CHARACTERIZATION OF TWO PHASE FLOW IN A HORIZONTAL AND INCLINED 4-INCH PIPE

BY

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This thesis, written by **Muhammad Mudasar Imam** under the direction of his thesis advisor and approved by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE in MECHANICAL ENGINEERING**.

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بسم الله الرحمن الرحيم

Dedicated to my parents, my brothers and my sisters

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In the Name of Allah, the Most Beneficent, the Most Merciful.

> Praise belongs to Allah, the Lord of all the worlds (2) The All-Merciful, the Very-Merciful. (3) The Master of the Day of Requital. (4) You alone do we worship, and from You alone do we seek help. (5) Take us on the straight path (6) The path of those on whom You have bestowed Your Grace, Not of those who have incurred Your wrath, nor of those who have gone astray. (7)
>
> Al-Fatiha

I begin with the name of Allah, the most beneficent, the most merciful. May Allah bestow peace on our beloved Prophet Mohammed (*peace and blessings of Allah be upon him*), and his family. I would not have able to complete this work without the help of Allah who endowed me with health, courage, aptitude and patience.

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THESIS ABSTRACT (ENGLISH)

NAME:	Muhammad Mudasar Imam
TITLE:	Characterization of Two Phase Flow in a Horizontal and Inclined 4-inch Pipe
MAJOR FIELD:	MECHANICAL ENGINEERING
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Pressure gradient data are presented for air-water flow in a horizontal and inclined 0.1016 m i.d. pipe (stainless steel,14 m length and pipe inclinations of 0°,15°,30°,-15°and -30°).The pipe inclination was varied from 0 to 30° and the flow rates of each phase were varied over wide ranges. The objective of this work was to measure the pressure drop in a horizontal and inclined pipe and investigate the effect of upward and downward inclination on the pressure gradient. The pressure gradients were investigated for the air-water two-phase flow at different flow conditions in a horizontal and inclined pipe. Experimental measurements were obtained for various pipe inclinations. The total average pressure drop data crossed over the horizontal data from higher to lower values at water velocity range 1.5-2.5 m/s. Below this range the horizontal pipe gave the lowest pressure drop while above this range the upwardly inclined pipe gave the lowest pressure drop. A pressure loss minimum occurred at VSW=2.1 m/s for upward flows. Below VSW=2.1 m/s the pressure loss for downward flows was virtually dependent of water flow rates being mainly due to hydrostatic head. As the water flow rates increases above this value there was very little effect of inclination on the pressure drop.

ABSTRACT (ARABIC)

ملخص الرسالة

الاسم: **محمدمدثر إمام**

عنوان الرسالة: : توصيف التدفق ثنائي المرحلة في الأنابيب 4 بوصة الأفقية و المائلة

التخصص العام: **الهندسة الميكانيكية**

تأريخ لتخرج: مايو 2014

تستعرض الدراسة بيانات الضغط المتدرجة لتدفق الهواء والماء في أنابيب أفقية ومائلة ذات قطر داخلي 0.1016 م (أنابيب من الفولاذ المقاوم للصدأ بطول 14 م وزوايا ميل 0°، 15°، 30°، -15° و -30°). وقد تباينت زوايا ميل الأنابيب من 0-30 درجة ومن ثم تفاوتت معدلات التدفق لكل مرحلة بدرجات كبيرة. وقد كان الهدف من هذا البحث هو قياس انخفاض الضغط في الأنابيب الأفقية والمائلة، ودراسة تأثير الميل صعودا وهبوطا على تدرج الضغط. وقد تم دراسة تدرجات الضغط لتدفقالمياه والهواء ثنائي المرحلة في ظل ظروف تدفق مختلفة في الأنابيب الأفقية والمائلة. وتم الحصول على القياسات التجريبية لمختلف درجات ميول الأنابيب. وقد تجاوزإجمالي بيانات متوسط انخفاض الضغط البيانات الأفقية من قيم أعلى إلى أدنى في ظل سرعة مياه 2.5-1.5 /ث.أما في ظل سرعات دون هذا النطاق المحدد فقدأظهرت الأنابيب الأفقية أدنى انخفاض في الضغط، في حين أنه في ظل سرعات المياه الأكبر من هذا النطاق أظهرت الأنابيب المائلة للأعلى أدنى انخفاض في الضغط. وظهر الحد الأدنى من انخفاض الضغط في التدفقات التصاعديةعندVSW=2.1 م / ث،ودون هذه القيمة كان فاقد الضغط في التدفقات الهابطة يعتمد فعلياعلى معدلات تدفق الماء ويرجع ذلك بشكل أساسي إلى الارتفاع الهيدروستاتيكي . ومع زيادة معدلات تدفق المياه عن هذه القيمة يصبح تأثير درجة الميل على انخفاض الضغط ضئيل جدا.

CHAPTER 1 **INTRODUCTION**

1.1 BACKGROUND

The term multiphase flow was coined by the late Prof. Soo of the University of Illinois in 1965 and includes fluid dynamics motion of various phases. Multiphase flow can be referred to as the flow of more than one phase through a channel or pipe at the same time. The different phases are distributed in the pipe and they affect each other in different ways which makes it very difficult to accurately predict the flow behavior of multiphase flow. Two phase flow is the simplest case of multiphase flow and two-phase flow is a difficult subject principally because of the complexity of the form in which the two fluids exist inside the pipe, known as the flow regime. For example, a flow of steam and water is a two-phase flow with a single component, while an air-water flow is a two-phase/two component flow.

In the process of oil production from older wells, brine and carbon dioxide gas are commonly present in the pipelines. These oil, water, and gas mixtures can create a highly corrosive environment for typical carbon steel pipelines. To compound the problem, the oil wells are often at remote locations forcing this corrosive mixture to be transported many miles before it can be separated. During this transport, the multiphase mixture travels through numerous changes of inclination which affects the flow pattern and flow characteristics. This can further enhance the corrosion because in oil and gas production, the factors determining the corrosion conditions include temperature, pressure, chemical compositions of the fluids, state of metal surface, flow rates, and flow regimes. While it is relatively easy to reproduce temperature, pressure or chemistry of the fluids in laboratory tests, other parameters are more difficult to simulate, like the exact nature of the flow and the intermittent fluctuations in the flow. It is important to quantify the corrosivety of multiphase flow, under varying conditions, so effective corrosion control can be achieved. Corrosion inhibitors work by either adsorbing to the metal pipe surfaces or by reacting with corrosion products to form a protective layer. These inhibitors are added in either a batch or continuous process. Currently, corrosion inhibitors are not working well for slug flow conditions.

Corrosion inhibitors play an important role in preventing internal corrosion in carbon steel pipelines that transport mixture of oil, water, natural gas and carbon dioxide gas. The successful selection of inhibitors depends on a clear understanding of the operational conditions, fluid properties, solution pH and chemistry, and flow conditions. Fluid conditions include flow velocity and water cuts.

1.2 TERMENOLOGIES OF MULTIPHASE FLOW

1.2.1 Flow patterns

An important distinction in single phase flow is whether the flow is laminar or turbulent, or whether flow separation exists. This helps in modeling specific phenomena because one has an indication of the flow character for a particular geometry. Analogously in multiphase flow probably the key toward understanding the phenomena is the ability to identify the internal geometry of the flow; i.e. the relative location of interfaces between the phases, how they are affected by pressure, flow, heat flux and channel geometry, and how transitions between the flow patterns occur. Flow patterns are identified by visual inspection, for some of the simpler flows, such as those in vertical or horizontal pipes, a considerable number of investigations have been conducted to determine the dependence of the flow pattern on volume fraction, component volume fluxes, and the fluid properties such as density, surface tension and viscosity.

The boundaries between the different flow patterns in a flow pattern map happen because a regime becomes unstable as the boundary is approached and surge of this instability causes transition to another flow pattern. Like the laminar-to-turbulent transition in single phase flow, these multiphase transitions can be rather unforeseeable since they may depend on otherwise minor features of the flow, such as the roughness of the walls or the entrance conditions. Hence, the flow pattern boundaries are not characteristic lines but more poorly defined transition zones. But there are other serious difficulties with most of the existing literature on flow pattern maps. One of the basic fluid mechanical problems is that these maps are often dimensional and therefore apply only to the specific pipe sizes and fluids properties.

In single phase flow it is well established that an entrance length of 30 to 50 diameters is necessary to establish fully developed turbulent pipe flow. For multiphase flow the corresponding entrance lengths patterns are less well established and it is quite possible that some of the reported experimental observations are for temporary or developing flow patterns. There remain many challenges associated with an understanding of flow patterns in multiphase flow and notably research is necessary before reliable design tools become available.

1.2.2 Flow pattern classifications

One of the most fundamental characteristics of a multiphase flow pattern is the extent to which it involves separation of the phases or components mean separation of the different phases is very important as in case of slug flows the separation is not easy andAt the two ends of the spectrum of separation characteristics are those flowpatterns that are termed disperse and those that are termed separated. The flow patterns in horizontal pipes are shown in Figure 1.1. One of the basic characteristics of a flow pattern is the degree of separation of the phases into stream tubes of different concentrations. The degree of separation is actually the separation of phases at the end of the loop that how these phases are separated. The degree of separation will, in turn, be determined by (a) some balance between the fluid mechanical processes enhancing dispersion and those causing segregation, or (b) the initial conditions or mechanism of generation of the multiphase flow. A second basic characteristic that is useful in classifying flow patterns is the level of intermittency in the volume fraction. Examples of intermittent flow patterns are slug flows in both vertical and horizontal pipe flows. The first separation characteristic was the degree of separation of the phases between stream tubes; this second, intermittency characteristic, can be viewed as the degree of periodic separation in the stream wise direction.

A disperse flow pattern is one in which one phase or component is widely distributed as drops, bubbles, or particles in the other continuous phase. On the other hand, a separated flow consists of separate, parallel streams of the two phases. Annular flow is a multiphase flow regime in which the lighter fluid flows in the center of the pipe, and the heavier fluid is contained in a thin film on the pipe wall. Churn flow also referred to as froth flow is a highly disturbed flow of gas and liquid. Wavy flow is one when a gas and a liquid flow together in parallel streams, the interface between them are flat at low gas velocities.

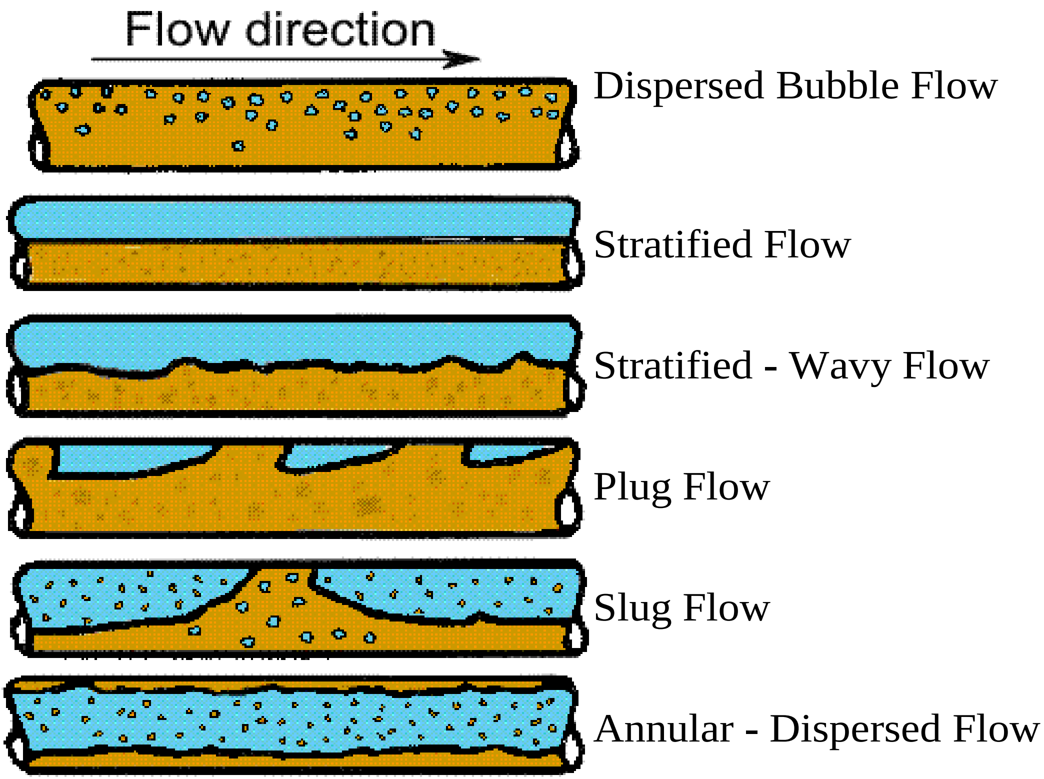

Figure 1.1:- Flow patterns in Horizontal pipes[1]

1.2.3 Inclined pipe flow

When the pipe is oriented vertically, the regimes of gas-liquid flow are a little different as shown in Figure 1.2. The flow regimes occurring in vertical are similar to those in horizontal pipes, but one difference being that the there is no lower side of the pipe which the densest fluid. One of the implications this has is that stratified flow is not possible in vertical pipes. Most of the published measurements have been carried out on horizontal and vertical pipes. Pipelines generally follow the terrain and most often have other inclinations, so the complexity is often larger than illustrated here. In an inclined pipe when the angle is increased, the gravity forces acting on the liquid become important causing an increase or decrease in the velocity of the liquid depending on the direction of flow. This behavior causes an increase or decrease in the slip and void fraction parameter for similar conditions, directly affecting the pressure drop. Knowledge of the flow pattern developed is very important in order to evaluate the pressure drop correctly.

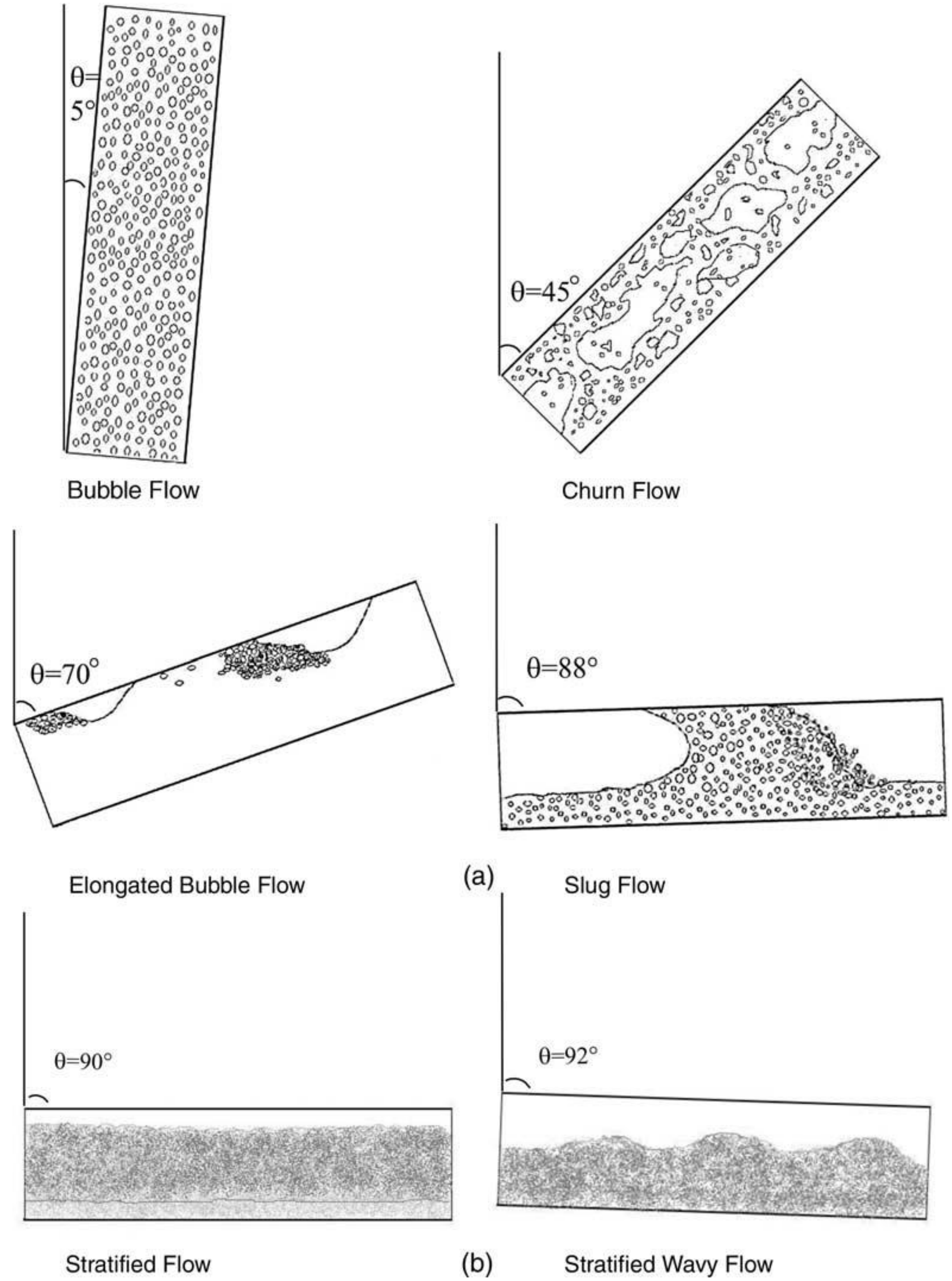

Figure 1.2:- Flow pattern in inclined pipes[2]

1.3 THESIS STRUCTURE

The thesis is divided into four (5) chapters. Chapter 1 includes introduction and project objectives. It also includes background information and methodology about multiphase flow, research motivation and thesis objectives. Chapter 2 includes the literature review presents briefly some researches carried out in the field of air-water two phase flows as it relates to flow patterns and pressure drop.Chapter 3 outlining the experimental setup and test procedure. It also include with the uncertainty analysis. It considers all the term related to multiphase flow that must be known while chapter 4 include results and discussion and all the graphs of the experimental work. Chapter 5 presents the conclusions and recommendations. It discusses the outcome of the research and the recommendations resulting from the present work.

1.4 THESIS OBJECTIVES AND METHODOLOGY

The objective of this research work is to investigate the characteristics of air-water two phase flows in horizontal and inclined pipe. Specifically, the inclination effect on the pressure drops at different flow conditions was investigated. Water cut effect on the pressure gradient for horizontal, upward and downward flows was also observed. For this purpose first flow in horizontal pipes was run and measured the pressure drop then all procedure is repeated until all experiments were done.

CHAPTER 2 LITRATURE REVIEW

2.1 REVIEW AND SUMMARY

The objective of this literature review is to understand the existing work pertaining to two-phase flow classification and prediction in gas-liquid flow with particular focus on pipes flows. No studies to date have addressed the two phase flow with so much detail and wide range of data.

Kokal and Stanislav[3] used 25 m long acrylic pipe to conduct experiments of air-oil two phase flows. They concluded that pressure gradient and holdup are flow pattern dependent. Both upward and downward pipelines were used to conduct the experiments and concluded that for upward flow intermittent is dominant flow regime and for downward flow stratified flow is dominant regime. A separated flow model for stratified flow and for dispersed flow, homogenous model is proposed to calculate the pressure drop for inclined pipes.

Stanislav et al.[4] calculated the pressure drop and liquid holdup for intermittent two phase flow in upward inclined pipes and flow patterns were investigated. Then they compared their experimental values of pressure drops with the values calculated from Taitel and Duckler theory and results showed a good agreement.

Taitel and Duckler[5] proposed simplified model of stratified two phase flow to predict non-unique values of liquid holdup in upward inclined pipeline. Landman et al [6] showed that flow with the lowest holdup is more stable predicted by separated flow model. The highest equilibrium is unstable and the intermittent equilibrium can be stable or unstable.

Experiments were conducted by Spedding and Spence [7] on 0.0935 m inner diameter horizontal pipeline. Data was collected for co-current air-water flow and data of pressure drop and holdup was also collected and high speed camera was used to visualize the flow pattern in the pipeline. All these experiments were done on 0.0454 m inner diameter pipe. The results together were used to test existing flow maps and found that many flow patterns did not predicted correctly thus they showed that there is a need to develop a more satisfactory method of phase transition predictions.

Hashizume[8] investigated the two phase flow in a horizontal pipeline and data was obtained for flow pattern, void fraction and pressure drop. The data was tabulated and presented graphically. A large data was necessary to clarify the range of applicability of these correlations.

Two phase flow in pipeline in mountain terrains was considered by Sanchez and Alvarez [9].They conducted this study because pipe design must be taken into account for all inclinations in order to minimize the error in sizing. Operation of these pipelines depends on accurate prediction of flow patterns. Data was obtained and compared with the existing models and the results showed a good agreement with the homogenous drift model.

MARS (modified apparent rough surface) model was presented by Grolman and Fortuin[10] . With this model pressure drop and holdup for two phase flow in horizontal and inclined pipes was predicted. They also considered the interfacial friction factor. Then 2400 experimental data points were collected to measure the pressure drop and liquid holdup. Then these two were compared with the existing ones to validate these models. In this work pipe used having inner diameter 51 mm and liquid holdup range used was 0 to 0.42. The average error of pressure gradient and holdup was found that was less than 10 percent which showed a good agreement between the experimental the theoretical results.

Spedding et al.[11] conducted experiments with 0.058 m inner diameter pipe having +5 to -5 inclination. Two phase air and water co-current flow was considered. Flow regimes were predicted and compared with the existing models and flow patterns found to be inadequate. In upward flow large liquid holdup rates occurred and lowest liquid holdup rates occurred for downward flow and the concluded that flow pattern highly affect the liquid holdup.in this work pressure gradient was also successfully predicted.

Experiments were done on inclinable steel pipe 15 m long, 8.28 cm diameter by Rodriguez and Oliemans[12]. They used the oil-water two phase flows to get the data for large range of flow rates and inclination for pressure gradient, holdup and flow pattern.

Melkam et al.[13] conducted experiments for two and three phase flow in horizontal and inclined pipeline.2845 data points were obtained then compared the 68 void fraction correlation based on these data points. After comparison of these data points recommendations were drawn. This study showed that many correlations developed are restricted to a wide variety of data sets. They suggested a very accurate and improved void fraction correlation.

Grassi et al.[14] proposed a model for two phase flow to predict the features of the flow pattern.to validate this model they conducted a series of experiments. They measured the pressure drop and flow pattern for two phase flow in horizontal and incline pipe. The theoretical and experimental data have been compared in this study. A satisfactory agreement was observed especially for pressure gradient comparison.

A series of experiments were done on two phase flow in horizontal pipeline by Cole et al.[15].in this study gas wall, liquid wall and interfacial friction factor were predicted. Then compared their data with the reliable data obtained under a wide range of conditions. To validate the Liquid wall friction factor proved to be more difficult.

Two phase flow experiments were done by Rodriguez and Baldani and Kawaji et al.[16][17]to predict the pressure gradient and liquid holdup in inclined pipe. The pipe used having inner diameter 0.026 m and 15.5 m in length. High viscosity oil was used with the water to conduct these experiments .in this work they suggested a closure relationship for interfacial friction factor .they observed that friction factor is low for slower lighter phase than single phase friction factor. The data used to validate the phenomenological model. The comparison showed a favorable agreement.

The study of mechanistic method was developed by Heydari andSadeghi[18] to calculate the pressure drop and liquid holdup for three phase flow. Then they compared their data with this model that shows a good agreement. They also considered the effect of liquid and gas velocities

Foletti et al.[19] did an experimental study on two phase flow in horizontal pipe having inner diameter 22 mm. First they predicted the flow pattern for air-water flow and air-oil flow. From these predictions they concluded that flow pattern heavily dependent on fluid properties and pipe diameter. Experimental flow patterns then compared with theoretical flow maps and the result showed a poor agreement. Similarly pressure drops were also measured and compared. The comparison again showed a poor agreement.

Experiments were conducted for two phases flow by Xiao-Xuan[20] in horizontal pipelines. In this work flow pattern and its transition is observed. Then pressure gradients were measured for this two phase flow. This work concluded that flow pattern; pressure gradient and phase inversion has great impact on the design and working of oil-water flow system.

Angeli and Hewitt [21] conducted an experimental study using low viscosity oil and water in a 1 inch inner diameter horizontal pipe made of stainless steel and its test section made of acrylic resin. Pressure drops were calculated for 0 to 100 percent water cut. Results showed a large difference for the respective tube material this is due to the wettability characteristics. They also concluded that there is a peak in pressure gradient during phase inversion.

Pressure gradient correlations for separated flow in a horizontal pipe were developed by Al-Wahaibi[22].In the study work of Angeli and Hewitt [23] work is extended. Then they validate these correlations against 11 pressure drops data sources. This study claimed that it is the first one that published for two phase flow with such a wide range of database. A reasonable agreement was shown between the predicted and measured pressure gradient. Percentage error and standard deviation was calculated to prove this argument.

Spedding et al.[23] obtained the data for two phase pipe flow and correlations were tested against this data. Two phase flow patterns were considered were stratified and annular flows. When these correlations used against the three phase gas-oil-water flows they predicted for slug type flow.

Experiments on two phase air-water were conducted in vertical pipeline by Spedding et al.[24]. Pipe diameter used have diameter 0.026 m and maximum value of pressure drops observed at the end of the churn flow and the lowest value was observed at the end of the annular ripple and slug flow regimes. The main finding of this work was that pipe diameter highly affects the pressure gradient. They concluded that to predict bubble flow low gas rates are required and to predict annular flow high gas rates are required.

