MULTIPHASE FLOW IN PIPELINE

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CHEMICAL ENGINEERING
UNIVERSITI TEKNOLOGI PETRONAS
JULY 2009

Multiphase Flow in Pipeline

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Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Chemical Engineering)

JULY 2009

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CHEMICAL ENGINEERING)

Approved by,

____
(Prof. Duvvuri Subbarao)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
July 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

KHAIRUL SYAZWAN BIN ABU SAMAH

ACKNOWLEDGEMENT

First and foremost, I would like to thank to my supervisor for this project, Professor Duvvuri Subbarao for the valuable guidance and advice. He inspired me greatly to work in this project. His willingness to motivate has contributed tremendously to the project. I also would like to thank him for showing me some example that is related to the topic of our project.

Besides, I would like to thank the authority of Universiti Teknologi PETRONAS (UTP) for providing me with a good environment and facilities to complete this project.

Next, I would like to thank Mr Surya Abadi Ganting, PhD student who had help me in setting the prototype and assist me on completing the project.

Finally, an honorable mention goes to my family and friends for their understandings and supports during the completion of this project. Without helps of the particular that are mentioned above, I would have faced many difficulties while doing this project.

ABSTRACT

Transferring oil and gas using pipeline is common way of how the oil and gas industry operate their business. Pipeline is a very economical way to transport large quantities of oil and gas over land. The Transferring of fluids in pipes needs a lot of calculation and consideration.Multiphase flow occurs in transferring oil using pipeline as multiple component are present such as oil and water during the transfer to the refinery plant. In this project, we would like to determine the pressure drop in the pipe as per length of the pipe. The theory of the project lies in the concept of fluid mechanics where the study of fluid and force on them.

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INTRODUCTION

1.1 BACKGROUND OF STUDY

The petroleum industry is involved in the global processes of exploration, extraction, refining, transporting (often with oil tankers and pipelines), and marketing petroleum products. The largest volume products of the industry are fuel oil and gasoline (petrol). Petroleum is also the raw material for many chemical products, including pharmaceuticals, solvents, fertilizers, pesticides, and plastics. The industry is usually divided into three major components: upstream, midstream and downstream. Midstream operations are usually included in the downstream category. The most important in petroleum extraction is the pipeline. This is because in transporting the sources it contains multiphase flow which are in form of liquid, gas and solid. Multiphase flow is used to refer to any fluid flow consisting of more than one phase or component. In the oil and gas industry, it is common to transport a multiphase flow in the pipeline system. This pipeline system is very economical way to transport the oil and gas to other places. The designing of pipeline needs to consider the theory of fluid mechanics and hydraulics. Fluid mechanics is the study of the physics of continuous materials which take the shape of their container. In transferring fluids through pipeline, the need of fluid mechanics is very important in order to design a suitable pipe or pumps in order to achieve optimum volume transfer using less power. The study of fluid mechanics will give the better designing of the pipeline as it will consider all the factors that will affects the optimization of volume transfer. Multiphase flow is commonly encountered in the pipeline of drilling of oil and gas. in the pipeline, there usually contain more than one phase. They are petroleum which in liquid form, the natural gas in gas form and mud in solid form.

1.2 PROBLEM STATEMENT

Transferring oil and gas using pipeline is common way of how the oil and gas industry operate their business. Pipeline is a very economical way to transport large quantities of oil and gas over land. The Transferring of fluids in pipes needs a lot of calculation and consideration.Multiphase flow occurs in transferring oil using pipeline as multiple component are present such as oil and water during the transfer to the refinery plant. In this project, we would like to determine the pressure drop in the pipe as per length of the pipe. The theory of the project lies in the concept of fluid mechanics where the study of fluid and force on them. One of the problems to design a pipeline is that we must consider the pressure drop along the conveying of the flow in the pipes. The pressure at point A and to point B is not the same as there will be loss of pressure due to certain factors. In achieving the desired pressure at the end point of pipeline, these factor needs to be considered. Pressure drop in pipes is caused by:

- Friction
- Vertical pipe elevation
- Changes of kinetic energy
- Calculation of pressure drop caused by friction in circular pipes

1.3 OBJECTIVE

The objective of the project is to study and measure the pressure drop per length of pipeline as the function of gas flowrate and liquid flowrate through pipe. In this project also, the behaviour of the multiphase in the pipeline will also be considered as the point to study. In designing pipe, we need to consider the pressure drop in the pipeline where it can affect the energy loss in the pipeline. The pressure drop occurs as the result of friction of the fluid against the tube or pipe. High flow rates in small tubes give larger pressure drop. Low flow rates in large tubes give lower pressure drop in order to move the fluid through pipe, we need to consider the pressure drop that occur in the pipeline in order to get the optimum or desirable transfer rate in the pipe.

