseudo slug	40
3.08	5.14	25847	Dispersed Bubbly	13500	Pseudo slug	40
3.08	6.17	27920	Dispersed Bubbly	15050	Pseudo slug	40
3.08	7.20	29287	Dispersed Bubbly	15823	Pseudo slug	40
3.08	8.22	31280	Dispersed Bubbly	17172	Pseudo slug	40
3.08	9.25	32067	Dispersed Bubbly	18359	Pseudo slug	40
3.08	10.28	33680	Dispersed Bubbly	19323	Pseudo slug	40
3.08	11.31	35080	Intermittent	20441	Annular	40
3.08	12.33	36607	Intermittent	22022	Annular	40
3.08	13.36	37787	Intermittent	23196	Annular	40
3.08	14.39	41200	Intermittent	24471	Annular	40

V_{sl} (m/s)	V_{sg} (m/s)	dP/dL without (pa/m)	Flow pattern without	dP/dL with (pa/m)	Flow pattern with	ppm
3.70	1.03	19480	Dispersed Bubbly	9566	Pseudo slug	33
3.70	2.06	22667	Dispersed Bubbly	11897	Pseudo slug	33
3.70	3.08	25507	Dispersed Bubbly	13961	Pseudo slug	33
3.70	4.11	27493	Dispersed Bubbly	15946	Pseudo slug	33
3.70	5.14	29647	Dispersed Bubbly	17777	Pseudo slug	33
3.70	6.17	31767	Dispersed Bubbly	19371	Pseudo slug	33
3.70	7.20	33460	Dispersed Bubbly	20819	Pseudo slug	33
3.70	8.22	35093	Dispersed Bubbly	22481	Pseudo slug	33
3.70	9.25	36680	Dispersed Bubbly	23691	Pseudo slug	33
3.70	10.28	38200	Dispersed Bubbly	25249	Pseudo slug	33
3.70	11.31	39193	Intermettent	27166	Annular	33
3.70	12.33	41120	Intermettent	28345	Annular	33
3.70	13.36	42740	Intermettent	30705	Annular	33
3.70	14.39	44793	Intermettent	32713	Annular	33

V_{sl} (m/s)	V_{sg} (m/s)	dP/dL without (pa/m)	Flow pattern without	dP/dL with (pa/m)	Flow pattern with	ppm
4.32	1.03	24273	Dispersed Bubbly	15078	(-)	28
4.32	2.06	27400	Dispersed Bubbly	16108	(-)	28
4.32	3.08	30907	Dispersed Bubbly	17785	(-)	28
4.32	4.11	32767	Dispersed Bubbly	19614	(-)	28
4.32	5.14	34387	Dispersed Bubbly	21449	(-)	28
4.32	6.17	36207	Dispersed Bubbly	23187	(-)	28
4.32	7.20	38033	Dispersed Bubbly	25290	(-)	28
4.32	8.22	39780	Dispersed Bubbly	26523	(-)	28
4.32	9.25	41287	Dispersed Bubbly	31611	(-)	28
4.32	10.28	43187	Dispersed Bubbly	34432	(-)	28
5.14	1.03	31167	Dispersed Bubbly	22906	(-)	24
5.14	2.06	34353	Dispersed Bubbly	23884	(-)	24
5.14	3.08	38247	Dispersed Bubbly	27406	(-)	24
5.14	4.11	40607	Dispersed Bubbly	29813	(-)	24
5.14	5.14	42347	Dispersed Bubbly	32019	(-)	24

40 ppm					
V_{sl} (m/s)	V_{sg} (m/s)	dP/dL without (pa/m)	Flow pattern without	dP/dL with (pa/m)	Flow pattern with
0.1	0.41	613	Stratified	400	Stratified
0.1	0.51	667	Stratified	467	Stratified
0.1	0.62	760	Stratified	600	Stratified
0.1	0.72	800	Stratified	687	Stratified
0.1	0.82	880	Stratified	733	Stratified
0.1	0.93	1160	Stratified - Slug	800	Stratified wavy
0.1	1.03	1200	Stratified - Slug	933	Stratified wavy
0.1	1.64	1800	Slug	667	Stratified wavy
0.1	2.06	1933	Slug	800	Stratified wavy
0.1	2.47	2467	Slug	1000	Stratified wavy
0.1	2.88	3000	Stratified wavy	1067	Stratified wavy
0.1	3.7	1467	Stratified wavy	667	Stratified wavy
0.1	4.11	1667	Stratified wavy	733	Stratified wavy
0.1	4.52	1800	Annular	867	Stratified wavy
0.1	4.93	1867	Annular	867	Stratified wavy
0.1	5.34	2000	Annular	1000	Stratified wavy

40 ppm					
V_{sl} (m/s)	V_{sg} (m/s)	dP/dL without (pa/m)	Flow pattern without	dP/dL with (pa/m)	Flow pattern with
0.1	7.2	1467	Annular	773	Stratified wavy
0.1	7.81	1533	Annular	800	Stratified wavy
0.1	8.43	1600	Annular	867	Stratified wavy
0.1	9.05	1800	Annular	1000	Stratified wavy
0.1	9.66	1867	Wavy Annular	1133	Stratified wavy
0.1	10.28	2000	Wavy Annular	1267	Stratified wavy
0.1	10.9	2067	Wavy Annular	1400	Stratified wavy
0.1	11.51	2133	Wavy Annular	1467	Stratified wavy
0.1	12.13	2400	Wavy Annular	1640	Stratified wavy
0.1	12.75	2667	Wavy Annular	1713	Stratified wavy
0.72	0.41	2133	Slug	1000	Slug
0.72	0.51	2267	Slug	1533	Slug
0.72	0.62	2400	Slug	1733	Slug
0.72	0.72	2467	Slug	1933	Slug
0.72	0.82	2667	Slug	2133	Slug
0.72	0.93	3000	Slug	2200	Slug
0.72	1.03	3133	Slug	2333	Slug
0.72	1.13	3333	Slug	2467	Slug
1.03	1.03	4000	Pseudo Slug	2667	Wavy Annular
1.03	2.06	5667	Pseudo Slug	3333	Wavy Annular
1.03	3.08	7333	Pseudo Slug	4333	Wavy Annular
1.03	4.11	8467	Pseudo Slug	6400	Pseudo Slug
1.03	5.14	9800	Pseudo Slug	7067	Pseudo Slug
1.03	6.17	10800	Pseudo Slug	8000	Pseudo Slug

100 ppm					
V_{sl} (m/s)	V_{sg} (m/s)	dP/dL without (pa/m)	Flow pattern without	dP/dL with (pa/m)	Flow pattern with
0.72	0.41	2133	Slug	733	Stratified wavy
0.72	0.51	2267	Slug	933	Stratified wavy
0.72	0.62	2400	Slug	1067	Stratified wavy
0.72	0.72	2467	Slug	1067	Stratified wavy
0.72	0.82	2667	Slug	1067	Stratified wavy
0.72	0.93	3000	Slug	1267	Stratified wavy
0.72	1.03	3133	Slug	1400	Stratified wavy
0.72	1.13	3333	Slug	1667	Stratified wavy
1.03	1.03	4000	Pseudo Slug	2667	Wavy Annular
1.03	2.06	5667	Pseudo Slug	3333	Wavy Annular
1.03	3.08	7333	Pseudo Slug	4333	Wavy Annular
1.03	4.11	8467	Pseudo Slug	6400	Pseudo Slug
1.03	5.14	9800	Pseudo Slug	7067	Pseudo Slug
1.03	6.17	10800	Pseudo Slug	8000	Pseudo Slug

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