Bannwart et al.[25] conducted experiments on three phase oil, water and gas in vertical and horizontal pipelines having inner diameter 2.84 cm and made up of glass. Flow pattern and pressure gradient were calculated. They used heavy viscosity oil with water and gas at many combinations of individual flow rates. Then they compared the three phase pressure gradient with the single phase and two phase oil-gas flow patterns.

Flow patterns for slightly inclined pipelines also presented. The result showed remarkable agreement with the theoretical models.

Three phase oil, gas and water experimental study was done by Jing et al.[26] on upward flows in a vertical pipeline.it showed a influence of gas injection on the pressure gradient. The pipe used has inner diameter 50 mm.Water velocity ranges from 0 to 0.885 m/s and oil velocity ranges from 0 to 0.90 m/s and gas velocity ranges from 0 to 0.85 m/pressure drops were calculated in order to show a influence of gas injection. A good agreement was achieved between theory and experimental results.

Desamps et al.[27] conducted an experimental study on three phase flow in vertical pipeline. Fluids used were air, water and oil. Phase inversion phenomenon was studied and different flow rates for liquid and gas were used. Pressure gradient is associated with phase inversion. The presence of dispersed oil-water phase is important phenomenon because it has significant influence on the bubble size.

Experiments for three phase flow in pipes having diameter 5.6 mm and 7 mm were done by Wegmann and Rohr [28]. Flow maps are presented in this work. They concluded that as the diameter of the pipes decreases flow pattern changes. A high speed camera was used for photography of these maps. Then the flow maps were compared with the literature maps.

An experimental study was conducted in detail by Lovick and Angeli[29] on continuous flow pattern in oil and water flows. Fluids retain the continuity in the pipe at top and bottom because of two immiscible fluids. Pressure drops and volume fraction data was collected. The pipe used has diameter 38 mm.it is a horizontal pipe and made up stainless steel. Oil volume fraction was used from 10 percent to 90 percent. The standard oil-water model was failed to predict the pressure gradient and liquid during continuous flow.

Meng et al.[30] did an experimental work in a 20 mm inner diameter pipe. First water holdup was measured for two phase oil-water flow. Then flow maps were presented with water superficial velocity ranges from 0.258 m/s 3.684 m/s and oil velocity ranges from 0.184 m/s to 1.474 m/s.

Lum et al.[31] used the upward and downward pipe for two phase flow to experimentally determine the pressure gradient and the flow pattern. Water fraction 10 percent to 90 percent used and mixture velocity used ranging from 0.7 m/s to 2.5 m/s. A high speed video camera was used to capture the videos of flow maps. And it is found that for upward and downward flow the value of frictional pressure gradient is low as compared to horizontal flow.

An experimental work was done by Jana et al.[32] to investigate the flow pattern of two phase liquid-liquid flow through a vertical pipe. Two fluids used were dyed kerosene and water. Velocities used for both the fluids ranging from 0.05 m/s to 15 m/s. Three probes were inserted in the loop. The intermittent flow region between bubble and annular flow is achieved which they called it the churn turbulent flow map.

Chakrabarti and Das [33] conducted a series of experiments to identify the stratified two phase flow in a horizontal pipe. Two immiscible liquids flow through this pipe and different flow patterns are investigated.to identify the flow pattern the probability density function analysis is used.

An experimental work was done by Ottens et al.[34] to determine the liquid holdup and pressure gradient in a horizontal pipe line for two and three phase flow. Two correlations are used to calculate these values. The used pipes have diameter 0.0127<D/m<0.0953 and its length is between 11<L/m<22 and the inclination used was -5 to 6 degree .the theoretical and experimental database were compered in this work. The author developed a new model to calculate the liquid holdup and pressure gradient.

Spedding and cooper [35] presented a note on prediction of liquid holdup for gas-liquid co current flow in a horizontal pipeline. They concluded that holdup increases steadily with the velocity of liquid. They also determine that diameter of the pipe affect the liquid holdup. There are many models to predict the flow map but none is universal model that we can use anywhere under every conditions. These models are valid only for specific conditions.

An experimental work calming to accurately determine the flow patterns and pressure drops was carried out by Kawahara et al.[36]. The experiments were done for two phase flow in a pipe of diameter 100 mm and a video camera was used to capture the flow patterns of two phase flow. Water and gas was injected at velocities 0.1-0.60 m/s and 0.02-4 m/s respectively. Data for pressure drop and void fraction was collected and analyzed. Except bubble and churn flow all the other flow patterns were observed. Then they compared their flow patterns map with the existing ones. Results were satisfactory for single phase and two phase flows.

Chisholm[37] used the Lockhant-Martinelli correlation equation and developed a correlation to calculate the pressure gradient of two phase gas liquid mixture in a horizontal pipe. When the results were compared with the Lockhant-Martinelli model it showed a good agreement.

Chen and Spedding[38] studied the separated flow and they extended the Lockhant-Martinelli work. For holdup and pressure drops different relationships were developed. Pressure gradient were compared with the Taitel and Duckler model. The results showed a close agreement. Similarly holdup data when compared also showed a good agreement. They concluded that pressure gradient and holdup are dependent on pipe diameter.

CHAPTER 3 **EXPERMENTAL SETUP AND PROCEDURE**

3.1 DESCRIPTION OF THE FLOW LOOP

The air-water two phase experiments were conducted at recently established multi-phase laboratory at King Fahd University of Petroleum and Mineral (KFUPM), Dhahran Saudi Arabia. Its schematic layout diagram is shown in Figure 3.1 and its photograph is shown in Figure 3.2.The multi-phase flow loop is equipped with a screw type compressor (AC), two compressed air tanks (CAT), five centrifugal variable speed pumps(3 for pumping water WP and 2 for pumping oil, OP), two-pass 4-inch stainless loop (28 m length), a horizontal separator tank(WOST), two level indicators for oil and water each. The loop is constructed on moveable platform (inclination can be varied from 0 deg -60 deg), which toggles on flexible pipe connection (FC). The loop can be positioned at any given angle using over-head jack.The water and oil was pumped using 5 induction motors having output 18.5 KW, 25 hp, RPM 3535 per mint 3 phase induction motors to the pipeline and these motors operates on volts 230/380/460,Amps 56.8/34.4/28.4 are shown in Figure 3.3. At steady-state water and air enter the loop and combine at the section of the loop as shown in Figure 3.4 then flow along the test section, and finally leave the outlet through valves.

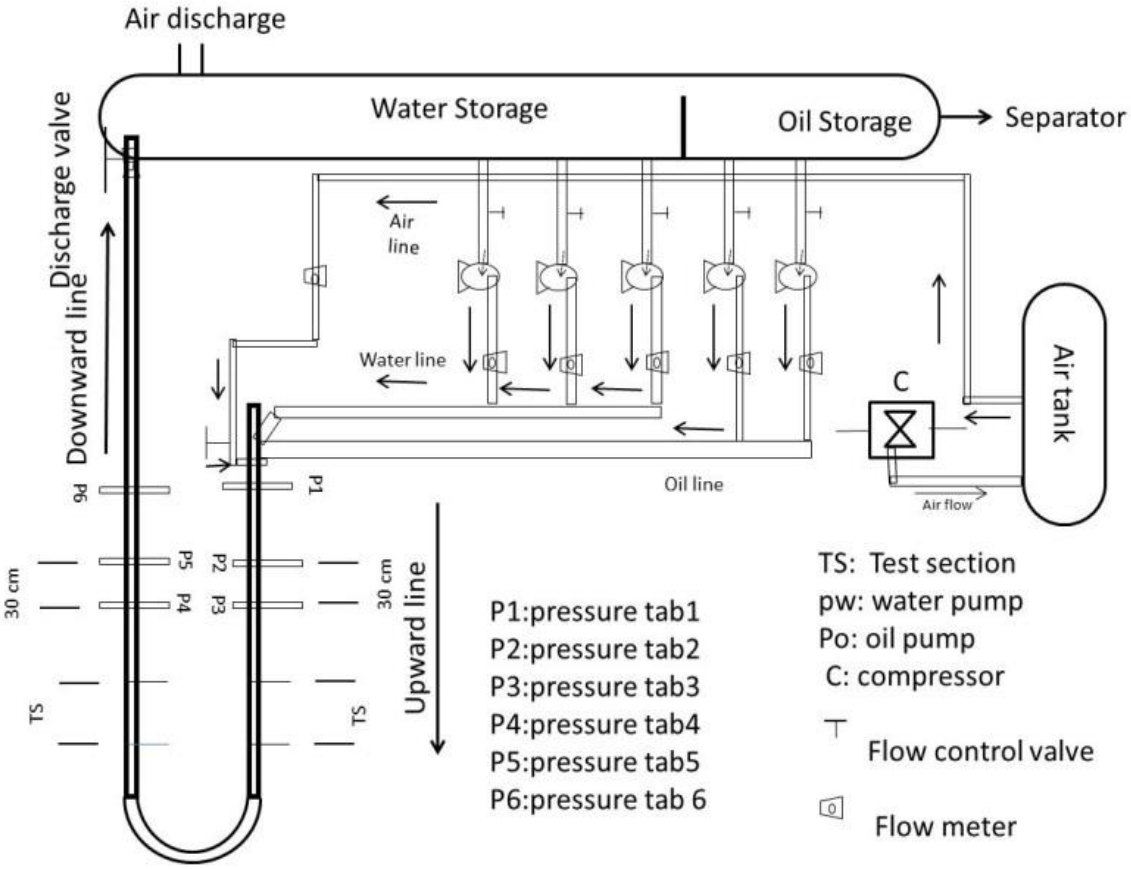

Figure 3.1:- Schematic layout diagram of the Multiphase flow loop

Figure 3.2:-Photograph of Multiphase flow loop in horizontal position

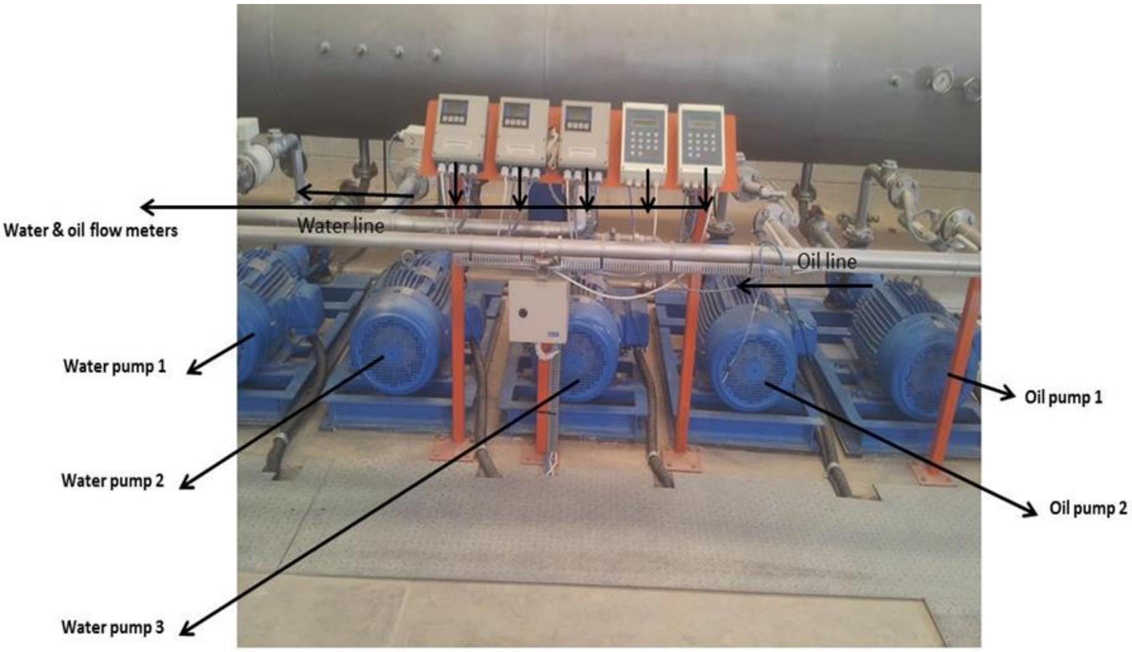

Figure 3.3:-Photograph of the water and oil induction motors

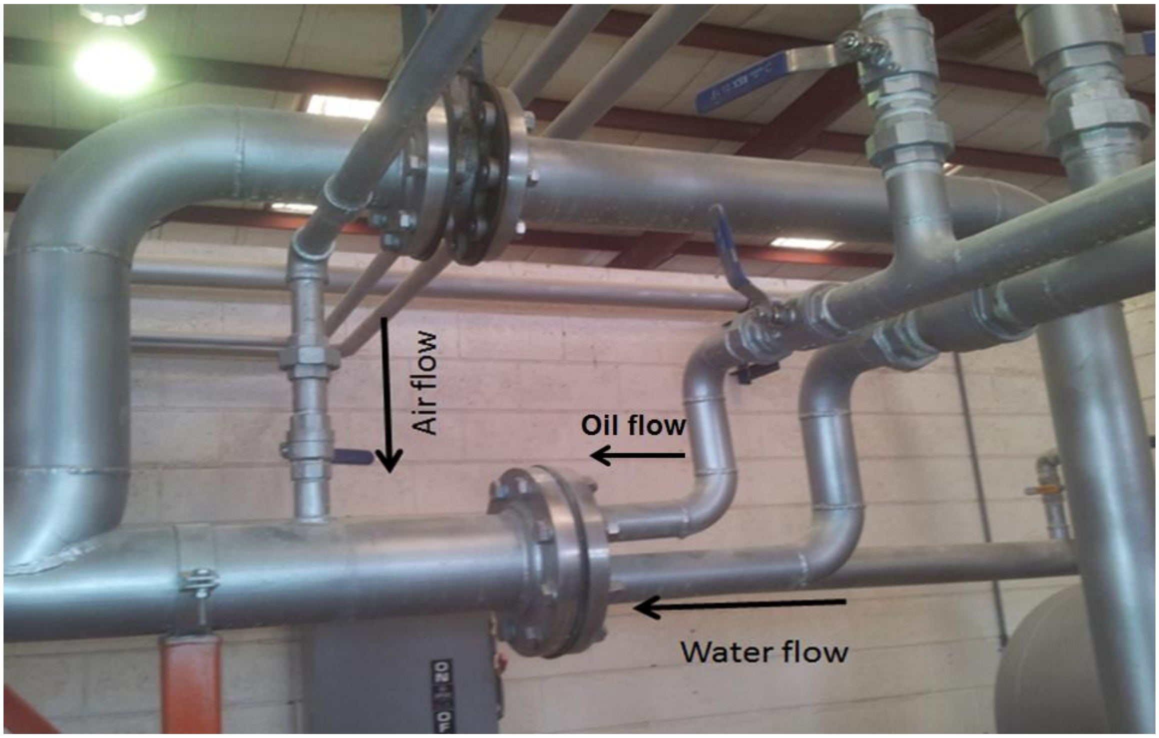

Figure 3.4:- Photograph of the section where the fluids combine

The liquids were stored in the large storage tanks and pumped from the tank through a series of pumps, with which the liquid rate was set and controlled. Pressures at six points in test loop were recorded continuously by means of transducers. Instantaneous pressure readings were taken at the same six points.

Four pneumatic horizontal gate valves (HGV0–HGV3) are present on the loop to switch the flow between the test section and the storage tank. In the steady-state, all the valves HGV0 to HGV3 are open and allow the fluid to flow along the test section. The air increases the compressibility of the system and minimizes the mass in the loop that must be accelerated from rest at the beginning of the test.

The water is pumped using three induction motors air is then mixed with the water through a hose connected to the pipeline. The two-phase fluids (air-water) then flow simultaneously to the pipe along the test section. The pressure transducers were connected to the pressure taps along the loop to measure the pressure drop. Both water (portable water) and oil (with a density of 795 kg/m3) were kept in the same large tank. Because of the density difference, oil rest on the upper part of the vessel while water remains in the lower part. Two series pumps and flow meters were used to pump the pure oil and pure water from tank to the loop. At the outlet of the flow-loop Gas reaches the top of the separator and escapes through to environment, while the oil and water liquid phases remain in the separator. The separator separates the two fluids on the basis of their density difference while the mixture of the oil and water that could not be separated in the tank was dumped inside the drain. The loop process was repeated again till all the experiments were conducted. Then same process is repeated after varying the inclination of the pipe as shown in Figure 3.5.

The air compressor is the jaguar compressor air center EAS20 manufactured by JAGUAR Compressor Inc. It has an integrated refrigerated air dryer DD0020 to avoid moist air inside the system and it also has variable speed drive to regulate the air flow rate inside the pipeline. There are two air storage tanks and the controlled pressure capacity of the one air storage tank is 7.9 bar and compressed air system is shown in Figure 3.6. The multiphase flow loop has five 18.5 KW and induction motors manufactured by TECO Elec. & Mach co, Ltd. Two of the induction motors were used to pump the oil and three to pump the water. Flow loop has air pressure gauge having range 0-160 lb/in2 or 0-11 kg/cm2.the three water flow meters manufactured by MAG 888 and two oil flow meters are ultrasonic flow meters manufactured by Spire metering and all these instruments are controlled by a control panel which is shown in Figure 3.7.

Figure 3.5:- Photograph of the Multiphase flow loop at 15 degree angle

Figure 3.6:- Photograph of compressed air system.

Figure 3.7:-Photograph of control panel of multiphase flow loop

3.1.1 Flow-loop instrumentation

The instrumentations used in these experiments are

Table 3-1 Table of instruments used in experimentation

items	Manufacturer	Model	Capacity/Range	Accuracy/Error
Screw type compressor	JAGUAR	EAS20	8.5 bar	-
Two compressed air tanks	1-JAGUAR 2-JAGUAR	1-GB150-98 2-60034-1	1-1.43 mpa 2-0.8 mpa	-
Five pump(three water, two oil)	NEWAR FLOW SERVE	50-32CPX200	35 m3/hr	-
Two-pass 4-inch	TIG TESCO	MPR-9000	35 m3/hr X 5 pumps	-
Air flow meter	OMEGA	FMA-1613A	4-60 ACFM	±1.0 %
Two ultrasonic flow meter	Spire metering technology	EF10	-10-10 m/s	±1.0 %
Three electromagnetic flow meter	Spire metering technology	MAG888	≤12m/s	±0.5%
DP1 upward	ROSEMOUNT	300S2EAE5M9	0-70 inches of water column	±0.1%
DP2 downward	ROSEMOUNT	300S2EAE5M9	0-10 inches of water column	±0.1%

Differential pressure. Three Differential pressure transmitters were used to measure the pressure drop in inches of water column. One pressure transducer ranging 0 to 100 inch of water column and second and third ranging from 0 to 70 and 0 to 12 inches of water column respectively. The detail of all these instruments is given in table 3.1.

3.2 EXPERIMENTAL OPERATION OF FLOW LOOP

Pressure gradients were measured in stainless steel pipeline. The steel pipe is rougher and also has very different wetting characteristics. The test fluids used were tap water and compressed air and exxol D80 oil.

3.2.1 Calibration runs

At the completion of the multiphase flow loop setup, the pressure transmitters were tested by comparing the experimental single phase data with theoretical single phase data calculated from Blasius correlation.

The results showed a close agreement between experimental data and Blasius data which means that the pipe is smooth. For the roughness of the pipe, it was estimated by comparing experimental data with Zigrang and Sylvester correlation. The roughness of the pipe was $1 \times 10^{-5}\ m$ which can be considered as a smooth pipe. This was done in order to ensure reliability of the experimental instruments and set up.

The roughness of the phexiglass test section was estimated using water single phase pressure drop measurements for an average water velocity range of $0.6m$/s to $3.0\ m$/s. In order to avoid the wettability effect of the pipe on pressure drop measurements, water with oil was not used to achieve this objective. Pressure drops were measured and friction factor was calculated. The measured friction factor was then compared with the friction factor calculated from Blasius equation used for smooth pipe and also the Zigrang & Sylvester correlation for different roughness.

Finally, the oil flow meters were calibrated for oil with the Exxol D80 while the air flow meter was also calibrated accordingly. Figure 3.8 shows the single phase pressure gradient for oil and water in horizontal pipe.as can be seen from the Figure 3.9 the theoretical and experimental values are almost same therefore we can say that there is good agreement between experimental and theoretical pressure gradient both for oil and water. Figures 3.10 and 3.11 shows the graph between theoretical and experimental pressure gradient.as can be seen in the figures that for horizontal upward-line flow the theoretical and experimental data is 98.2% correlated with each other so there is only difference of 1.5 % and also for horizontal downward-line both the data are in good agreement there is only 2.5 % error between experimental and theoretical pressure gradient.

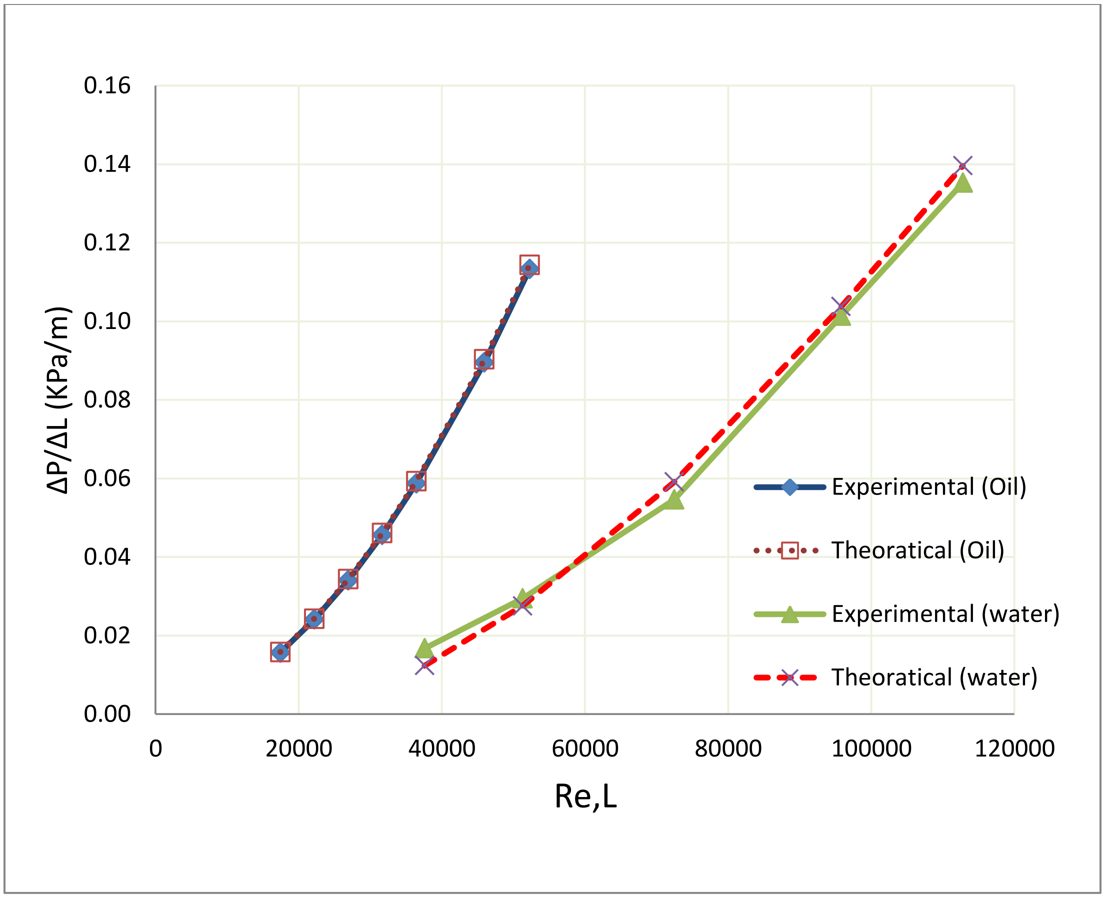

Figure 3.8:- Pressure gradient for single phase oil and water for horizontal (upward-line) pipe.

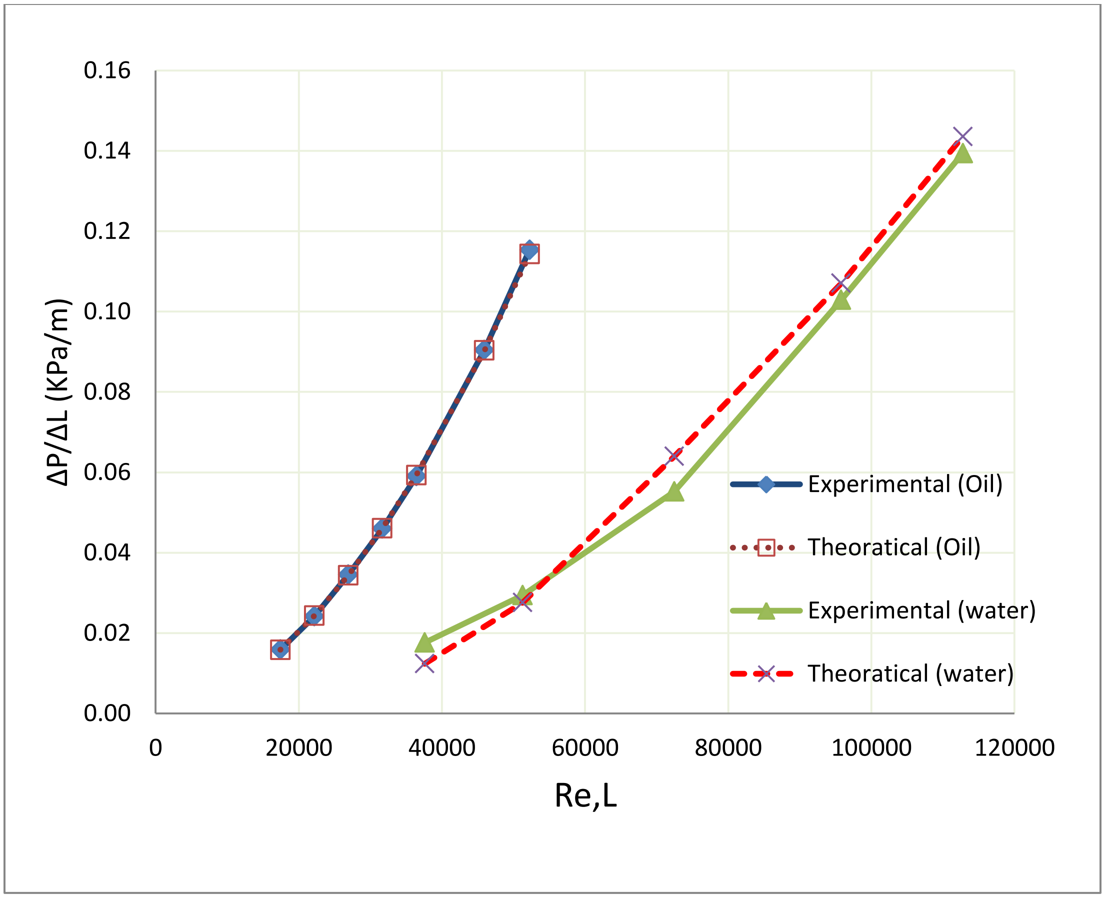

Figure 3.9:-Pressure gradient for single phase oil and water for horizontal (downward-line) pipe.