1.4 SCOPE OF STUDY

The overall of the project is to determine or to measure the effect of pipe friction that can caused pressure to drop in the pipe. As in the objective, we want to study and measure the pressure drop per length of pipeline as the function of gas flowrate and liquid flowrate through pipe. We will conduct an experiment on determining the pressure drop of the flow in the pipe. The theory on this project is mainly relying on the concept of fluid mechanics where the equation of multiphase flow will be very useful on calculating the pressure drop in the pipelines. The estimation of frictional losses in such pipelines is necessary to specify the pumping power needed to achieve the desired flows.

LITERATURE REVIEW

One of the problems to design a pipeline is that we must consider the pressure drop along the conveying of the flow in the pipes. The pressure at point A and to point B is not the same as there will be loss of pressure due to certain factors. In achieving the desired pressure at the end point of pipeline, these factor needs to be considered. Pressure drop in pipes is caused by:

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2.1 PIPELINE IN GENERAL

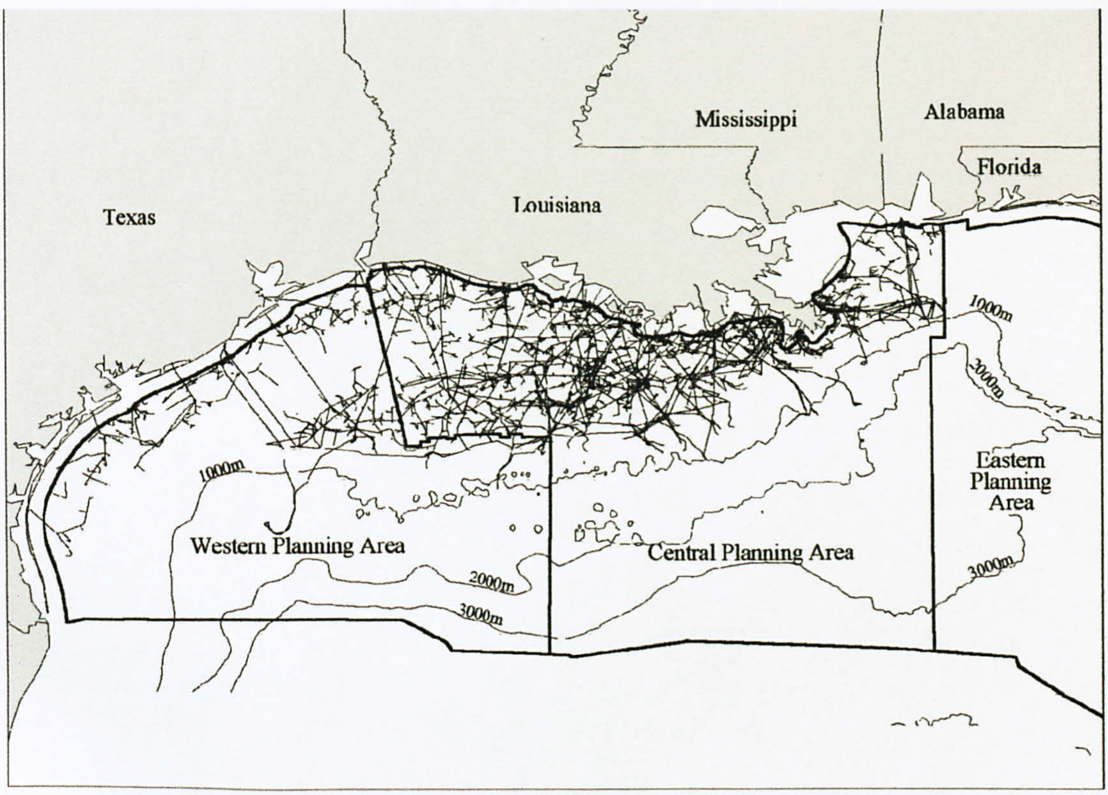


Figure 1: Gulf of Mexico OCS Oil & Gas pipelines[1]