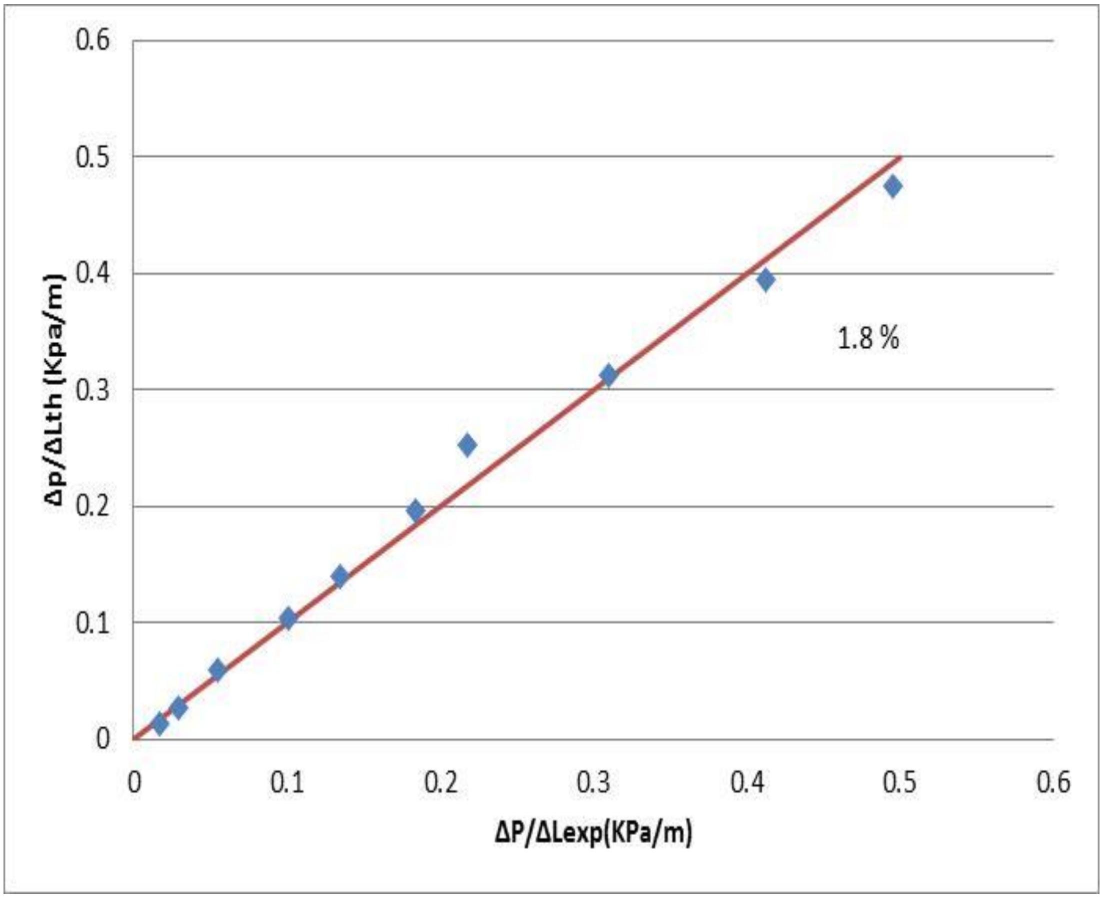

Figure 3.10:- Experimental VS theoretical pressure gradient for horizontal (upward-line) single phase water.

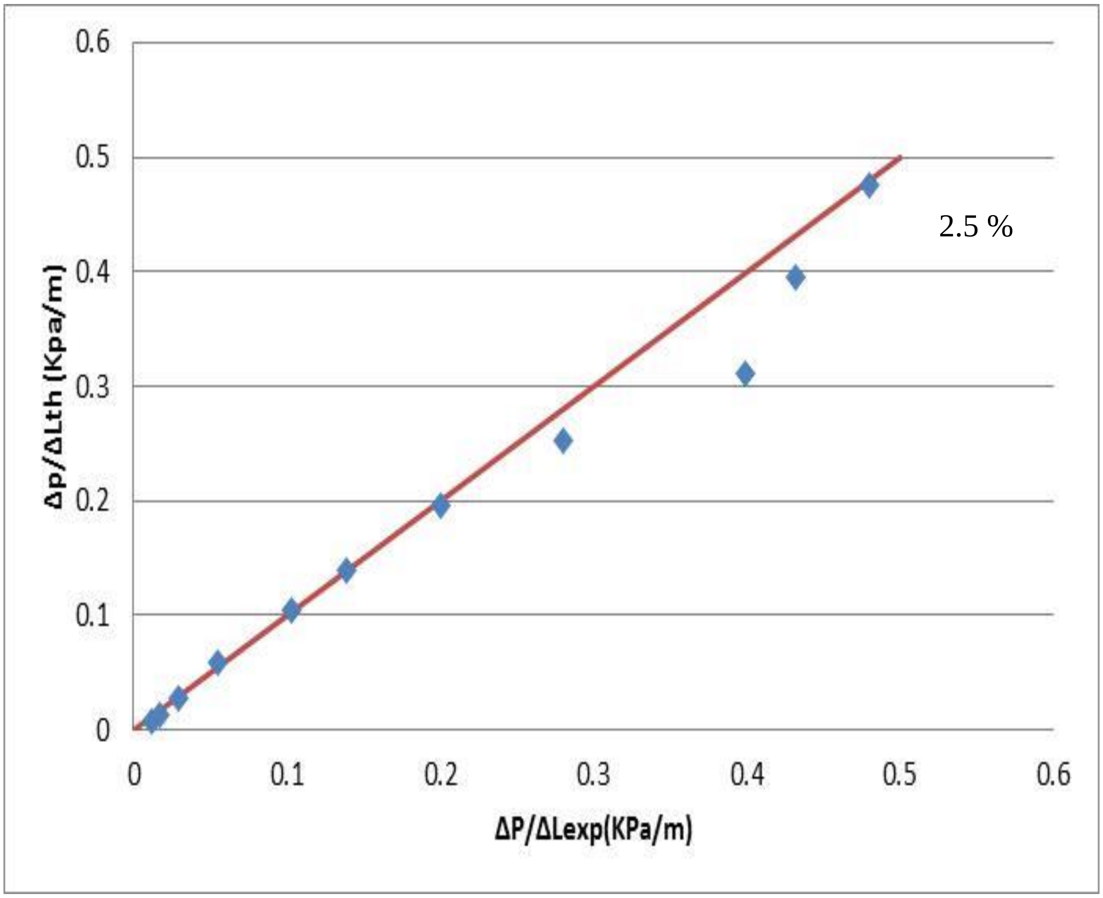

Figure 3.11:- Experimental VS theoretical pressure gradient for horizontal (downward-line) single phase water.

3.3 KEY TERMS

There are some terms that are used to characterize multiphase fluid flow in a pipe.

4. Dispersed flow: This is the flow described by a uniform phase distribution in all direction for example bubble or mist flow.

5. Dissolved water: This is the quantity of water in solution in petroleum products.

6. Dry gas: As the name indicates the gas flow without any liquids under the actual operating conditions but with further change of temperature or pressure liquid may fall on it.

7. Emulsion: It is the mixture of two immiscible fluids.one fluids is dispersed in other fluid in the form of droplets. The flow of other fluid is call continuous flow.

8. Entrained water: It is the quantity of water suspended in oil.

9. Flow regimes: It is defined as the physical geometry presented by a multiphase flow in a pipe. For example two phase flow, free water settled at bottom of the pipe.

10. Fluid: It is the substance that assume the shape of the container quickly for example oil, gas, water or mixture of any of these.

11. Froude Numbers: This is defined as the ratio of inertial force and gravitational force for a phase or it can also be defined as the ratio of kinetic to potential energy of the liquid or gas.

12. Gas-Liquid-Ratio (GLR): The ratio of volume flow rate of gas and the volume flow rate of the liquid. Both these volume flow rates should be converted to the same pressure and temperature.

13. Gas volume fraction (GVF): It is the volume flow rate of gas relative to multiphase volume flow rate at the pressure and temperature set in that section.it is expressed in percentage.

14. Homogenous multiphase flow: the multiphase flow in which all phases are evenly distributed in the cross section of a pipe. That is the composition is the same at all points in a pipe and liquid and gas velocities are same. Bubbly flow regimes are probably the best homogenous multiphase flow.

15. Intermittent flow: It is the non-continuous flow in the axial direction therefore it is unsteady flow for example elongated bubble, churn and slug flow are example of these flows.

16. Liquid-Gas-Ratio (LGR): the ratio of volume flow rate of liquid and the total volume flow rate of gas. Both should be at same temperature and pressure.

17. Liquid holdup: It is the ratio of cross sectional area in the pipe occupied by liquid and the total cross sectional area of the pipe. It is expressed in percentage.

18. Liquid volume fraction (LVF): the ratio of liquid flow rate and the total fluid flow rate. Both should be at same temperature and pressure and is expressed in fraction.

19. Lockhart-Martinelli parameter (LM): It is donated by ‘X’ and defined as the ratio of Froude no of liquid to the Froude no of gas or it can also be defined as the ratio of pressure gradient for the liquid to the pressure gradient for the gas in the conduit under actual flow conditions.

20. Mass flow rate: it is defined as the mass of the fluid that is flowing through the pipe in unit time.

21. Multiphase flow meter (MPFM): It is the device used to measure the flow rates of individual oil, water and gas. For example two or three phase test separator is a multiphase flow meter.

22. Multiphase flow velocity: the ratio of volume flow rate of multiphase flow and the cross sectional area of the pipe.it is the sum of gas superficial and liquid superficial velocities.

23. Slip: This term is used to describe the flow condition that occurs when the two phases have different velocities at the cross sectional area of the pipe.it may be point out be phase velocity difference between the two phases. And slip ratio is the ratio of two phase velocities.

24. Slip velocity: it is the phase velocity difference between the two phases.

25. Void fraction: the ratio of cross sectional area of the pipe occupied by the gas and the total cross sectional area of the pipe.it is expressed as a percentage.

26. Volume flow rate: It is the volume of the fluid flowing through the pipe in unit time at the standard pressure and temperature settled in that section.

27. Accuracy of measurement: it is the agreement between the result of a measurement and the value of the measured according to standard.

28 Superficial phase velocity: the flow velocity of one phase assuming that this phase occupies the whole pipe.it can also be defined as the ratio of phase volume flow rate to the pipe cross sectional area.

It is the actual volumetric flow rate per unit area.

$$V_{SW} = \frac{Q_w}{A} \tag{3-1}$$

Where V_{SW} is the superficial velocity of the water and A is the pipe cross sectional area Q_W is the input volumetric flow rates of water inm^3/s.

$$V_{SG} = \frac{Q_a}{A} \tag{3-2}$$

Where V_{SG} is the superficial velocity of the gas and A is the pipe cross sectional area Q_G is the input volumetric flow rates of gas inm^3/s.

29. Water cut (WC): The volume flow rate of the water, relative to the total liquid volume flow rate. Both volumes at converted at actual pressure and temperature.it is expressed as percentage. Or water cut (WC) can be defined as water quantity at the pipeline inlet as volume percentages of the total inlet volumetric flow rate of the liquid.

$$\mathrm{WC} = \frac{Q_w}{Q_{\mathrm{Liquid}}} \tag{3-3}$$

Where Q_{Liquid} is the input volumetric flow rate of liquid.

Reynolds Number (Re) for the single phase water was calculated using

$$\mathrm{Re} = \frac{\rho_w V_w D}{\mu_w} \tag{3-4}$$

3.4 DATA REDUCTION

The friction factor (f) is a function of the Reynolds number of the flow and the pressure drop. For a horizontal pipe flow, it can be calculated from the following relation:

In addition, for turbulent flow (Reynolds number up to 10^5) in smooth pipes, a very widely used empirical equation that gives very good approximation of the friction factor is a correlation that was proposed by Blasius for single phase:

$$f = 0.316\mathrm{Re}^{-0.25} \tag{3-5}$$

The turbulent friction factor can also be determined using other correlations, such as the Zigrang & Sylvester 1985 correlation defined in equation (3-6) below.

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{\varepsilon/D}{3.7} - \frac{5.02}{\mathrm{Re}}\log\left[\left(\frac{\varepsilon/D}{3.7}\right) + \frac{13}{\mathrm{Re}}\right]\right] \tag{3-6}$$

Where

$\Delta P$is the Pressure drop (Pa).

L is the distance between the two pressure taps (m).

D is the inner diameter of the pipe (m).

ρ is the fluid density $(\mathrm{Kg/m^3})$.

v is the in-situ average velocity of the fluid (m/s).

ε is the pipe roughness (m).

Re Reynolds number

The pressure drop (ΔP) along the pipe was calculated after measuring velocity when steady and fully developed flow has been achieved in the pipe. The following equation can be used to calculate the pressure drop

$$\Delta \mathrm{P} = \mathrm{f}\ (\mathrm{l}\ /\ D)\ (\rho\ \mathrm{v2}\ /\ 2) \tag{3-7}$$

Where:

ΔP is the Pressure drop (Pa).

f   is friction factor

D is the inner diameter of the pipe (m).

ρ is the fluid density $(\mathrm{Kg/m^3})$.

v is the in-situ average velocity of the fluid (m/s)

3.5 UNCERTAINTY ANALYSIS

Uncertainty analysis is the method used to estimate the limits of the unknown error and also describe the credibility of the experimental data. There are two types of uncertainties.

The uncertainty due to random error $\delta_{r,e}$ of any quantity is determined using the standard deviation of the mean as:

$$\delta_{r,e} = \left[\frac{\sum_{i=1}^{N}(x_i - \tilde{x})^2}{N(N-1)}\right]^{1/2} \tag{3-8}$$

Where N is the number of measurements and $\tilde{x}$ is the arithmetic mean of each reading which is given as:

$$\tilde{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{3-9}$$

b) Second uncertainties are those that affect the accuracy of a measurement. These uncertainties are one sided estimates and are difficult to trace. To avoid this kind of uncertainty, all the measuring instrument used for the experiments were calibrated. This was the reason the single phase friction factor was measured and then compared with Blasius and Zigrang & Sylvester correlations to confirm the accuracy of these instruments.

Consider δ_R to be the uncertainty in the calculated result, and δ_1,δ_2, δ_3,……..$\delta_n$be the uncertainties in the independent variables, then the uncertainty in the calculated result is given as:

$$\delta_R = \left[\left(\frac{\partial R}{\partial x_1}\delta_1\right)^2 + \left(\frac{\partial R}{\partial x_2}\delta_2\right)^2 + \; \ldots . + \left(\frac{\partial R}{\partial x_{1n}}\delta_n\right)^2\right]^{1/2} \qquad (3\text{-}10)$$

The overall uncertainty

The overall uncertainty can be calculated using equation (3-11).

$$U = \pm\sqrt{(\delta_{r,e})^2 + (\delta_R)^2} \qquad (3\text{-}11)$$

Table 3-2 Uncertainty Analysis Results

Parameter	Instrument	Uncertainty %
Water flow rate (m3/hr)	MAG888 electromagnetic flow meter	2.6
Oil flow rate (m3/hr)	EF10 Ultrasonic flow meter	3.0
Pressure drop (kpa)	Pressure transmitter	1.5
Diameter (mm)	Varnier Caliper	0.01
Density (kg/m3)	Viscometer	0.24
Friction factor F	Software EES	3.13

3.6 FLOW PATTERN

This is the geometric configuration of the gas and liquid phases in the pipe. The flow configurations differ from each other in the spatial distribution of the interface. In order to achieve a more accurate model of the flow and also to have a better understanding of the phenomena occurring during the gas-liquid phase flow, it is very paramount to recognize the boundaries between flow patterns

1. **Stratified flow pattern (ST):** This occurs at relatively low air and water flow rates. The two phases are separated by gravity, where the water flows at the bottom of the pipe and the air on the top. The stratified flow pattern is subdivided into **Stratified-Smooth (SS),** where the gas-liquid interface is smooth, and **Stratified –Wavy (SW)** occurring at relatively higher air flow rates and stable waves form on the surface.
2. **Elongated bubble flow pattern (EB):** This occurs at relatively lower air flow rates when the flow is calmer. This flow pattern is considered as the limiting case of slug flow, in which the liquid slug is free of entrained bubbles.
3. **Slug flow pattern (SL):** This occurs when the air bubbles are almost the diameter of the pipe. The bubble has a characteristic spherical cap and the air in the bubble is separated from the pipe wall by a slowly descending film of liquid. The water flow is contained in liquid slugs which separate successive air bubbles.
4. **Annular flow pattern (AN):** This occurs at very high air flow rates. The air flows in a core of high velocity, which may contain entrained oil and water droplets. The oil and water flow as a thin film around the pipe wall. The film at

the bottom is usually thicker than that at the top, depending upon the relative magnitude of the air and water flow rates. At the lowest air flow rates, most of the water flow at the bottom of the pipe, while aerated unstable waves are swept around the pipe periphery and wet the upper pipe wall occasionally.

5. **Dispersed Bubble flow pattern (DB):** This occurs at very high superficial liquid velocities, the liquid phase is the continuous phase, in which the gas phase (air) is dispersed as discrete bubbles. At higher water flow rates, the air bubbles are dispersed more uniformly in the entire cross sectional area of the pipe. Under this flow conditions, due to high water flow rates, the two phases (air and water) are moving at the same velocity and the flow is considered homogenous no-slip.

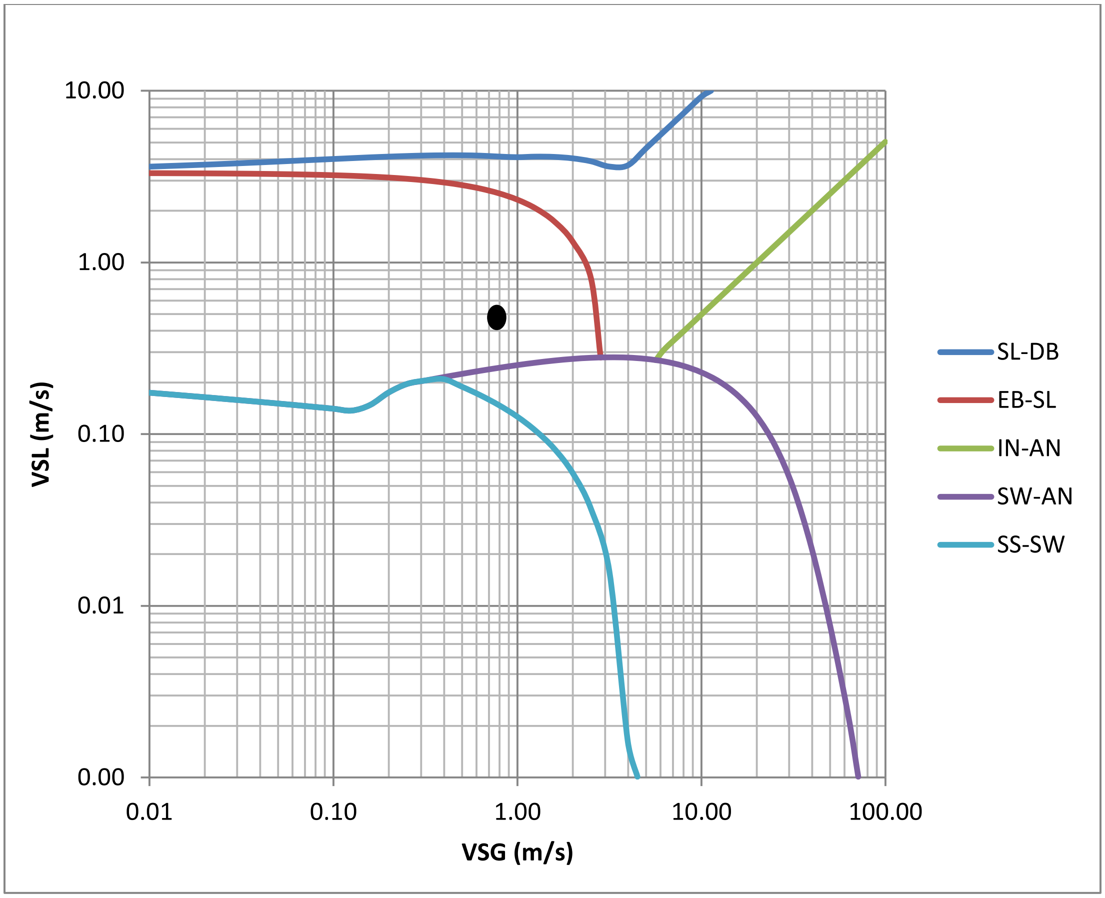

Figure 3.12:- Flow Pattern map of Air-Water in horizontal pipe.

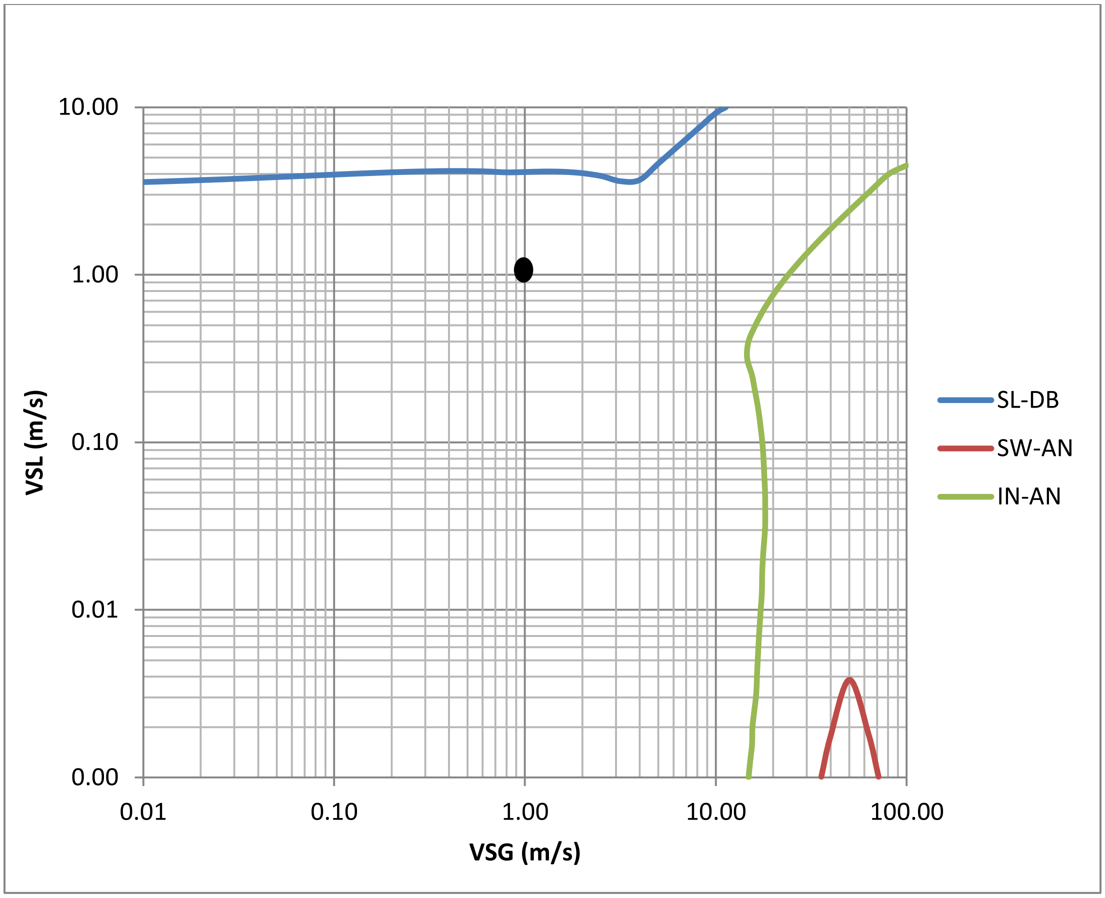

Figure 3.13:- Flow Pattern map of Air-Water in 15° inclined pipe.

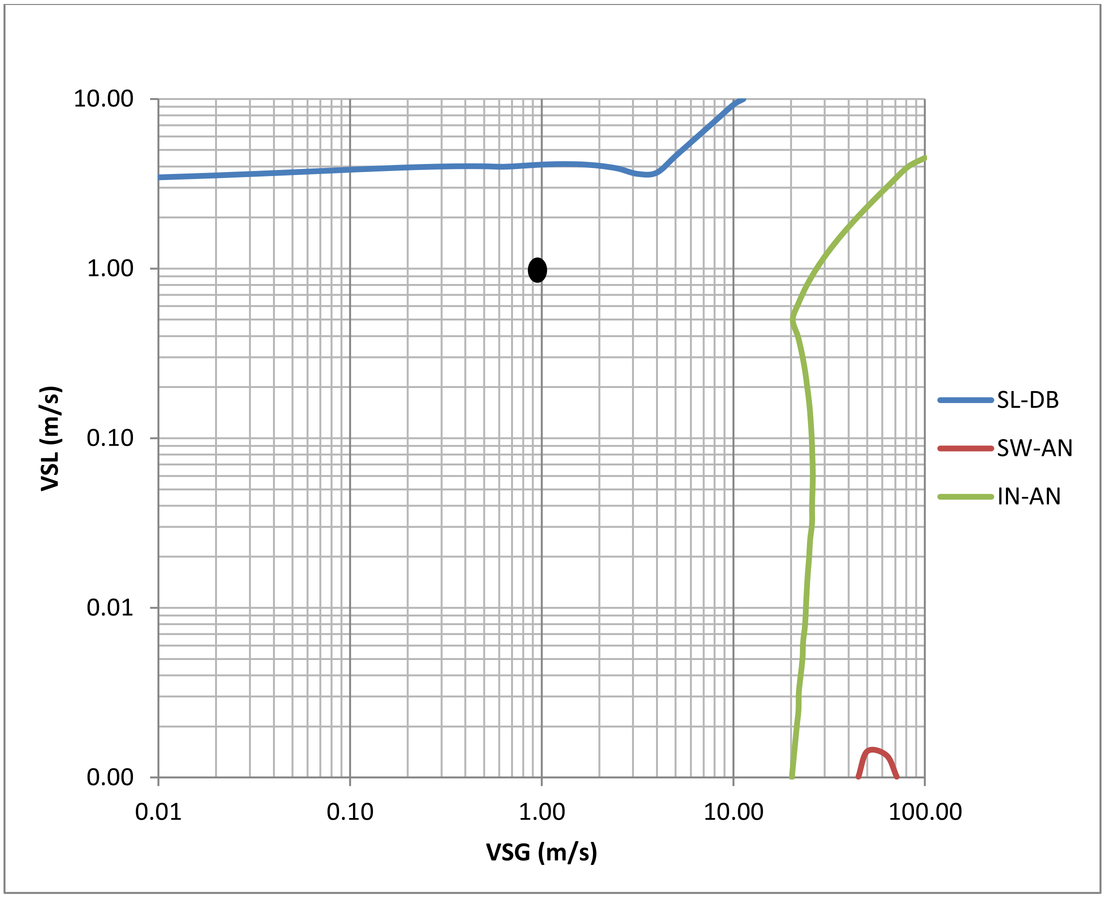

Figure 3.14:- Flow Pattern map of Air-Water in 30° inclined pipe.

CHAPTER 4 **RESULTS AND DISCUSSIONS**

4.1 SINGLE PHASE EXPERIMENTS

Single phase experiments were done first using water in a horizontal pipeline then at different inclination 0, 15, 30 degrees. After making sure that there is no air trapped in the pipeline pressure drop were measured horizontal, upward flow and downward flow. Two methods were used to collect the pressure drop in the pipeline for single phase water. First pressure drop were measured while maintain the line pressure constant in the pipeline. This line pressure can be controlled by using discharge valve.it is closed if more pressure is required in the pipeline and it is opened if less pressure is required in the pipeline.in this work 2 bar pressure is kept constant in the line and pressure drops were measured. The second way to collect the pressure drop is at atmospheric pressure that is to open the discharge valve and vary the volume flow rate of the fluid. So in this work both the methods were used to collect the experimental data points for single phase pressure drops. Then these pressure drops were compared with theoretical pressure drops.as shown in the figures 4.1-4.2.

Figure 4.1 shows the Pressure gradient of single phase water for upward flows against flow rate. Pressure gradient increases as the flow rate increases and maximum pressure gradient for horizontal flow is 0.50 kPa/m at 13800 bpd flow rate. The maximum value of pressure gradient increases to 0.52 kPa/m as we move from 0 to 15 degree inclination that is obvious that with increase in inclination there will be more resistance and gravitational pressure gradient will be added so pressure gradient will increase. The maximum value of pressure gradient increases to 0.56 kPa/m as we move to 30 degree inclination.

Figure 4.2 shows the pressure gradient of single phase for downward flows.as can be seen pressure gradient decreases as the inclination increase.

Then using the experimental pressure drop the friction factor was measured using equation 3.8. Then this friction factor was compared with the friction factors calculated by using Blasius correlation and Zigrang & Sylvester correlations as shown in the figure 4.5. The result showed a close agreement particularly with the Blasius friction factor.

The Blasius and Zigrang & Sylvester correlation of $k = 1 \times 10^{-5}\ m$ gave a good approximation to the friction factor of the measured values. We can therefore say that, the roughness of the pipe was $1 \times 10^{-5}\ m$ which can be considered as a smooth pipe. The calculation of the friction factor has been included in Appendix A and experimental data for single phase water and oil are shown in Appendix B.

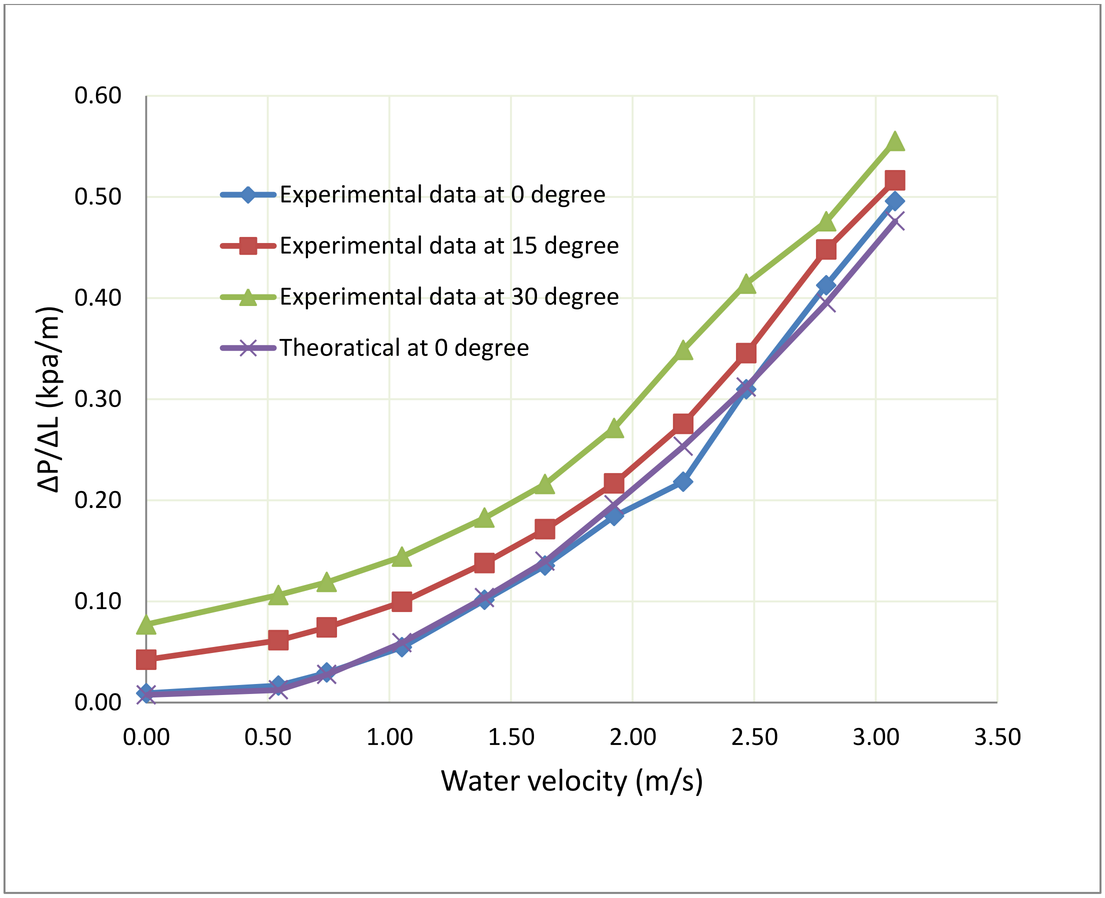

Figure 4.1:- Pressure gradient of single phase water upward flows

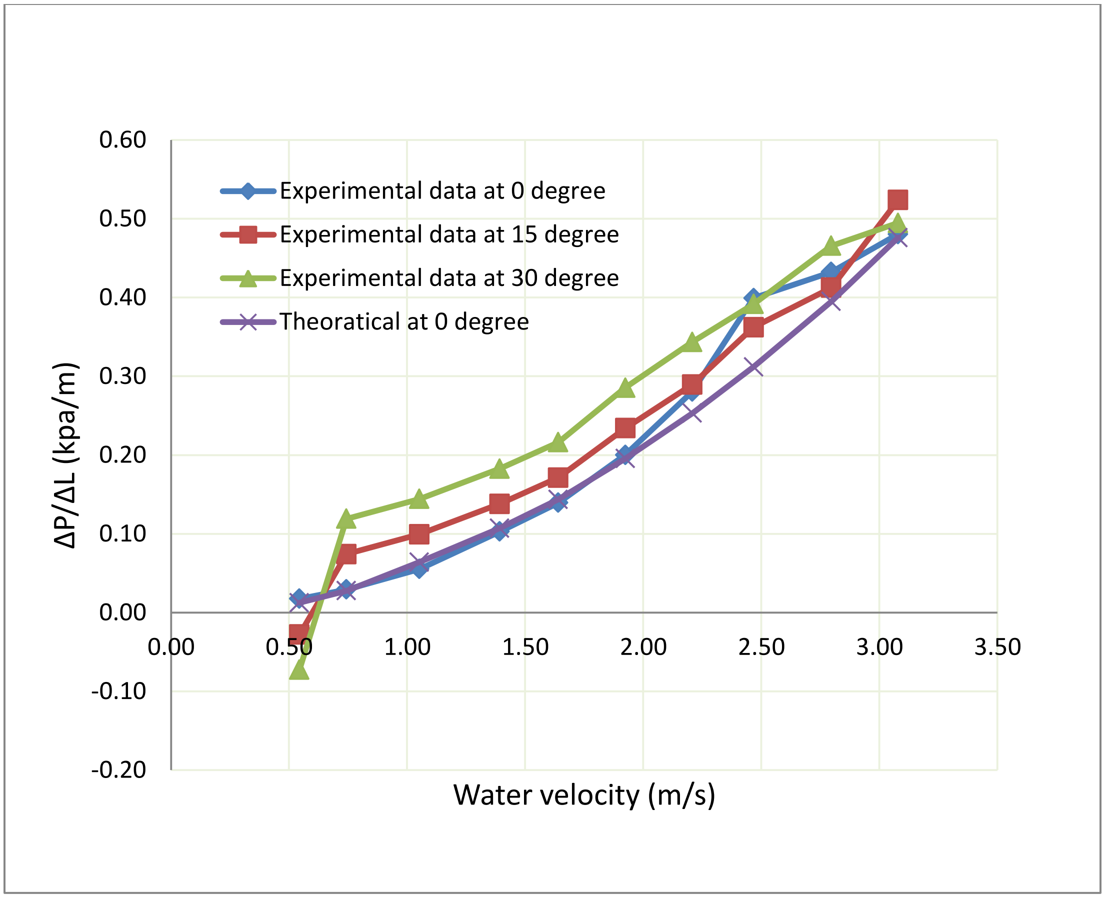

Figure 4.2:- Pressure gradient of single phase water downward flows

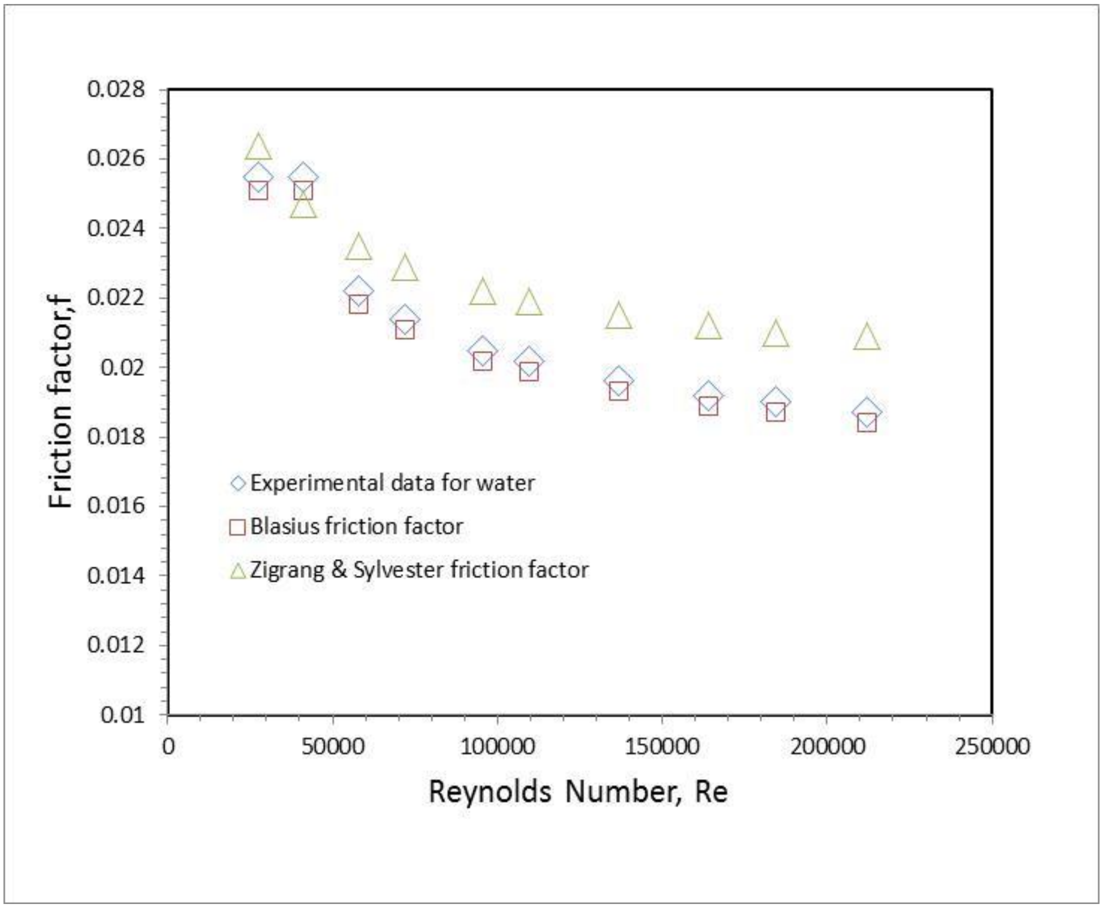

Figure 4.3:- Friction factors for single phase water horizontal flow.

4.2 INCLINATION EFFECT ON PRESSURE GRADIENT

The pressure gradient of air-water flow in a horizontal and inclined pipe for superficial liquid velocities between 0.3m/s and 3m/s and superficial gas velocities between 0.03m/s and 27.0m/s and water cuts from 0.1 to 0.9 were presented in Figures 4.6 to 4.23. In these figures pressure gradient data for horizontal and inclined flows for three angles 0, 15 and 30 degree presented as series of curves. For horizontal flows almost straight lines were formed for pressure gradient as shown in above mentioned figures.at water velocity 0- 1.2 m/s the pressure gradient increases linearly with the flow rates but it altered slope as the flow rate increased. For 0.1 to 0.3 water cut pressure drop increases up to 1.2 m/s water velocity and then it decreases suddenly up to 1.5 m/s water velocity because the region changed from SS_SW to IN-AN. The reason of increasing pressure gradient at low flow rate is common that flow is developing and it need more energy to develop and pipe is providing resistance until flow is developed. From 0.1 to 0.3 water cut there is more air in the pipeline than the water so once the flow is developed and air used the extra energy needed to form droplets then pressure drop decreases because at this point air don’t require extra energy to form droplets and suddenly decreases and drops to negative value but at higher water cut this negative pressure gradient region disappears. In inclined upward flows at low flow rates the pressure gradient is much higher than the horizontal pipes. There are two reasons of this high pressure gradient. a) In inclined flows the gravitational pressure drop is positive and adds to the total pressure gradient resulting increases in total pressure gradient as shown in figure 4.6 to 4.14. For downward flows the gravitational pressure gradient is negative so total pressure gradient will be frictional pressure gradient minus gravitational pressure gradient resulting a very low value of pressure gradient at low flow rates for downward flows. b) At low flow rates the flow is predominantly intermittent in which there is high loss in pressure so pressure gradient increases.

Pressure gradient is more for 30 degree than 15 degree and for 15 degree is more than 0 degree at low flow rates the reasons are mentioned in above paragraph. The maximum value of pressure gradient before sudden drop for a horizontal pipe is 0.27 kPa/m for 10 % water cut because 90 % air uses more energy to form droplets as the water cut increase the this value decreases because air quantity is being reduced resulting a minimum value of pressure gradient at 90 % water cut that is 0.03 kPa/m.it is also clear from the figures 4.6 to 4.14 as the water cut increase the line representing pressure gradient becomes almost straight for a horizontal flows at low flow rates and it is a straight line at 90 % water cut because here only 10 % air is contained that doesn’t use to much energy to form droplets. For downward flows at 15 degree the pressure gradient is almost zero from 0 to 1.2 m/s water velocity and then decrease from 1.2 to 1.5 m/s as shown in figures 4.15 to 4.23. Same trend is observed for downward flows at 60 degree but with higher values of pressure gradient.

The effect of inclination is noticeable at low flow rates but at higher flow rates the pressure gradient increases as the flow rate increases and formed a straight line region that was very similar to that with horizontal flows. For upward inclined flows both at 15 and 60 degree the minimum pressure gradient is observed between the 1.5-2.5 m/s water velocity as shown in figures 4.6-4.14.To the left of the this minimum value of the pressure gradient there is the region on the graphs the gravitational pressure gradient is dominating while in the region on the right side of this minimum pressure gradient the frictional forces become dominant because at high flow rates the effect of head on the total pressure gradient is only a few percent. This characteristic is clear from the figure 4.6-4.14.

At higher flow rates the lines representing inclined flows becomes very similar to that of representing horizontal flows. The reason of this behavior is that at high flow rates of water and air the pressure gradient become independent of inclination so the total pressure is only due to frictional therefore these lines showed same trend. The effect of upward inclination is that pressure gradient increased at low flow rates because as the angles increased the gravitational pressure gradient becomes large and adds to total pressure gradient and at high flow rate there is only frictional pressure gradient so total pressure gradient is less as compared to total pressure gradient low flow rates as can be seen on figures 4.6-4.14.

In the downward flows the pressure gradient is more complex.at low flow rates the gravitational pressure gradient is negative so total pressure gradient will be frictional pressure gradient minus the gravitational pressure gradient therefore a minimum values of pressure gradient is observed. There is only limited data points where pressure gradient suddenly increased then decreased. The reason of this increased pressure gradient is due to a phenomenon called unstable wave flooding phenomenon.as mentioned above nearly zero pressure gradients was observed at low flow rates. The pressure gradient fluctuation is different for downward flows to that of upward flows. The pressure gradients for 40 %

water cut almost similar to that of at 80 % water cut for upward flows and for downward flows the pressure gradient at 20 % is more likely the same at 90 % water cut. The figure 4.9 showed that at 50 % water cut there is inversion point at 2.1 m/s water velocity for downward flows and figure 4.10 showed that there is inversion points at 1.2 m/s water velocity for upward flows.it is evident from the graphs that the difference in pressure gradient between 0 to 15 degree inclination is more than that of 15 to 30 degree inclination. The reason is from 0 to 15 degree inclination there are more fluctuation in the flow because of discontinuities, phase inversion and droplet formation but at higher angle these phenomenon has less impact on the flow. Experimental data for air-water two phase flows is shown in Appendix C.

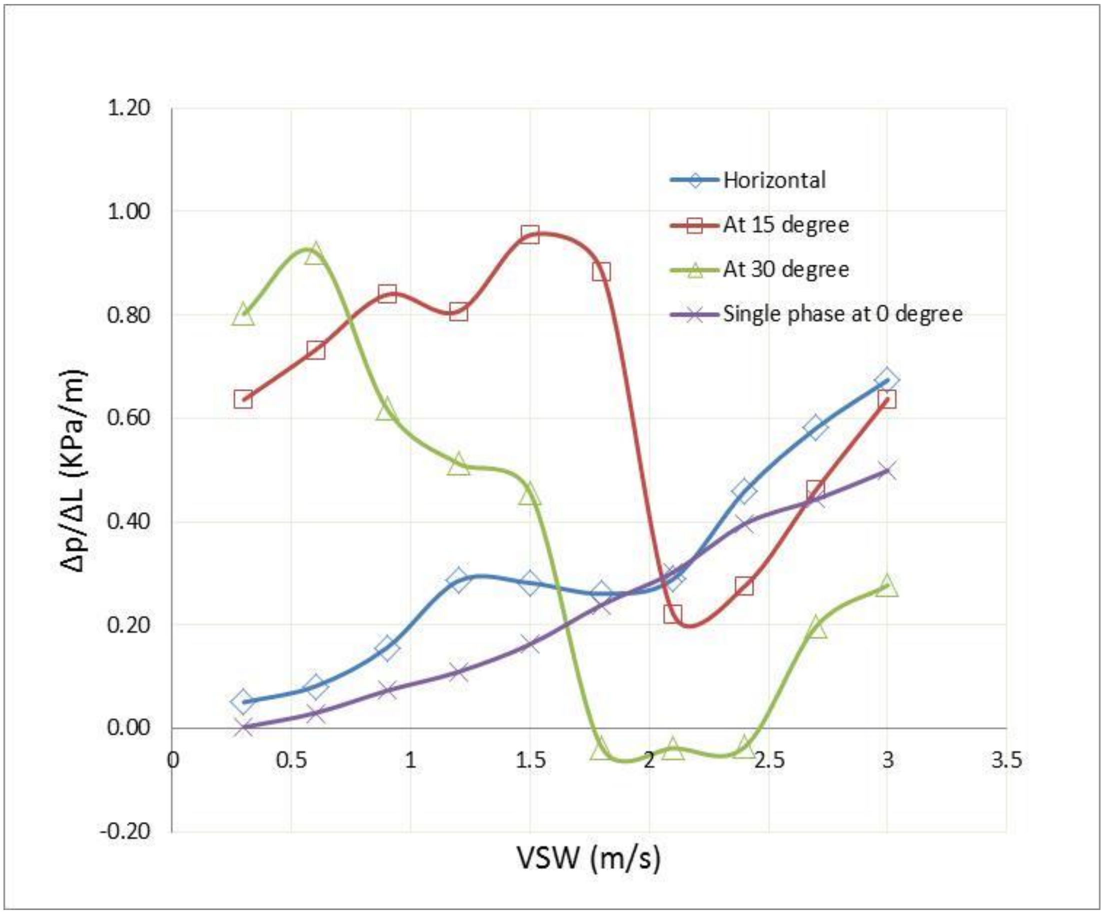

Figure 4.4:- Pressure gradient against VSW at 10 % water cut for upward flows.

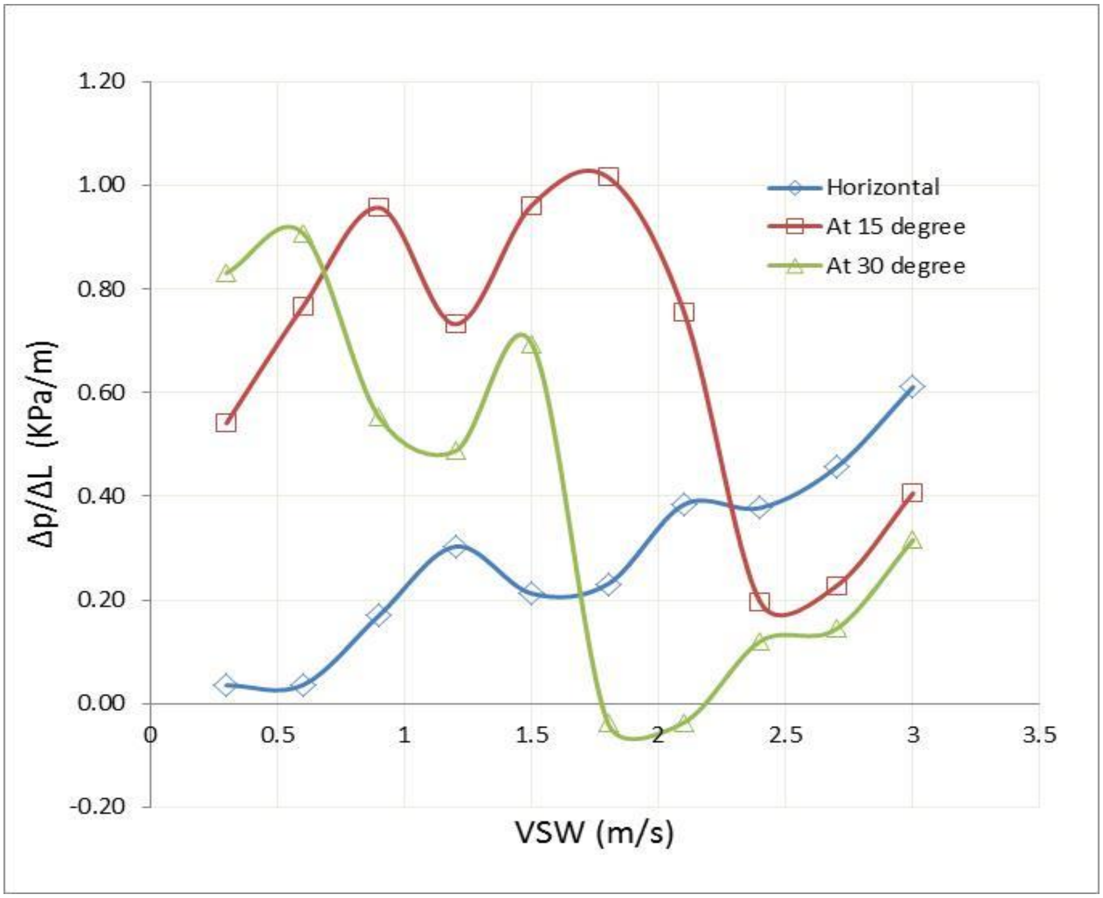

Figure 4.5:- Pressure gradient against VSW at 20 % water cut for upward flows.