Pipeline is the transportation of goods through a pipe. Most commonly, liquid and gases are sent, but pneumatic tubes that transport solid capsules using compressed air have also been used. As for gases and liquids, any chemically stable substance can be sent through a pipeline. Therefore sewage, slurry, water, or even beer pipelines exist; but arguably the most important are those transporting oil and natural gas. Most pipelines are buried at a typical depth of about 1 - 2 meters (about 3 to 6 feet). The oil is kept in motion by pump stations along the pipeline, and usually flows at speed of about 1 to 6 m/s. Multi-product pipelines are used to transport two or more different products in sequence in the same pipeline. Usually in multi-product pipelines there is no physical separation between the different products. Some mixing of adjacent products occurs, producing interface. This interface is removed from the pipeline at receiving facilities and segregated to prevent contamination.[2]

Crude oil contains varying amounts of wax, or paraffin, and in colder climates wax buildup may occur within a pipeline. Often these pipelines are inspected and cleaned using pipeline inspection gauges *pigs*. These devices are launched from pig-launcher stations and travel through the pipeline to be received at any other station down-stream, cleaning wax deposits and material that may have accumulated inside the line. In general, pipelines can be classified in three categories depending on purpose:

- **Gathering Pipelines** - Group of smaller interconnected pipelines forming complex networks with the purpose of bringing crude oil or natural gas from several nearby wells to a treatment plant or processing facility. In this group, pipelines are usually short- a couple of hundred meters- and with small diameters. Also sub-sea pipelines for collecting product from deep water production platforms are considered gathering systems.
- **Transportation Pipelines** - Mainly long pipes with large diameters, moving products (oil, gas, refined products) between cities, countries and even continents. These transportation networks include several compressor stations in gas lines or pump stations for crude and multiproducts pipelines.
- **Distribution Pipelines** - Composed of several interconnected pipelines with small diameters, used to take the products to the final consumer. Feeder lines to distribute gas to homes and businesses downstream. Pipelines at terminals

for distributing products to tanks and storage facilities are included in this group.

Pipeline networks are composed of several pieces of equipment that operate together to move products from location to location. The main elements of a pipeline system are:

- **Initial Injection Station** - Known also as **Supply** or **Inlet** station, is the beginning of the system, where the product is injected into the line. Storage facilities, pumps or compressors are usually located at these locations.
- **Compressor/Pump Stations** - Pumps for liquid pipelines and Compressors for gas pipelines, are located along the line to move the product through the pipeline. The location of these stations is defined by the topography of the terrain, the type of product being transported, or operational conditions of the network.
- **Partial Delivery Station** - Known also as **Intermediate** Stations, these facilities allow the pipeline operator to deliver part of the product being transported.
- **Block Valve Station** - These are the first line of protection for pipelines. With these valves the operator can isolate any segment of the line for maintenance work or isolate a rupture or leak. Block valve stations are usually located every 20 to 30 miles (48 km), depending on the type of pipeline. Even though it is not a design rule, it is a very usual practice in liquid pipelines. The location of these stations depends exclusively on the nature of the product being transported, the trajectory of the pipeline and/or the operational conditions of the line.
- **Regulator Station** - This is a special type of valve station, where the operator can release some of the pressure from the line. Regulators are usually located at the downhill side of a peak.
- **Final Delivery Station** - Known also as **Outlet** stations or Terminals, this is where the product will be distributed to the consumer. It could be a tank terminal for liquid pipelines or a connection to a distribution network for gas pipelines.