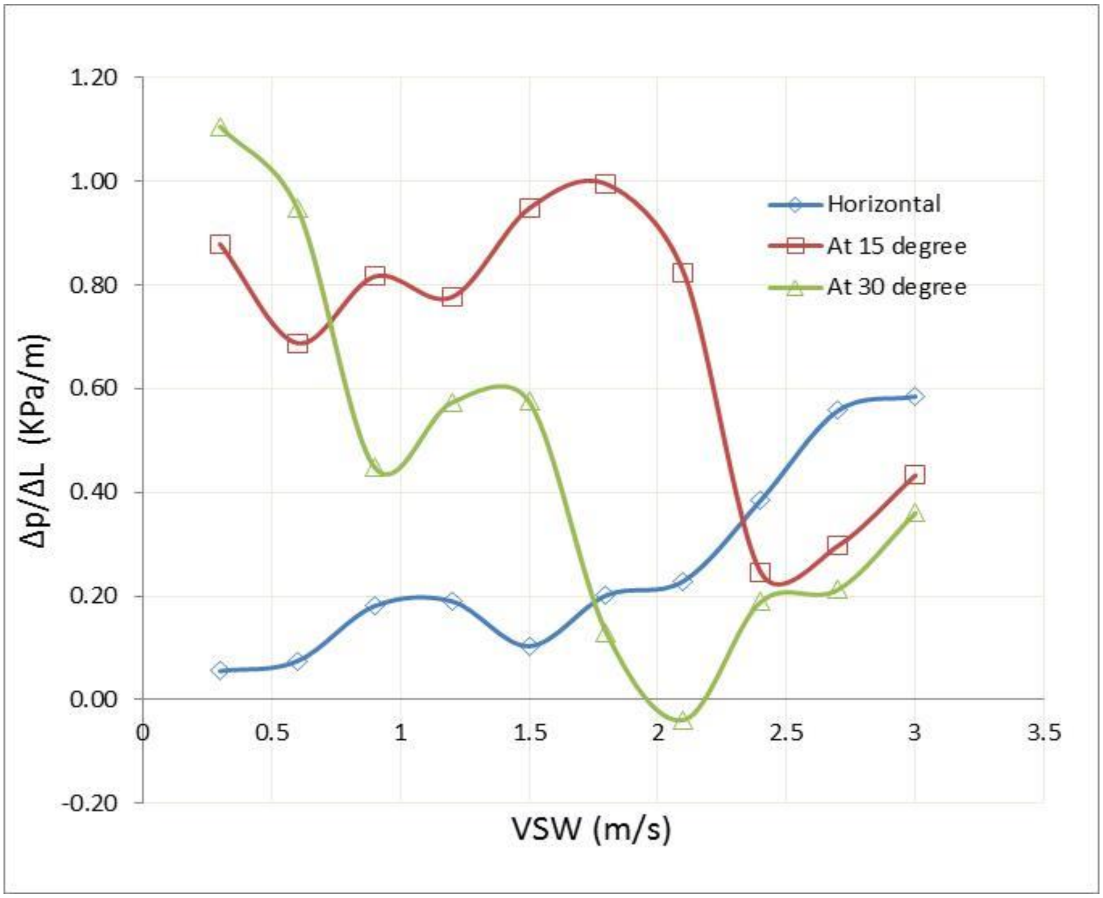

Figure 4.6:- Pressure gradient against VSW at 30 % water cut for upward flows

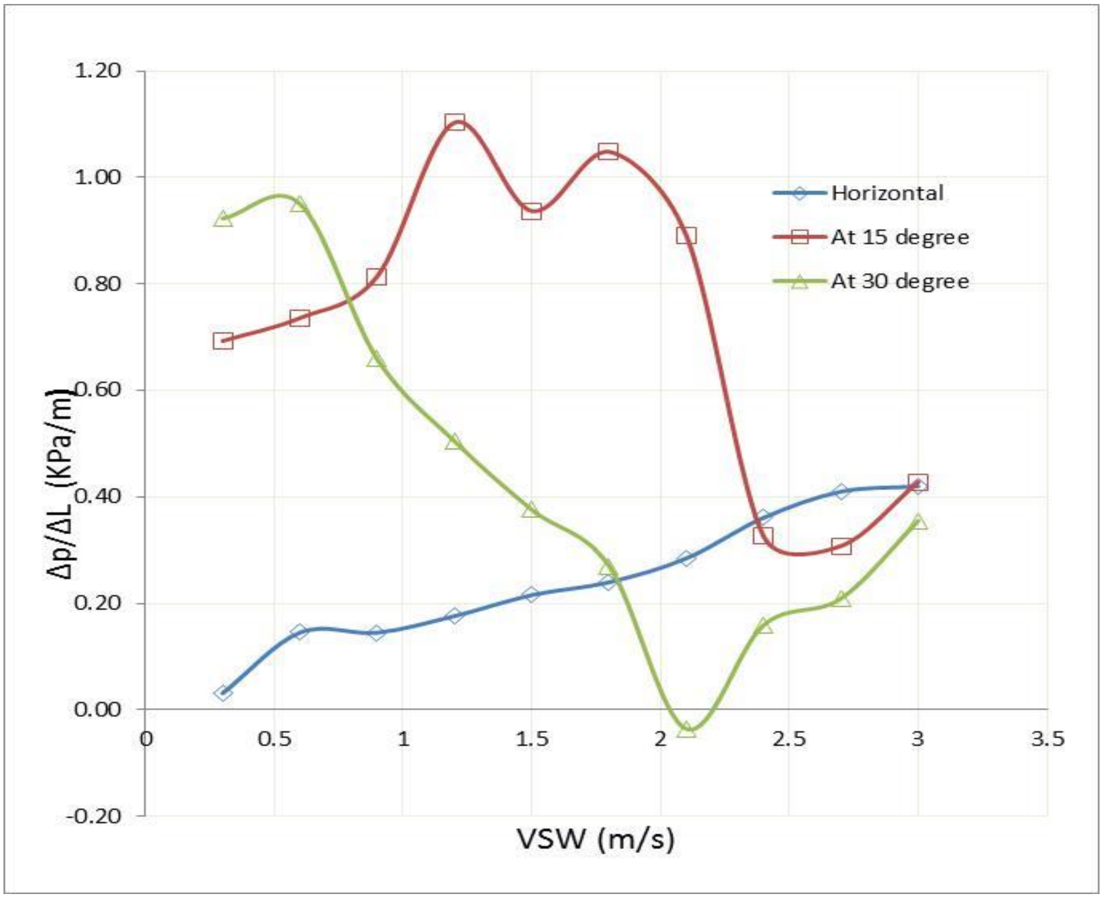

Figure 4.7:- Pressure gradient against VSW at 40 % water cut for upward flows

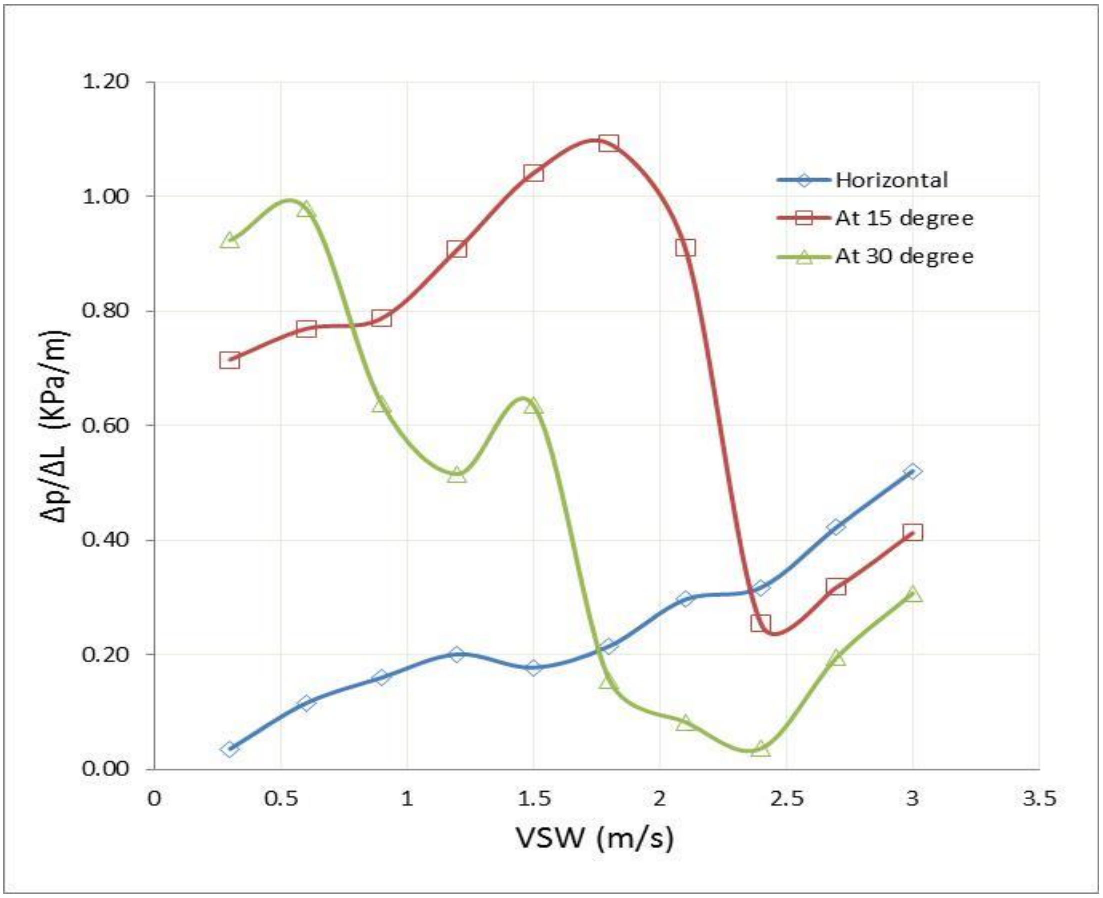

Figure 4.8:- Pressure gradient against VSW at 50 % water cut for upward flows

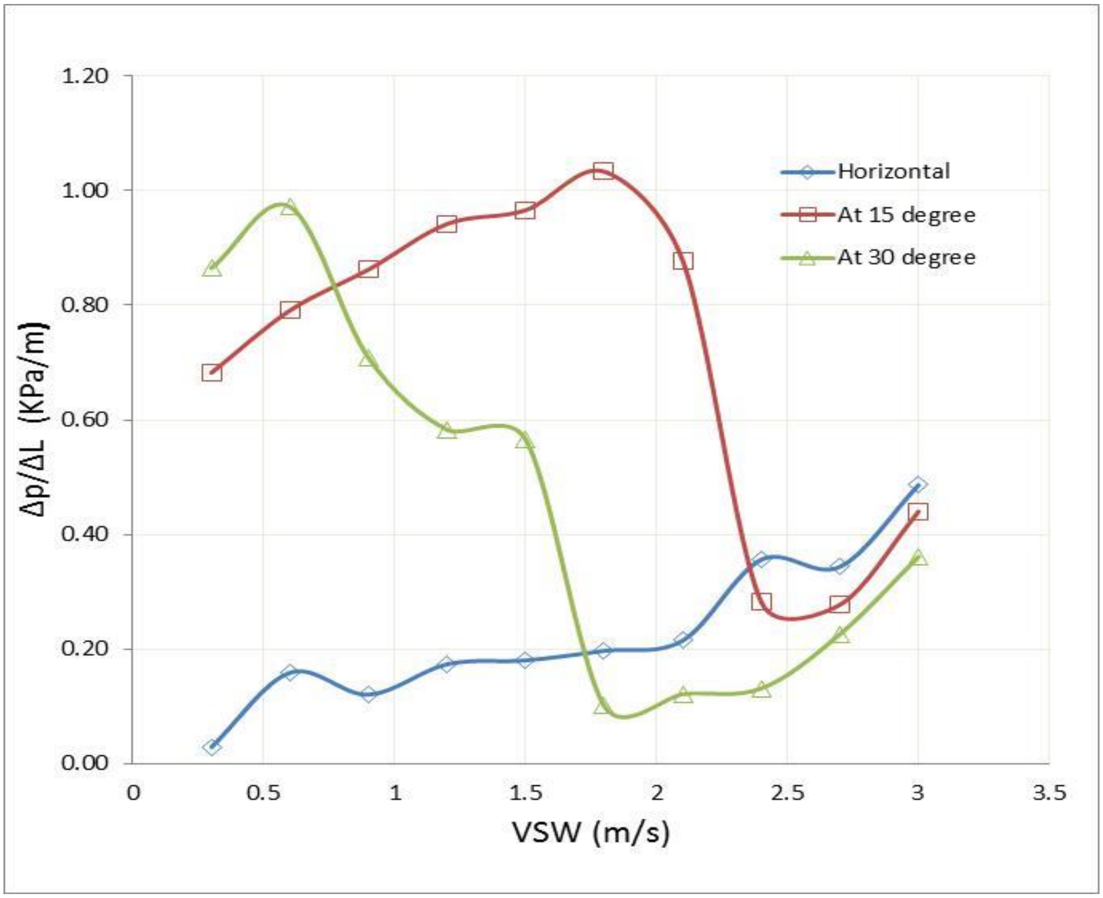

Figure 4.9:- Pressure gradient against VSW at 60 % water cut for upward flows

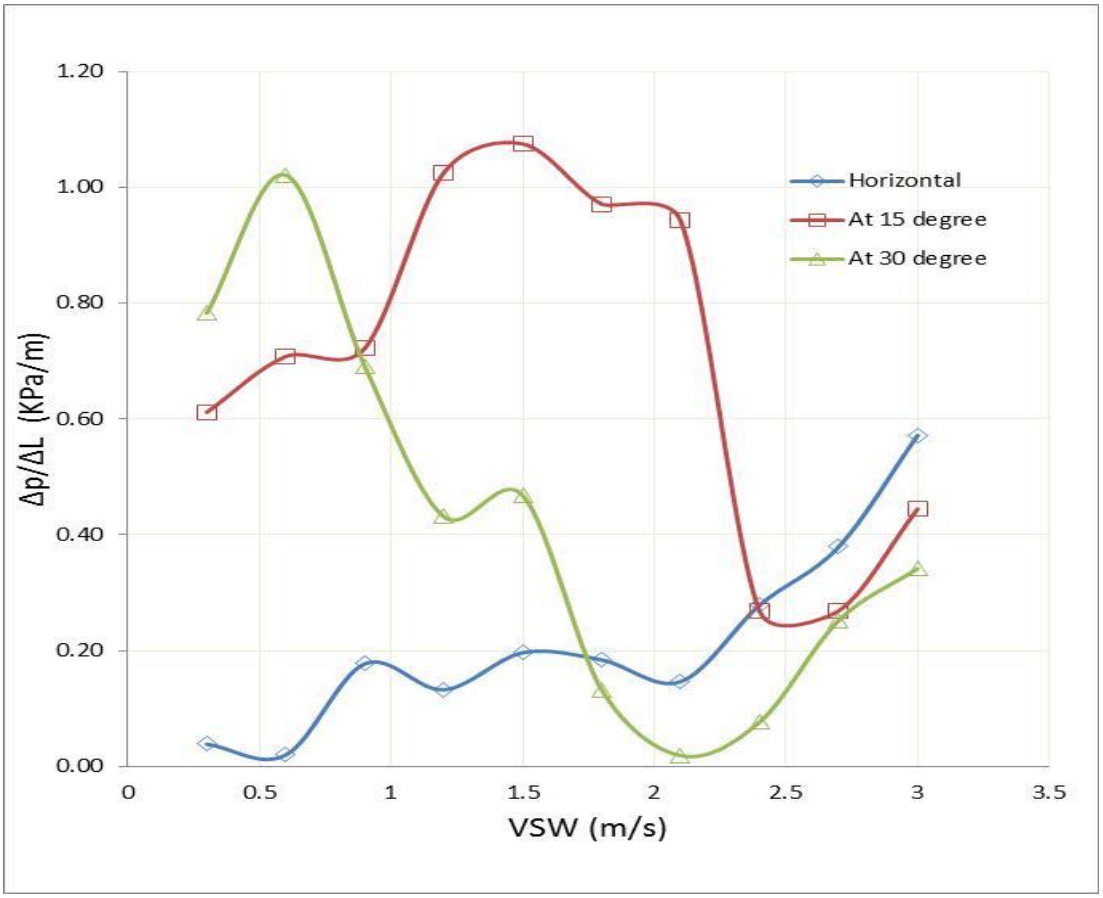

Figure 4.10:- Pressure gradient against VSW at 70 % water cut for upward flows

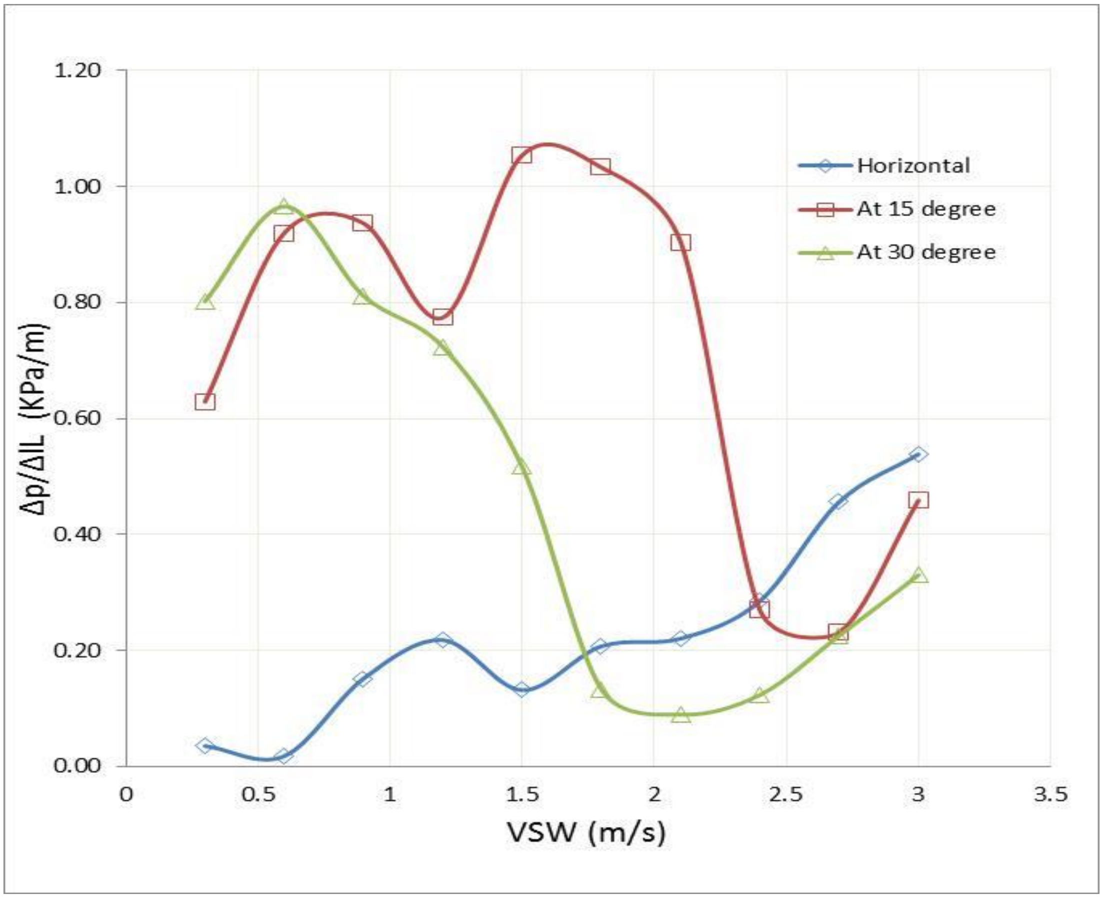

Figure 4.11:- Pressure gradient against VSW at 80 % water cut for upward flows

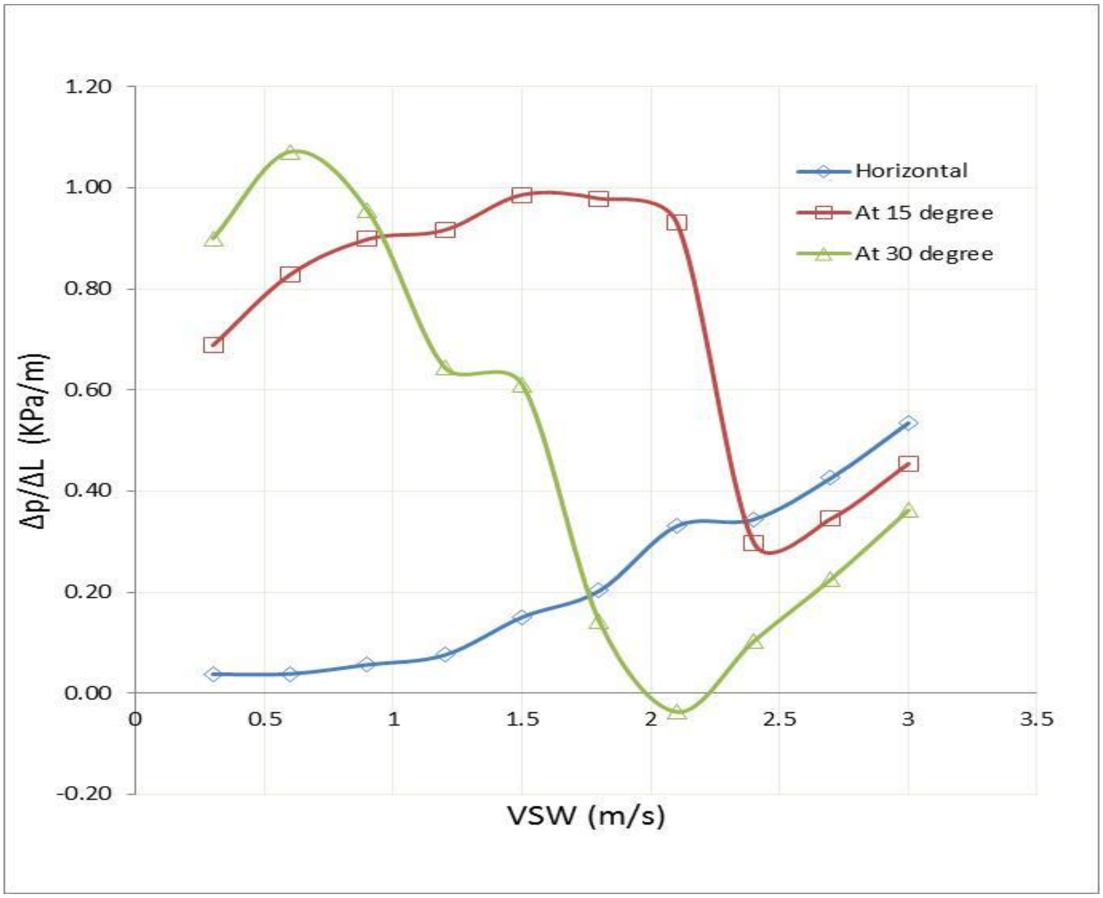

Figure 4.12:- Pressure gradient against VSW at 90 % water cut for upward flows

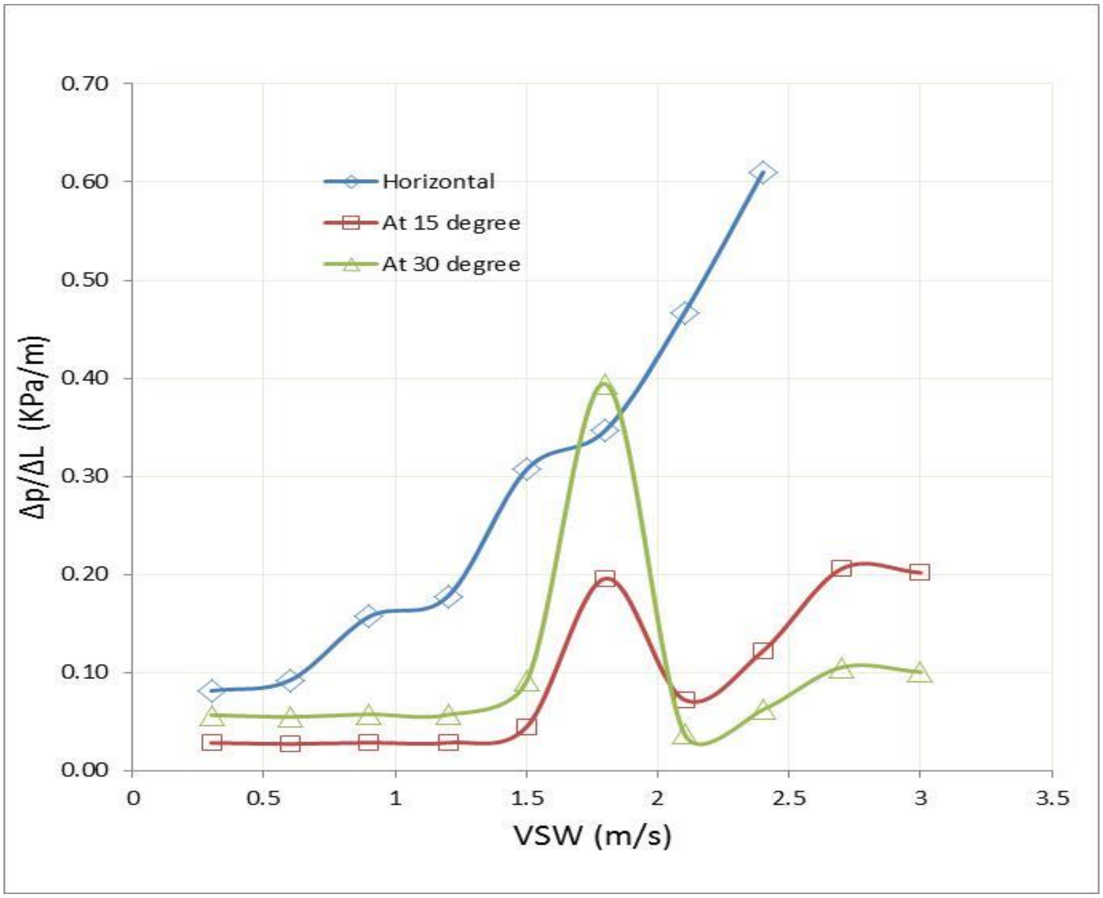

Figure 4.13:- Pressure gradient against VSW at 10 % water cut for downward flows

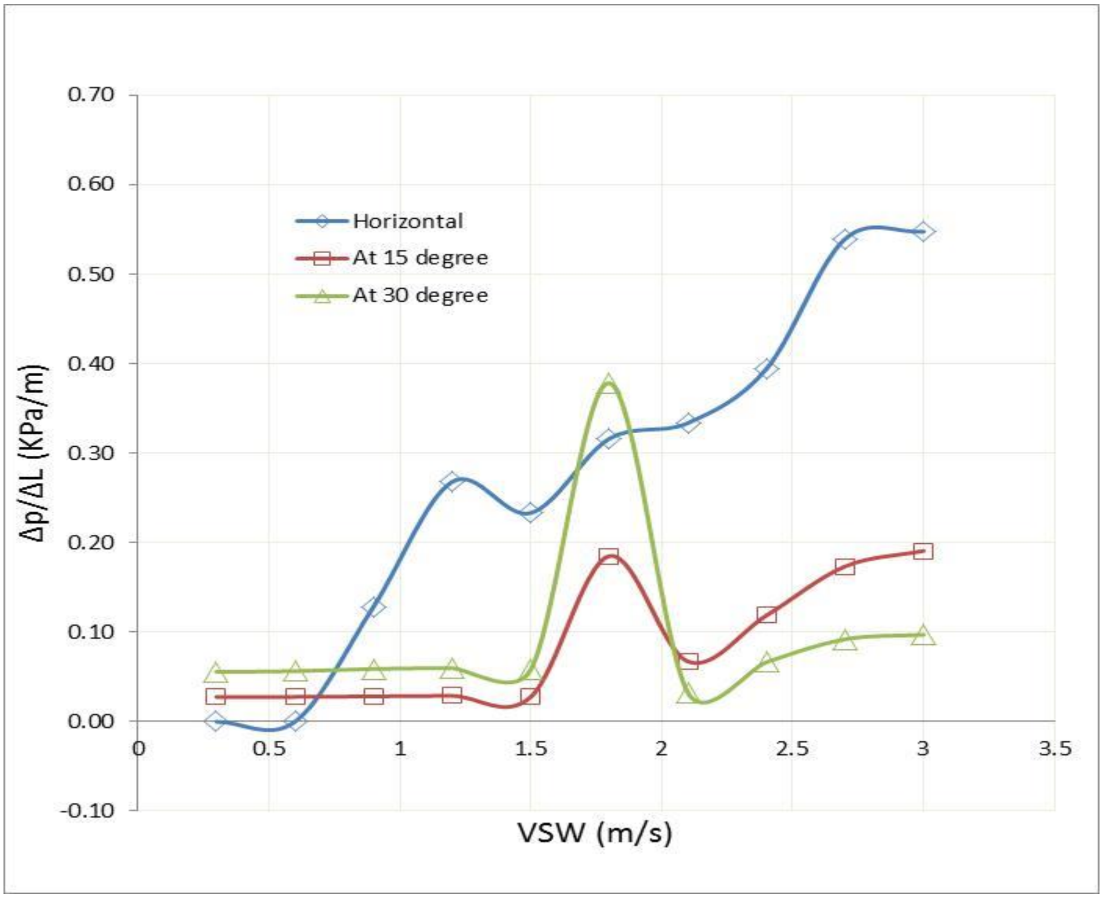

Figure 4.14:- Pressure gradient against VSW at 20 % water cut for downward flows

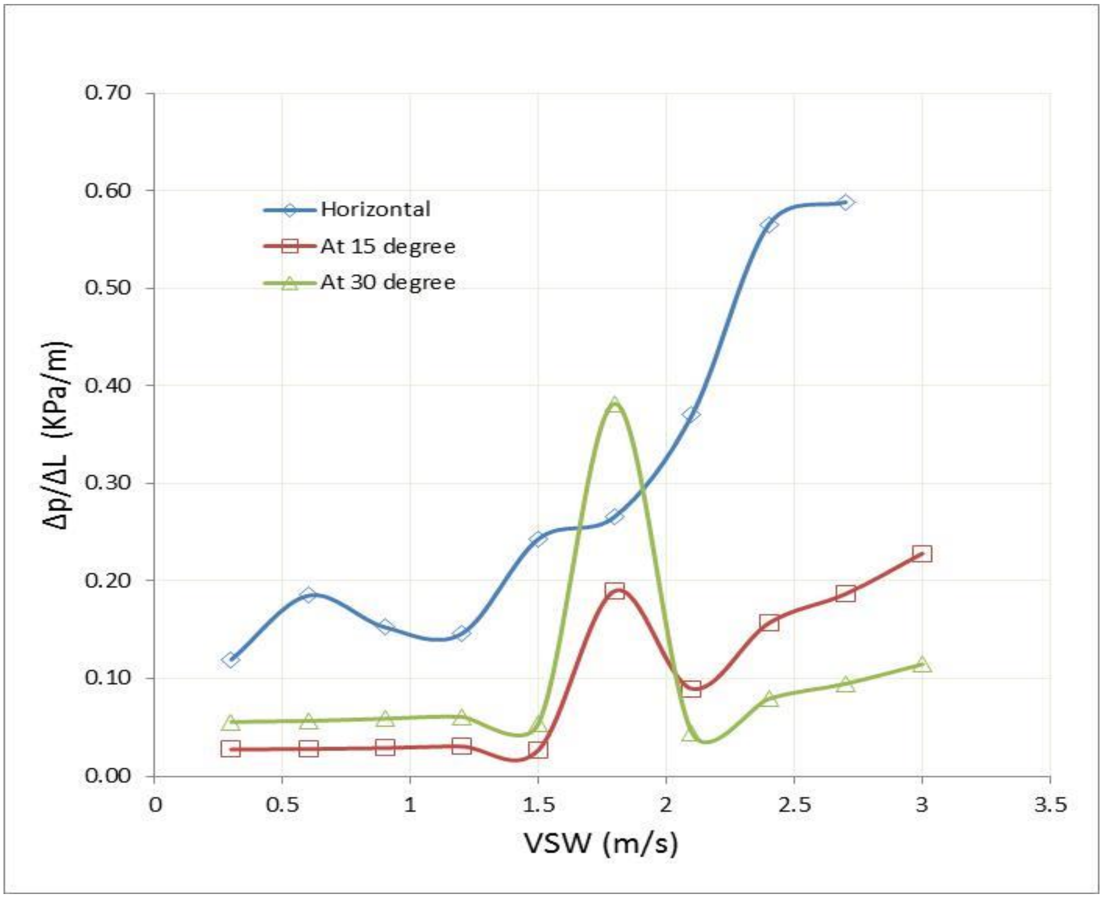

Figure 4.15:- Pressure gradient against VSW at 30 % water cut for downward flows

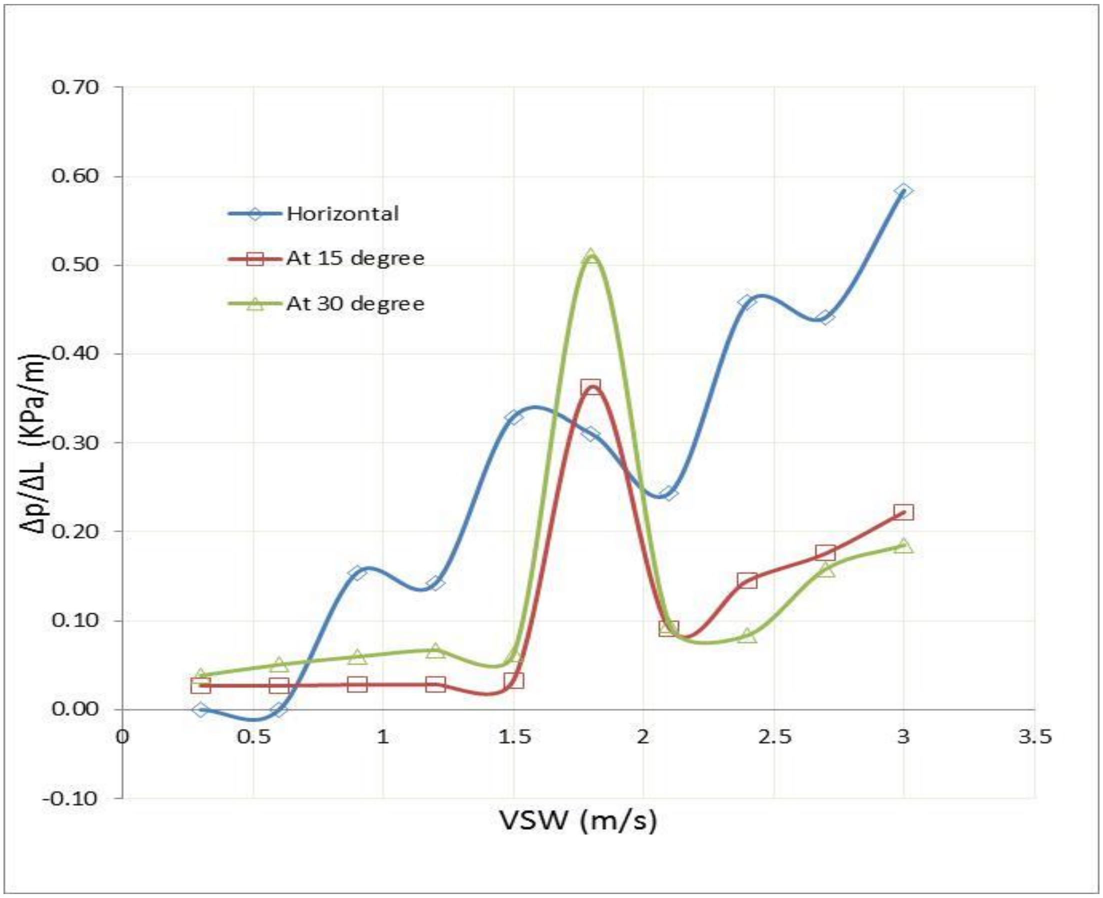

Figure 4.16:- Pressure gradient against VSW at 40 % water cut for downward flows

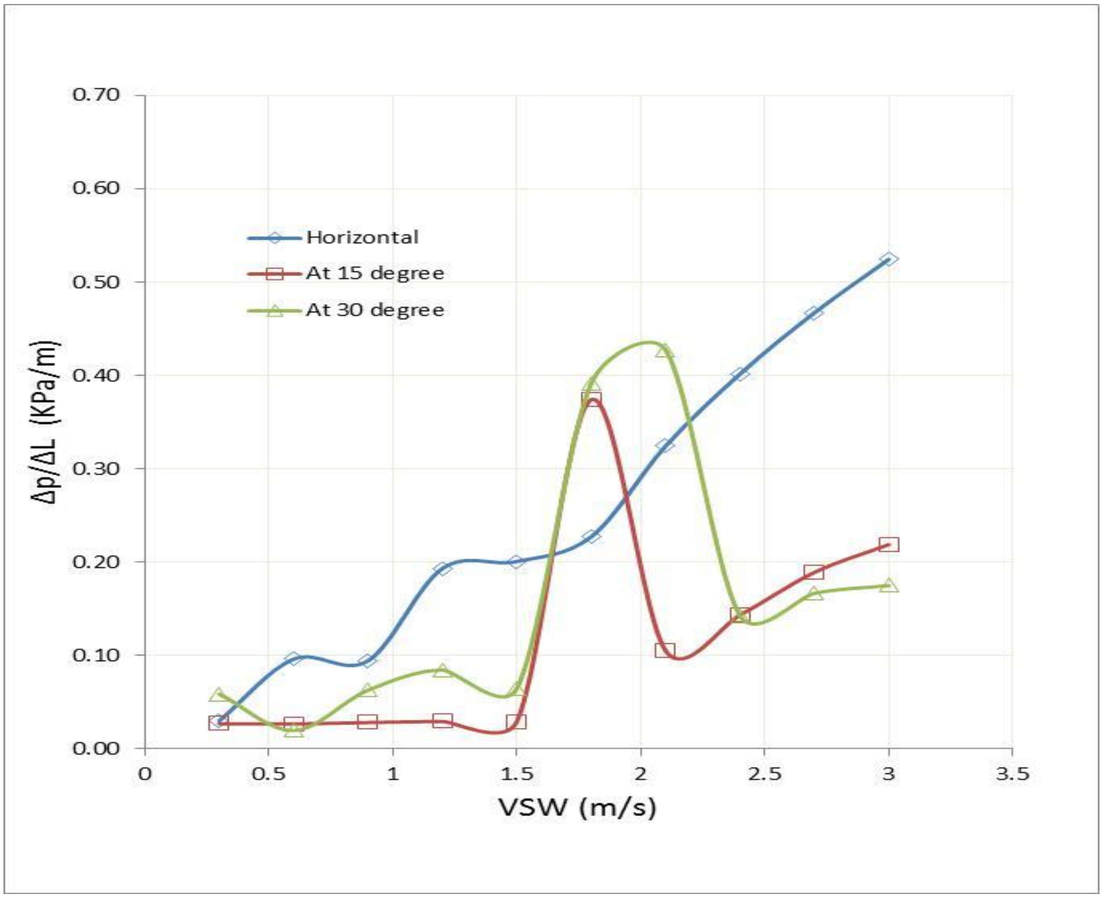

Figure 4.17:- Pressure gradient against VSW at 50 % water cut for downward flows

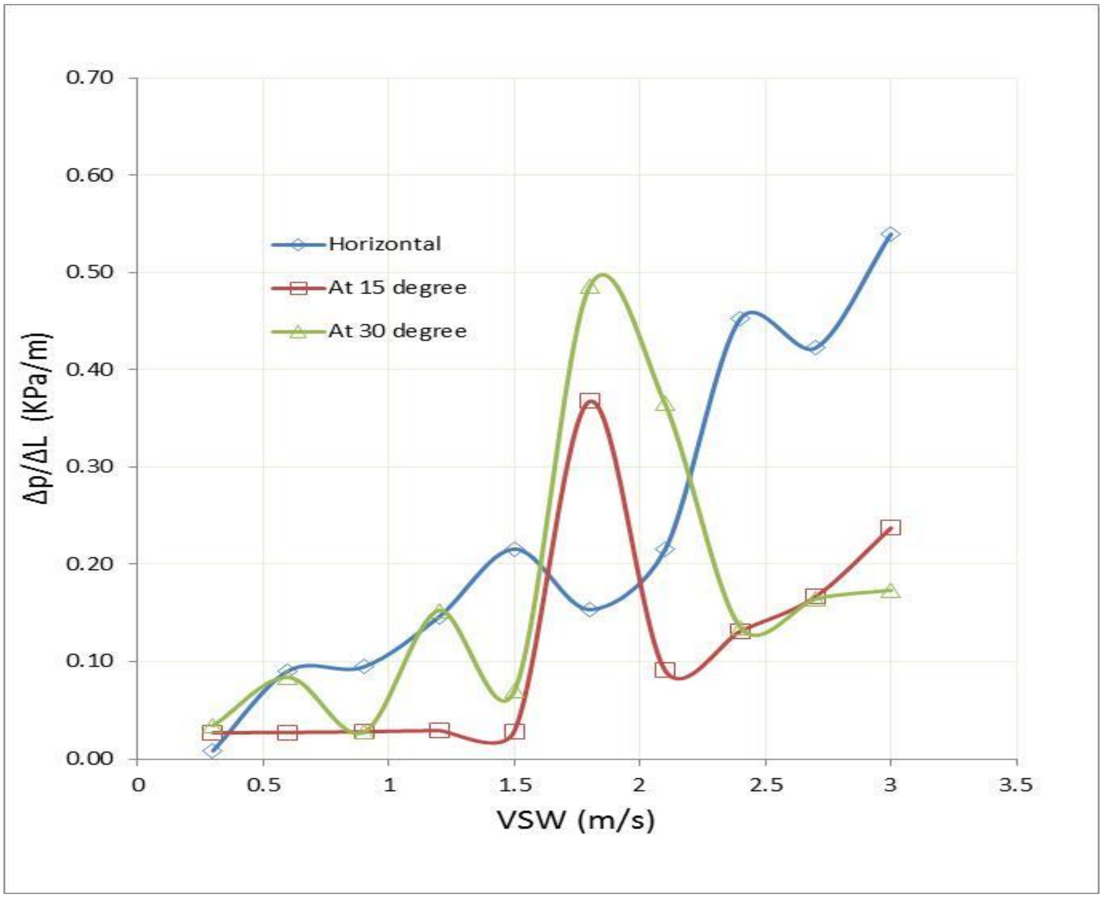

Figure 4.18:- Pressure gradient against VSW at 60 % water cut for downward flows

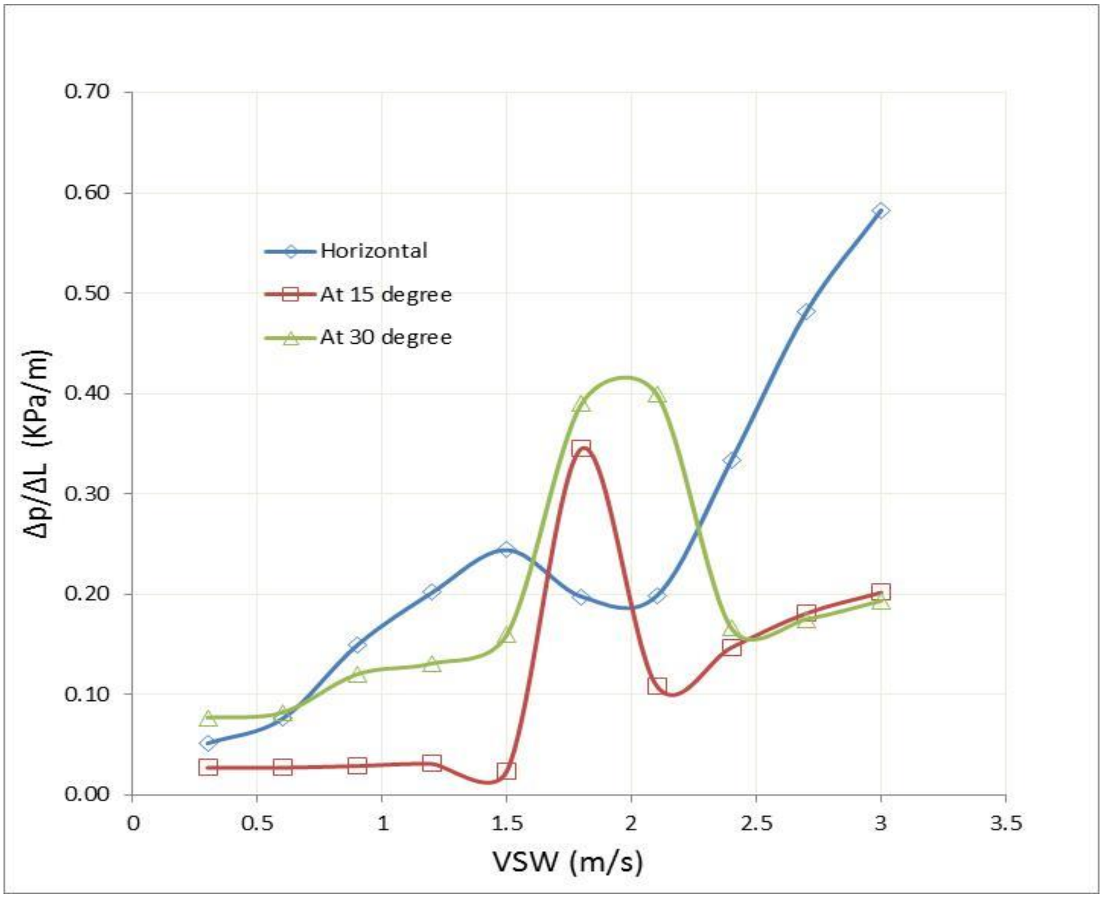

Figure 4.19:- Pressure gradient against VSW at 70 % water cut for downward flows

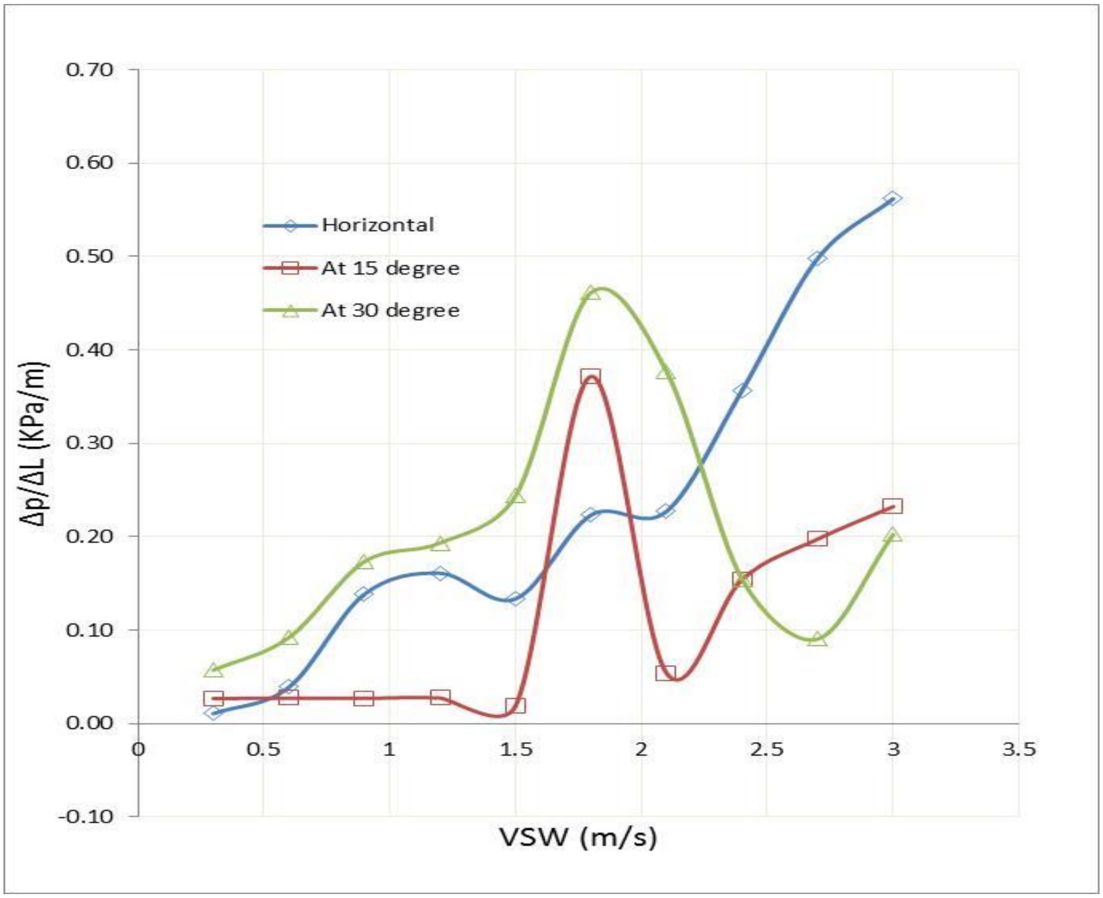

Figure 4.20:- Pressure gradient against VSW at 80 % water cut for downward flows

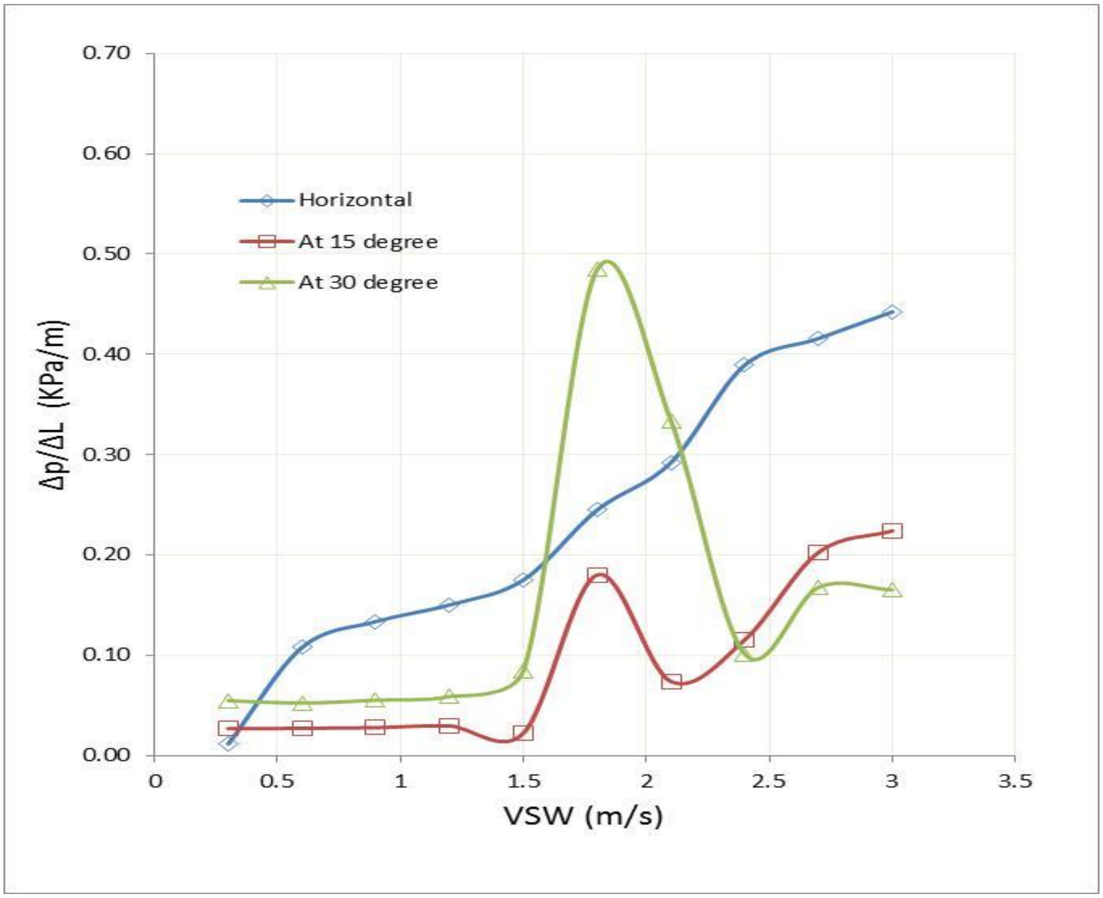

Figure 4.21:- Pressure gradient against VSW at 90 % water cut for downward flows

4.3 EFFECT OF WATER CUT ON PRESSURE GRADIENT

Figures 4.24-4.29 shows the effect of water cut on pressure gradient for horizontal, upward and downward flows. The maximum value of pressure gradient for horizontal pipe shown in figure 4.24 is 0.67 kPa/m at 10 % water cut. From 10% to 40 % water cut the value of pressure gradient decreases and at 40 % water cut it reaches its minimum value of 0.42 kPa/m. From 40 % to 70 % water cut pressure gradient increases gradually and its value at 70 % water cut is 0.58 kPa/m. After 70 % pressure gradient decreases suddenly for 80 % and 90 % its value is almost the same that is 0.55 kPa/m.

For VSW 0-1.5 m/s the maximum pressure gradient 0.30 kPa/m is at 20 % water cut then pressure gradient decreases as the water cut increase for this range of VSW and at 70 % water cut the pressure gradient decreases form 0.42 kPa/m to 0.15 kPa/m.at 90 % water cut the pressure gradient line is almost straight and its value decreases to 0.07 kpa/m.

For VSW 1.5-2.1 m/s the pressure gradient is maximum at 20 % water cut with value of 0.34 kPa/m then it decreases gradually till 70 % water cut and its value decreases from 0.34 kPa/m to 0.14 kpa/m then increases at 80 and 90 % water cut and its value is 0.22 kPa/m and 0.24 kPa/m respectively.

For VSW 2.1-3.0 m/s the pressure gradient value 0.69 kpa/m is maximum at 10 % water cut then decreases gradually up to 30 % water cut and then suddenly drop at 40 % water cut to 0.42 kPa/m then increases to 0.58 kpa/m at 70 % water cut then again decreases to 0.52 kPa/m at 90 % water cut.

Figure 4.25 illustrate the effect of water cut on the pressure gradient for upward flows at 15 degree inclination. For VSW 0-1 m/s the maximum pressure gradient is 0.0.97 kPa/m at 20 % water cut and then decreases to 0.82 kPa/m at 50 % water cut.at 60 % water cut pressure gradient increases again to the value of 0.86 kPa/m and keep increasing up to 80 % water cut and its value at 80 % water cut is 0.92 kPa/m then pressure gradient decreases again to 0.84 kPa/m at 90 % water cut.

For VSW 1-1.5 m/s the maximum pressure gradient is 1.5 kPa/m at 40 % water cut so when water velocity increases the pressure gradient shift from 20 to 40 % water cut. For this range of water velocity the minimum pressure gradient is 0.78 kPa/m at 20 % water cut. At low velocities the maximum peak of pressure gradient is achieved at 20 % water cut and as the water velocity increase to 1.5 m/s the peak of pressure gradient shifts to 40 % water cut.

For VSW 1.5-2.5 m/s there is s sudden drop in pressure gradient but for each water cut this drop in pressure gradient is almost the same expect at 10 % water cut.at 10 % there was a more air which used to much energy at start and then as the velocities increases the air extract energy results sudden drop in pressure gradient. For this range of water velocities the maximum peak of pressure gradient is achieved at 50 % water cut and there is also a inversion point at 50 % water cut. The maximum pressure gradient is 1.48 kPa/m at 50 % water cut and minimum pressure gradient 0.19 kPa/m is achieved at 20 % water cut.

For VSW 2.5-3.0 m/s the maximum peak of pressure gradient is at 10 % water cut and minimum peak of pressure gradient is at 20 % water cut other pressure gradient for all water cut lies between these two water cut. The maximum value of 0.62 kPa/m is achieved at 10 % water cut and minimum 0.19 kPa/m is achieved at 20 % water cut. From 10 to 50 % water cut the pressure gradient increase gradually and then decreases to 80 % water cut then again increases at 90 % water cut.

Figure 4.26 shows the effect of water cut on pressure gradient for upward flow at 30 degree. For VSW 0-1 m/s the maximum peak is achieved at 90 % water cut and minimum is at 10 % water cut. From 10 % water cut to 60 % water cut the pressure gradient increases smoothly and its value reaches to 0.59 kPa/m at 60 % water cut.at 70 % water cut there is inversion point at VSW 0.42 m/s and then again pressure gradient increases at 80 and 90 % water cut.at 90 % water cut pressure gradient 1.4 kPa/m is maximum and 0.42 kPa/m is minimum value of pressure gradient for this range of VSW.

For VSW 1.0-2.0 m/s the maximum peak of pressure gradient is achieved at 20 % water cut and minimum is achieved at 10 % water cut. For 10 and 20 % water cut the pressure gradient drops the same value that is minimum for this range of VSW.0.66 Pkpa/m is the maximum pressure gradient at 20 % water cut and -0.08 is minimum value of pressure gradient achieved for this range of VSW. At 70 % water cut there is inversion point because at this points pressure drop decrease otherwise pressure gradient increases for all water cut. From 10 to 60 % water cut pressure gradient increase from -0.08 kPa/m to 0.17 kPa/m and decreases to 0.04 kPa/m at 70 % water cut and then again increases to 0.12 kPa/m at 80 % water cut.

For VSW 2.0-3.0 m/s the maximum peak for pressure gradient is achieved at 60 % water cut and minimum is achieved at 10 % water cut. From 10 % to 40 % water cut pressure gradient increases and at 50 % water cut there is inversion point at 2.4 m/s water velocity so pressure gradient decreases to 0.06 kPa/m at 50 % water cut. From 50 % to 90 % water cut pressure gradient again increases gradually and reaches to 0.28 kPa/m at 80 % water cut.

Figure 4.27 shows the effect of water cut on pressure gradient for downward flow at 0 degree and it is clear from the figure that it is similar to the figure 4.24 that represented the upward flows at 0 degree. Only difference is at 10 % water cut pressure gradient was 0.68 kpa for upward flow but for downward it is 0.62 kPa/m otherwise the trend is exactly the same as upward flow at o0 degree. The maxima and minima are at the same velocities as was for the upward flows can be seen in figure 4.24

Figure 4.28 represents the effect of water cut on pressure gradient for downward flow at 15 degree inclination. For VSW 0-1.5 m/s the pressure gradient showed the same trend for all water cut first it is nearly zero then drops to negative values as the water velocity increases but the maximum drop occurred at 80 % water cut. For this range of velocities the maximum drop is -0.01 kpa/m at 80 % water cut and minimum drop in pressure gradient -0.03 kPa/m is at 10 % water cut.

For VSW 1.5-2.2 m/s there is a critical region where pressure gradient suddenly increased and then suddenly decreased. From 10 % water cut to 50 % water cut pressure gradient increased to a the same point but there is a sudden jump in pressure gradient as we move from 50 % water cut to 60 % water cut. Pressure gradient at 50 % water cut is 0.2 kPa/m and it jump to 0.36 kpa/m at 60 % water cut.so there is an inversion point at 60 % water cut at VSW 1.7 m/s. From 60 % to 90 % water cut the pressure gradient rise up to the same point but a bit less at 70 % water cut.as the velocities increased the pressure gradient decreased and maximum decreased occurred at 80 % water cut.at 80 % water cut the 0.49 kPa/m pressure gradient is maximum drop and minimum drop in pressure gradient is at 10 % water cut its value dropped to 0.11 kPa/m.

For VSW 2.2-3.0 m/s there is an increase in pressure gradient for all water cut. The maximum increase in pressure gradient occurred at 60 % water cut and minimum increase in pressure gradient occurred at 20 % water cut. The maximum value of 0.24 kPa/m is achieved at 60 % water cut and minimum value 0.19 kPa/m is achieved at 20 % water cut. From 20 % to 60 % water cut there is straight increase in pressure gradient to 0.24 kPa/m but it decreased at 70 % water cut to 0.20 kpa/m then again increased at 80 % and 90 % water cut to 0.23kPa/m and 0.22 kPa/m respectively.

Figure 4.29 illustrate the effect of water cut on pressure gradient for downward flows at 30 degree inclination. For VSW 1-1.5 m/s there are fluctuations in the pressure gradient for less water cuts as water cut increases fluctuations decreased and vanishes at 90 % water cut. The maximum peak of pressure gradient is achieved at 60 % water cut and minimum pressure gradient is achieved at 10 % water cut. The pressure gradient 0.17 kpa/m is in this range is maximum at 60 % water cut and minimum 0.01 kPa/m is achieved at 10 % water cut.

For VSW 1.5-2.5 m/s there is a critical region where pressure gradient increase and decrease dramatically. The maximum peak of pressure gradient is achieved at 40 % water cut and its value is 0.52 kPa/m and minimum increase in pressure gradient occurred at 70 % water cut and peak is 0.41 kPa/m. From 10 % to 60 % water cut the pressure gradient increase gradually and reached to 0.50 kPa/m at 60 % water cut then decreases to 0.41 kPa/m at 70 % water cut and then again increases at 80 % and 90 % water cut to 0.48 kpa/m and 0.49 kPa/m respectively.as the water cut increase the pressure gradient decreases and maximum decrease in pressure gradient occurred at 20 % water cut and minimum decreased occurred at 70 % water cut and decrease is gradual for 10 % to 60 % water cut.

For VSW 2.5-3.0 m/s there is increase in pressure gradient for all water cuts but maximum increase in pressure gradient is occurred at 70 % water cut and its peak is 0.20 kpa/m and minimum increase in pressure gradient occurred at 20 % water cut that is 0.10 kPa/m.20 % to 70 % water cut there is a gradual increase in pressure gradient and at 80 % water cut there is inversion point at VSW 3.0 m/s and pressure gradient decrease to 0.18 kPa/m at 90 % water cut.

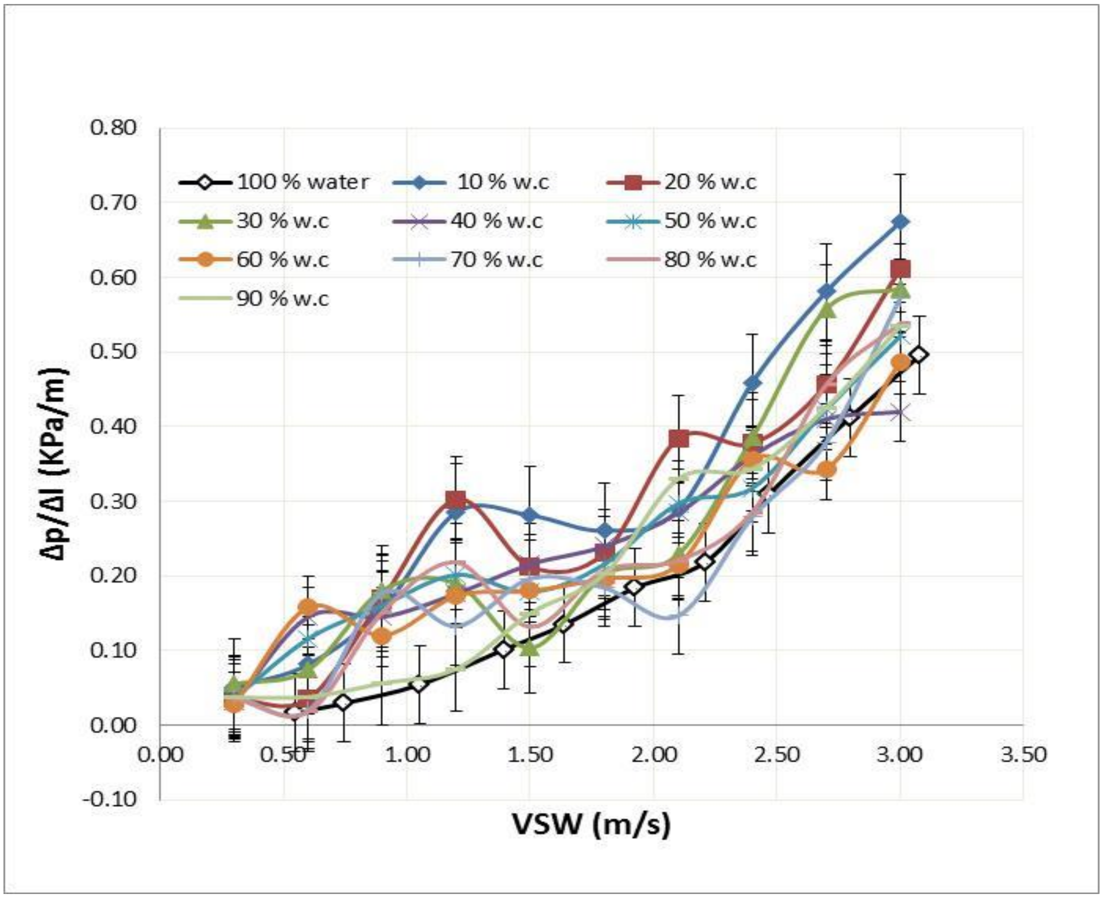

Figure 4.22:- Effect of water cut on pressure gradient for upward flows at 0 degree

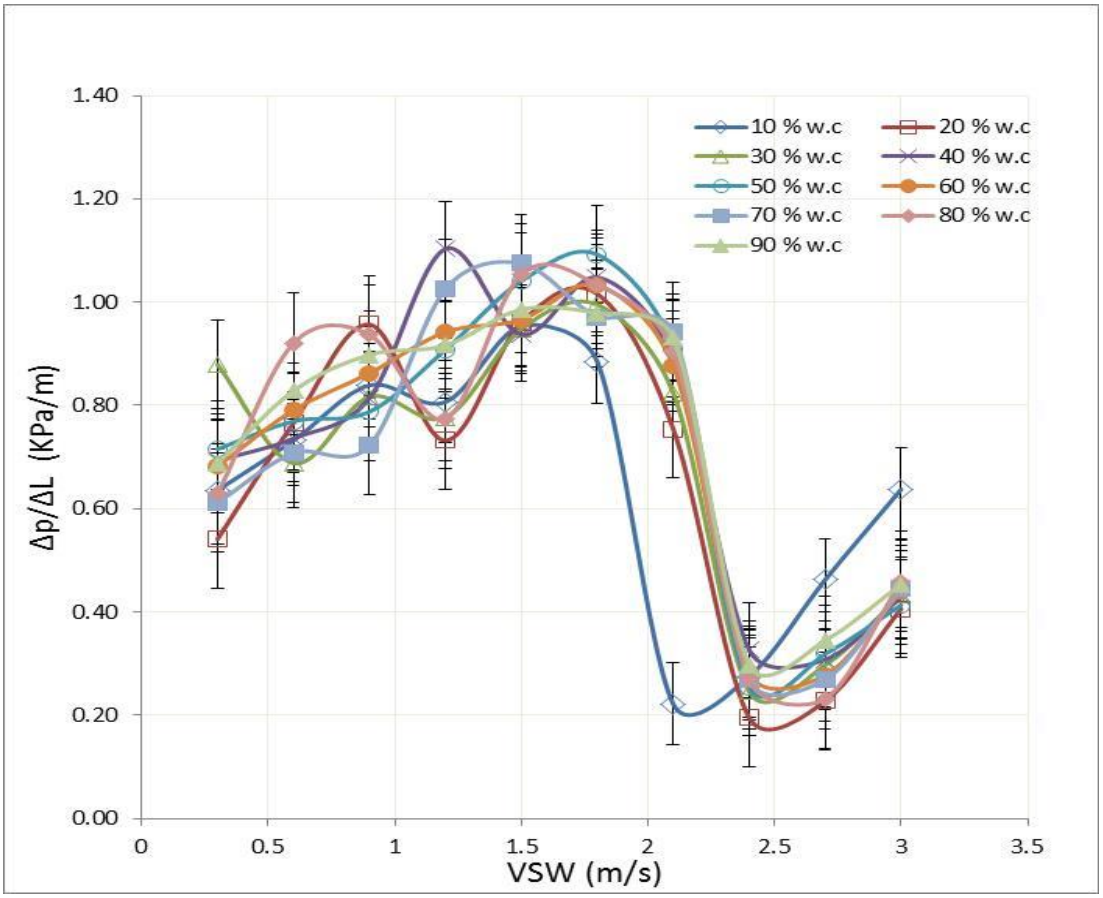

Figure 4.23:- Effect of water cut on pressure gradient for upward flows at 15 degree

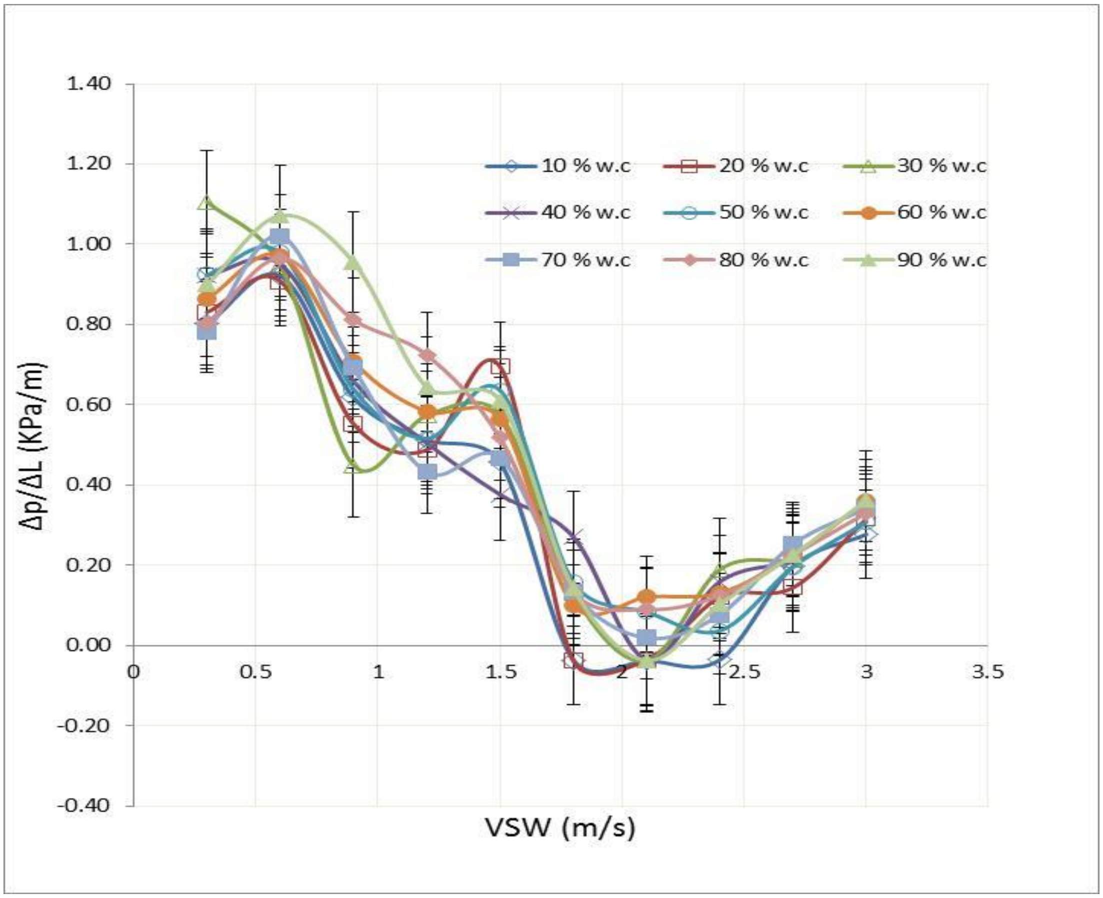

Figure 4.24:- Effect of water cut on pressure gradient for upward flows at 30 degree

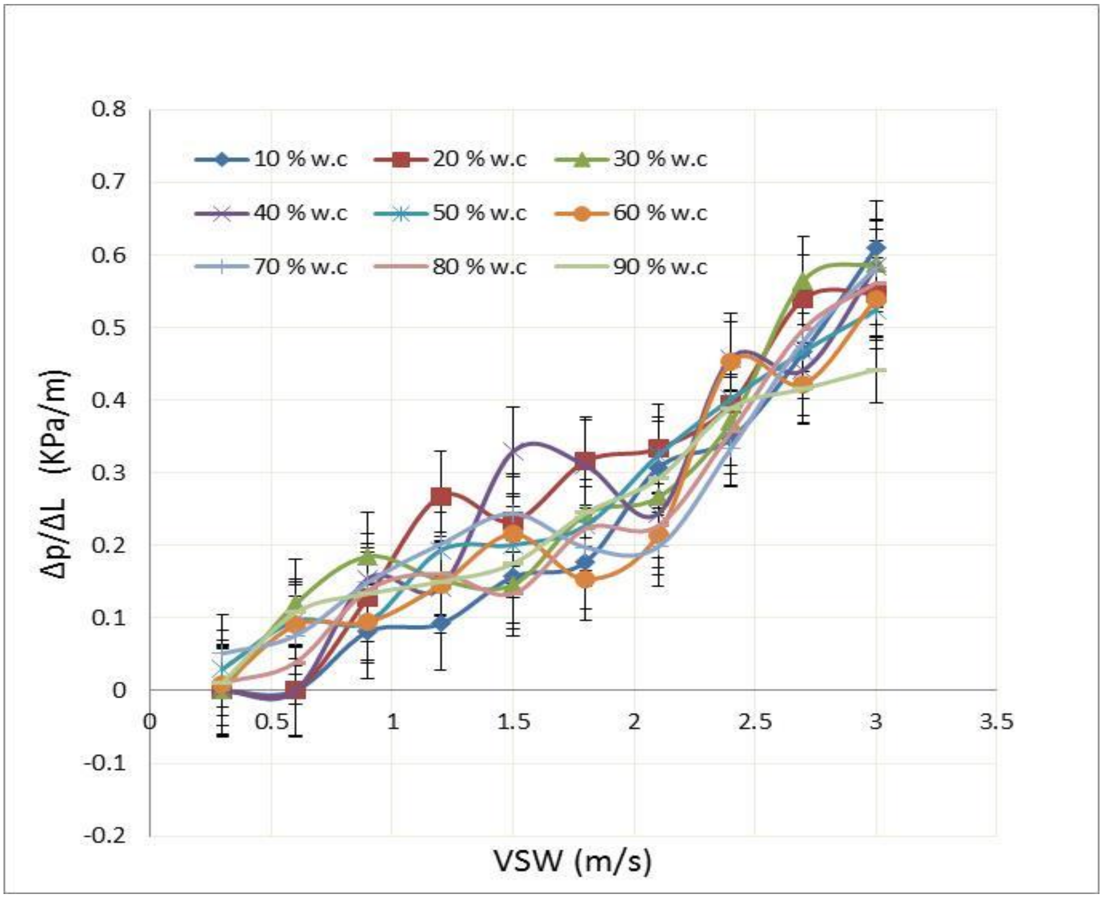

Figure 4.25:- Effect of water cut on pressure gradient for downward flows at 0 degree

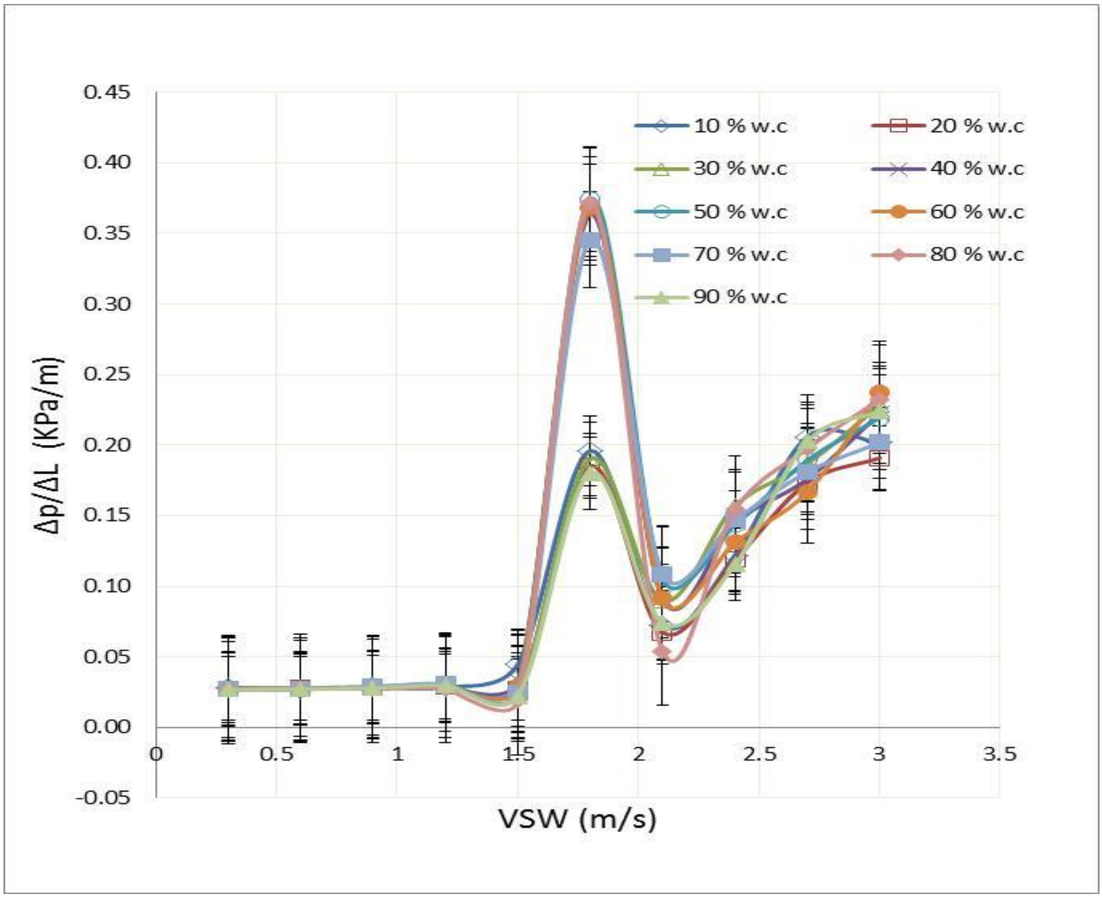

Figure 4.26:- Effect of water cut on pressure gradient for downward flows at 15 degree

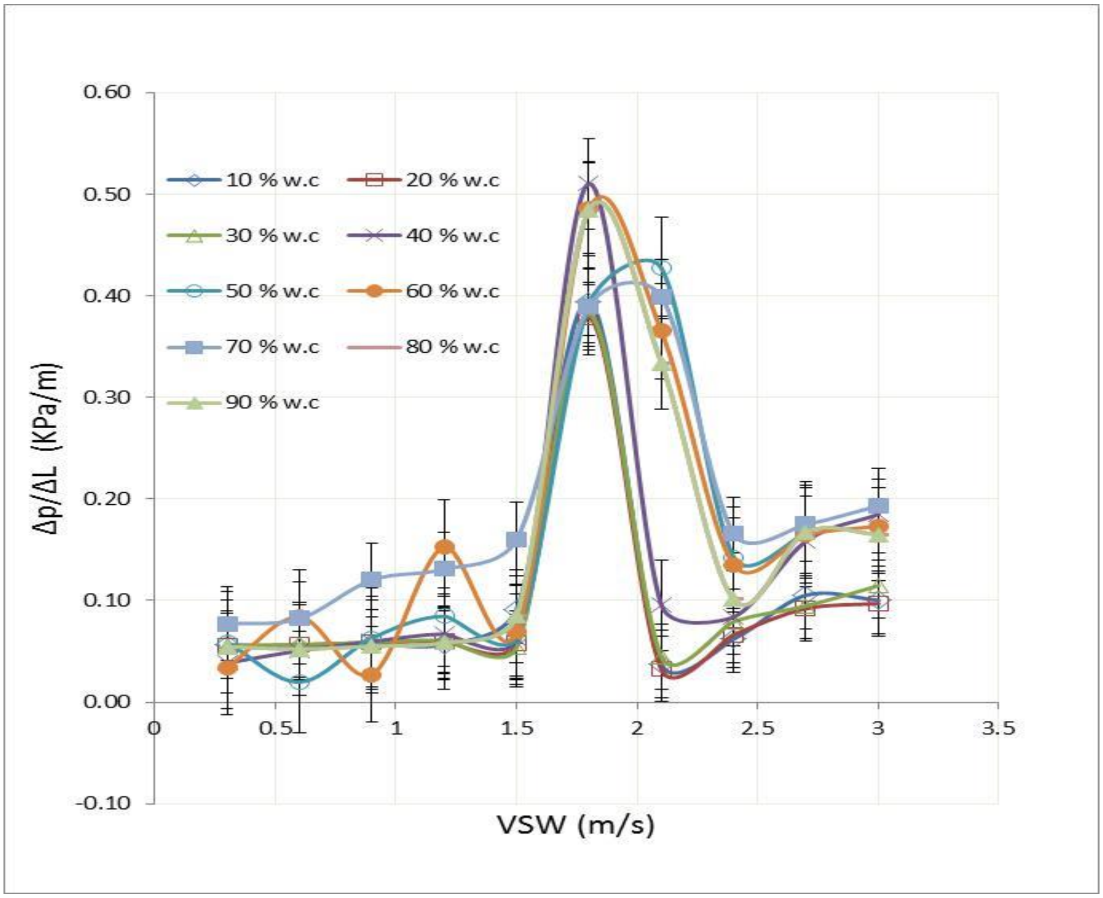

Figure 4.27:- Effect of water cut on pressure gradient for downward flows at 30 degree

CHAPTER 5 **CONCLUSIONS AND RECOMMENDATIONS**

A multiphase flow loop was constructed at North Compound in King Fahd University of Petroleum and Minerals (KFUPM) to calculate the pressure gradient of air-water in a horizontal and inclined stainless steel pipeline with inner diameter of 4 inch.

The effects of inclination on the pressure gradient is studied also effect of water cut on air-water two phase flow is taken into account. The experiments were performed for 10% to 90% water cut in step of 10%.

This chapter was divided into two sections. Section 5.1 presented the main conclusions of the work described in this thesis. Recommendations for future work were given in sectionb5.2.

5.1 CONCLUSIONS

The experimental data was recorded in stainless steel pipe at horizontal and large angles of inclination, with a wide range of superficial liquid and gas velocities.

5.1.1 Single Phase Water Flow

The single phase water friction factor was measured and compared with Blasius and Zigrang & Sylvester friction factor. It gave good agreement and the roughness of the pipe was determined to be $1 \times 10^{-5}\ m$ which showed that, the pipe is smooth.

5.1.2 Pressure Gradient

1. Experimental data were gathered for an air-water system in a 4 inch pipe at 0 ° , + 15 ° , - 15 °, + 30 ° , - 30°.
2. Pressure drop was different either side of a superficial water velocity of about 2.0 m/s. Below this value upward flows possessed the highest pressure gradient and above this value upward flows showed minimum values of pressure gradient and same criterion applies to downward flows.
3. The pressure gradient increases with increasing gas flow rates for horizontal flows.
4. In order to emphasize the effect of inclination on the behavior of air-water flow, the pressure drops were presented against liquid velocity. It was noted that the effect of inclination is not straightforward.
5. The pressure gradient first increases and then decreases with increasing water cut in upward flows.

6. Pressure drops were found high generally in upward flows. This is due to the two reasons. a) The intermittent flow is dominant in upward flow that's why it yields high pressure loss. b) in upward flow the hydrostatic term is positive so the pressure drop is high.

7. In downward pipes the pressure drop is less because the hydrostatic term is negative.

8. In horizontal pipes pressure drops is only due to friction and acceleration because the hydrostatic pressure component is zero.

5.2 RECOMMENDATIONS

The following recommendations are made based on the results of this thesis in order to improve the quality of the data and to extend the scope of the area of research:

1. Ultrasonic flow meters shouldn't be used for measurement of flow rate. Rotor type flow meters are more suitable

2. Flow meters that can cover both bigger and smaller scales should be used in order to have wider range of water velocities.

3. Pumps with lower pressure capacity should be used in order to have wider range of liquid velocities.

4. A data acquisition system should be connected to flow meters to avoid human error.

5. Flow pattern should be investigated.

6. A temperature sensor should be mounted on the settling tank of the liquid mixture in order to accurately observe the temperature of the mixture.

7. A braided rubber hose should be mounted on the pipe before getting to the mixture pipe in order to dampen pressure fluctuations before the phases enter the test section.

8. The effects of the following should be carried out on the pressure drop and flow pattern:

    a) Varying pipe diameters.
    b) Roughness and wettability of the test section.
    c) Varying angles of inclination of the pipe.
    d) Different testing fluids can also be used.

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NOMENCLATURE

A	Cross-sectional area of the pipe $[m^2]$
A_a	Cross-sectional area of the pipe occupied by air $[m^2]$
A_w	Cross-sectional area of the pipe occupied by water $[m^2]$
D	Diameter of the pipe $[\ m\ ]$
f	Friction factor
bpd	barrel per day
ID	Inner diameter $[\ m\ ]$
L	Length of the pipe $[\ m\ ]$
Q_a	Volumetric flow rate of air $[m^3/s]$
Q_w	Volumetric flow rate of water $[m^3/s]$
Q_{Liquid}	Volumetric flow rates of the liquid $[m^3/s]$
Q_{total}	Total volumetric flow rates $[m^3/s]$
Re	Reynolds’s number
VSG	Superficial velocity of gas (air) $[m/s]$
VSW	Superficial velocity of water $[m/s]$

WC	Water cut

Greek Symbols

ρ_a	Density of air $[kg/m^3]$
ρ_w	Density of water $[kg/m^3]$
μ_a	Viscosity of air $[\ Pa.s\ ]$
μ_w	Viscosity of water $[\ Pa.s\ ]$
ΔP	Pressure drop $[\ Pa\ ]$
$\frac{\Delta P}{\Delta L}$	Pressure gradient $[\ Pa/m\ ]$
$\left(\frac{\Delta P}{\Delta L}\right)_{Water}$	Pressure gradient of single-phase water $[\ Pa/m\ ]$
ε	Pipe roughness

APPENDIX A

Single phase water sample calculations

Theoretical pressure gradient for single phase can be calculated as:

We know the flow rate so we can calculate the velocity

Flow rate = Q = 21 m^3/hr

Inner diameter of the pipe (D) = 0.1016 m

Velocity calculated as

Velocity = V = $\frac{4*Q}{3.14*D^2} = \frac{4*21}{3.14*3600*0.1016^2}$ = 0.7198 m/s

Reynolds number calculated as

Re = $\frac{\rho*v*D}{\mu} = \frac{998*0.7198*0.1016}{0.001} =$ 72,985.42

This Reynolds number can be used to calculate the friction factor

For Blasius correlation,

$f = 0.316Re^{-0.25}$= 0.316*$(72985.42)^{-0.25}$ = 0.01922

For case of Zigrang & Sylvester friction factor:

Pipe roughness (ε) = 1×10^{-6} m

Internal diameter of pipe (D) = 0.1016 m

Reynolds number at 21 m^3/hr water flow rate = 72,985.42

Applying the Zigrang & Sylvester Correlation,

$$\frac{1}{\sqrt{f}} = -2log\left[\frac{\varepsilon/D}{3.7} - \frac{5.02}{Re}log\left[\left(\frac{\varepsilon/D}{3.7}\right) + \frac{13}{Re}\right]\right]$$

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{(1*10^{-6})/0.1016}{3.7} - \frac{5.02}{72985.42}log\left[\frac{(1*10^{-6})/0.1016}{3.7} + \frac{13}{72985.72}\right]\right]$$

$$\frac{1}{\sqrt{f}} = -2log(2.6\times10^{-6} - 6.87\times10^{-5}\log(2.6\times10^{-6} + 1.78\times10^{-4}))$$

$$\frac{1}{\sqrt{f}} = 7.1708$$

$$f = 0.01944$$

The Zigrang & Sylvester friction factor is very similar to that of Blasius friction factor and both are very similar to experimental friction factor particularly Blasius friction factor is almost the same as experimental friction factor.

Single Phase water friction factors

Water flow rate	Water velocity	Reynolds Number	Measured friction factor	Blasius friction factor	Zigrang & Sylvester friction factor	% error	% error
m3/hr	m/s					Blasius	Zigrang & Sylvester friction factor
8	0.274	27347	0.0255	0.0251	0.0264	1.5	3.4
12	0.411	41021	0.0255	0.0251	0.0247	1.5	3.2
17	0.582	58113	0.0222	0.0218	0.0235	1.8	5.5
21	0.719	71787	0.0214	0.0211	0.0229	1.4	6.5
28	0.959	95716	0.0205	0.0202	0.0222	1.4	7.6
32	1.096	109390	0.0202	0.0199	0.0219	1.5	7.7
40	1.37	136737	0.0196	0.0193	0.0215	1.5	8.8
48	1.644	164085	0.0192	0.0189	0.0212	1.5	9.4
54	1.849	184595	0.019	0.0187	0.021	1.6	9.5
62	2.123	211943	0.0187	0.0184	0.0209	1.6	10

APPENDIX B

Pressure gradient of single phase water for horizontal, upward and downward flows

Single phase water	Upward Flows			Downward Flows		
	Horizontal	15 degree	30 degree	Horizontal	15 degree	30 degree
Flow Rate	Δp/ΔL	Δp/ΔL	Δp/ΔL	Δp/ΔL	Δp/ΔL	Δp/ΔL
bpd	Kpa/m	kpa/m	kpa/m	kpa/m	kpa/m	kpa/m
1868.36	0.014	0.040	0.107	0.015	-0.039	-0.082
2920.69	0.030	0.051	0.126	0.033	0.019	0.062
4636.49	0.047	0.077	0.155	0.056	0.118	0.120
6134.79	0.092	0.143	0.189	0.080	0.140	0.184
7470.52	0.131	0.168	0.219	0.129	0.203	0.239
8481.10	0.184	0.217	0.271	0.200	0.234	0.286
9733.35	0.218	0.276	0.349	0.281	0.290	0.344
10875.75	0.310	0.345	0.414	0.339	0.362	0.392
12325.72	0.413	0.448	0.476	0.412	0.413	0.466
13599.93	0.496	0.516	0.555	0.460	0.524	0.495

Pressure gradient of single phase oil for horizontal, upward and downward flows

Single phase oil	Upward flows			Downward flows		
	Horizontal	15 degree	30 degree	Horizontal	15 degree	30 degree
Flow Rate	Δp/ΔL	Δp/ΔL	Δp/ΔL	Δp/ΔL	Δp/ΔL	Δp/ΔL
bpd	kpa/m	kpa/m	kpa/m	kpa/m	kpa/m	kpa/m
1660.450	0.017	0.059	0.092	0.032	-0.024	-0.057
2113.300	0.024	0.067	0.101	0.040	-0.013	-0.043
2566.150	0.033	0.077	0.107	0.046	-0.007	-0.038
3019.000	0.042	0.090	0.121	0.060	0.010	-0.030
3471.850	0.055	0.101	0.132	0.070	0.022	-0.011
4377.550	0.082	0.137	0.166	0.101	0.052	0.017
4981.350	0.107	0.159	0.198	0.129	0.076	0.037
5434.200	0.125	0.179	0.222	0.147	0.091	0.057

APPENDIX C

Matrix range for the pressure gradient of two phase flow at 10 % to 90 % water cut for horizontal, upward and downward flows

10 % water cut		Upward flows			Downward flows		
		0 degree	15 degree	30 degree	0 degree	15 degree	30 degree
VSW	VSG	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL
m/s	m/s	kpa/m	kpa/m	Kpa/m	kpa/m	Kpa/m	Kpa/m
0.3	2.7	0.051	0.636	0.802	-	0.028	0.057
0.6	5.4	0.082	0.732	0.921	-	0.027	0.055
0.9	8.1	0.156	0.839	0.618	0.081	0.028	0.057
1.2	10.8	0.286	0.807	0.512	0.092	0.028	0.057
1.5	13.5	0.281	0.955	0.457	0.157	0.045	0.091
1.8	16.2	0.261	0.885	-0.036	0.178	0.196	0.394
2.1	18.9	0.289	0.222	-0.038	0.307	0.072	0.038
2.4	21.6	0.459	0.275	-0.036	0.347	0.122	0.062
2.7	24.3	0.581	0.462	0.198	0.466	0.206	0.105
3.0	27.0	0.674	0.637	0.277	0.610	0.202	0.100

Air+water two phase flows							
20 % water cut		Upward flows			Downward flows		
		0 degree	15 degree	30 degree	0 degree	15 degree	30 degree
VSW	VSG	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL
m/s	m/s	kpa/m	kpa/m	Kpa/m	kpa/m	Kpa/m	Kpa/m
0.3	1.2	0.035	0.541	0.831	-	0.028	0.056
0.6	2.4	0.036	0.766	0.908	-	0.028	0.056
0.9	3.6	0.170	0.957	0.552	0.129	0.028	0.059
1.2	4.8	0.303	0.732	0.487	0.268	0.029	0.060
1.5	6	0.212	0.961	0.695	0.233	0.028	0.058
1.8	7.2	0.231	1.016	-0.038	0.316	0.185	0.378
2.1	8.4	0.384	0.754	-0.036	0.334	0.067	0.032
2.4	9.6	0.378	0.195	0.120	0.394	0.119	0.066
2.7	10.8	0.457	0.227	0.144	0.540	0.173	0.092
3	12	0.611	0.406	0.316	0.548	0.191	0.097

Air+water two phase flows							
30 % water cut		Upward flows			Downward flows		
		0 degree	15 degree	30 degree	0 degree	15 degree	30 degree
VSW	VSG	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL
m/s	m/s	kpa/m	kpa/m	Kpa/m	kpa/m	Kpa/m	Kpa/m
0.3	0.7	0.056	0.879	1.106	-	0.028	0.056
0.6	1.39	0.075	0.688	0.948	0.120	0.028	0.057
0.9	2.09	0.181	0.817	0.449	0.185	0.029	0.059
1.2	2.79	0.190	0.777	0.574	0.153	0.030	0.061
1.5	3.49	0.104	0.948	0.575	0.146	0.027	0.054
1.8	4.19	0.202	0.995	0.130	0.243	0.190	0.382
2.1	4.89	0.229	0.824	-0.039	0.266	0.090	0.045
2.4	5.59	0.385	0.246	0.189	0.370	0.157	0.079
2.7	6.29	0.558	0.297	0.212	0.565	0.187	0.095
3	7	0.585	0.433	0.360	0.588	0.228	0.115

Air+water two phase flows							
40 % water cut		Upward flows			Downward flows		
		0 degree	15 degree	30 degree	0 degree	15 degree	30 degree
VSW	VSG	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL
m/s	m/s	kpa/m	kpa/m	Kpa/m	kpa/m	Kpa/m	Kpa/m
0.3	0.45	0.032	0.693	0.923	-	0.027	0.039
0.6	0.9	0.145	0.736	0.950	-	0.027	0.051
0.9	1.35	0.145	0.814	0.659	0.154	0.028	0.060
1.2	1.8	0.176	1.103	0.505	0.142	0.029	0.067
1.5	2.25	0.216	0.937	0.376	0.330	0.033	0.062
1.8	2.7	0.240	1.048	0.271	0.310	0.364	0.510
2.1	3.15	0.285	0.891	-0.036	0.244	0.091	0.095
2.4	3.6	0.361	0.326	0.159	0.458	0.145	0.084
2.7	4.05	0.410	0.308	0.209	0.442	0.176	0.159
3	4.5	0.420	0.428	0.355	0.584	0.222	0.185

Air+water two phase flows							
50 % water cut		Upward flows			Downward flows		
		0 degree	15 degree	30 degree	0 degree	15 degree	30 degree
VSW	VSG	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL
m/s	m/s	kpa/m	kpa/m	Kpa/m	kpa/m	Kpa/m	Kpa/m
0.3	0.3	0.037	0.715	0.924	0.030	0.027	0.059
0.6	0.6	0.116	0.769	0.979	0.096	0.027	0.020
0.9	0.9	0.161	0.788	0.638	0.095	0.028	0.063
1.2	1.2	0.202	0.908	0.516	0.193	0.030	0.085
1.5	1.5	0.178	1.041	0.636	0.201	0.029	0.065
1.8	1.8	0.216	1.092	0.157	0.227	0.374	0.392
2.1	2.1	0.297	0.911	0.084	0.325	0.105	0.427
2.4	2.4	0.318	0.255	0.037	0.402	0.144	0.143
2.7	2.7	0.423	0.319	0.196	0.467	0.189	0.167
3	3	0.521	0.413	0.308	0.525	0.219	0.175

Air+water two phase flows							
60 % water cut		Upward flows			Downward flows		
		0 degree	15 degree	30 degree	0 degree	15 degree	30 degree
VSW	VSG	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL
m/s	m/s	kpa/m	kpa/m	Kpa/m	kpa/m	Kpa/m	Kpa/m
0.3	0.2	0.029	0.682	0.865	0.008	0.027	0.034
0.6	0.39	0.159	0.791	0.972	0.090	0.027	0.084
0.9	0.59	0.120	0.862	0.708	0.095	0.028	0.027
1.2	0.79	0.173	0.942	0.583	0.146	0.029	0.153
1.5	0.99	0.180	0.966	0.565	0.216	0.028	0.070
1.8	1.19	0.197	1.033	0.100	0.154	0.368	0.486
2.1	1.39	0.215	0.877	0.121	0.215	0.091	0.365
2.4	1.59	0.356	0.281	0.131	0.452	0.131	0.135
2.7	1.79	0.344	0.277	0.226	0.422	0.167	0.164
3	1.99	0.486	0.440	0.361	0.540	0.237	0.173

Air+water two phase flows							
70 % water cut		Upward flows			Downward flows		
		0 degree	15 degree	30 degree	0 degree	15 degree	30 degree
VSW	VSG	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL
m/s	m/s	kpa/m	kpa/m	Kpa/m	kpa/m	Kpa/m	Kpa/m
0.3	0.12	0.039	0.612	0.783	0.051	0.027	0.077
0.6	0.25	0.020	0.708	1.021	0.076	0.027	0.082
0.9	0.38	0.178	0.722	0.691	0.149	0.029	0.120
1.2	0.51	0.133	1.025	0.432	0.202	0.031	0.131
1.5	0.63	0.197	1.075	0.468	0.244	0.024	0.160
1.8	0.76	0.184	0.971	0.133	0.198	0.345	0.390
2.1	0.89	0.147	0.942	0.019	0.198	0.109	0.399
2.4	1.02	0.279	0.268	0.077	0.334	0.147	0.166
2.7	1.15	0.379	0.269	0.252	0.481	0.181	0.175
3	1.27	0.572	0.445	0.342	0.583	0.202	0.193

Air+water two phase flows							
80 % water cut		Upward flows			Downward flows		
		0 degree	15 degree	30 degree	0 degree	15 degree	30 degree
VSW	VSG	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL
m/s	m/s	kpa/m	kpa/m	Kpa/m	kpa/m	Kpa/m	Kpa/m
0.3	0.075	0.036	0.629	0.803	0.011	0.027	0.057
0.6	0.15	0.018	0.920	0.966	0.039	0.027	0.092
0.9	0.225	0.152	0.937	0.812	0.139	0.027	0.173
1.2	0.3	0.218	0.774	0.724	0.161	0.027	0.193
1.5	0.37	0.132	1.054	0.517	0.134	0.019	0.244
1.8	0.45	0.208	1.033	0.134	0.223	0.372	0.461
2.1	0.52	0.221	0.905	0.090	0.227	0.054	0.377
2.4	0.6	0.286	0.270	0.124	0.357	0.154	0.154
2.7	0.67	0.457	0.232	0.226	0.498	0.198	0.090
3	0.75	0.539	0.459	0.330	0.562	0.232	0.203

Air+water two phase flows							
90 % water cut		Upward flows			Downward flows		
		0 degree	15 degree	30 degree	0 degree	15 degree	30 degree
VSW	VSG	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL	ΔP/ΔL
m/s	m/s	kpa/m	kpa/m	Kpa/m	kpa/m	Kpa/m	Kpa/m
0.3	0.03	0.037	0.688	0.900	0.012	0.027	0.055
0.6	0.06	0.038	0.828	1.072	0.108	0.027	0.052
0.9	0.09	0.056	0.898	0.955	0.134	0.028	0.055
1.2	0.13	0.076	0.916	0.644	0.150	0.030	0.059
1.5	0.16	0.150	0.986	0.611	0.175	0.022	0.085
1.8	1.19	0.203	0.979	0.142	0.245	0.180	0.485
2.1	0.23	0.330	0.931	-0.037	0.292	0.074	0.334
2.4	0.26	0.344	0.297	0.103	0.389	0.115	0.101
2.7	0.29	0.426	0.345	0.226	0.416	0.203	0.168
3	0.33	0.535	0.454	0.362	0.442	0.224	0.165

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