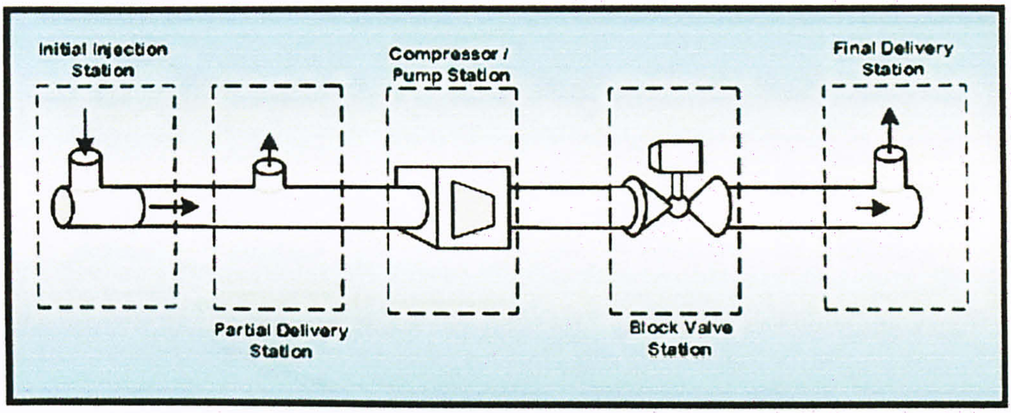


Figure 2: A pipeline schematic[2]

2.2 MULTIPHASE FLOW

Multiphase flow is a complex phenomenon that is very difficult to understand, predict and model. Common single-phase characteristics such as velocity profile, turbulence and boundary layer, are thus inappropriate for describing the nature of such flows (Thomas J. Danielson, 2000).

The flow structures are classified in flow regimes, whose are usually characteristics depend on a number of parameters. The distribution of the fluid phases in space and time differs for the various flow regimes, and is usually not under the control of the designer or operator.

The three components in multiphase any multiphase study are accurate prediction of flow regime, liquid holdup, and pressure drop, determine as the function of production rate. It is difficult to separate these three, as each is coupled to the other two, implying a simultaneous solution for all three components. However, as a practical matter, regime determination is often done first, followed by liquid hold-up and finally pressure drop (J.P & H.D, 1998).

Flow regimes vary depending on operating conditions, fluid properties, flow rates and the orientation and geometry of the pipe through which the fluids flow. The transition between different flow regimes may be a gradual process. The determination of flow regimes in pipes in operation is not easy. Analysis of fluctuations of local pressure or density by means of for example gamma-ray densitometry has been used in experiments and is described in the literature. In the laboratory, the flow regime may be studied by direct visual observation using a length of transparent piping. Descriptions of flow regimes are therefore to some degree arbitrary, and they depend to a large extent on the observer and his/her interpretation.

Multiphase production systems are quite complex, however, a priori prediction of their behaviour is essential for successful design and operation of offshore facilities. Multiphase flow models can be broken down into three distinct categories:

- Steady-state correlational
- Steady-state mechanistic
- Transient mechanistic

Steady-state correlational models have the advantage that they are based on parameters which are easy to measure, e.g. the superficial gas and liquid velocities, but which are difficult to relate to a force balance. Mechanistic models are generally believed to extrapolate better to conditions far from where the model was benchmarked. However, they involve terms such as the 'interfacial friction factor', which cannot be measured directly and must be inferred from the experimental data.

The flow models are applied to a discretized topography; both steady state and transient models reduce a complex pipeline profile to a series of straight pipes at constant angle. In order to properly capture temperature and pressure gradients, these straight pipes are further discretized into a number of section.[3]

2.3 FLOW REGIME

The main mechanisms involved in forming the different flow regimes are transient effects, geometry/terrain effects, hydrodynamic effects and combinations of these effects.

- Transients occur as a result of changes in system boundary conditions. This is not to be confused with the local unsteadiness associated with intermittent flow. Opening and closing of valves are examples of operations that cause transient conditions.

- Geometry and terrain effects occur as a result of changes in pipeline geometry or inclination. Such effects can be particularly important in and downstream of sea-lines, and some flow regimes generated in this way can prevail for several kilometres. Severe riser slugging is an example of this effect.

- In the absence of transient and geometry/terrain effects, the steady state flow regime is entirely determined by flow rates, fluid properties, pipe diameter and inclination. Such flow regimes are seen in horizontal straight pipes and are referred to as "hydrodynamic" flow regimes. These are typical flow regimes encountered at a wellhead location.

Flow regime is the large-scale variation in the physical distribution of the gas and liquid phases in a flow conduit. The multiphase flow is generally are considered into four classes. They are:

- Stratified flow – a continuous liquid stream flowing at the bottom of the pipe, with a continuous stream of gas flowing over.

- Slug flow – stratified flow, punctuated by slugs of highly turbulent liquid.

- Annular flow – a thin liquid film adhering to the pipe wall and a gas stream containing entrained liquid droplets

- Bubble flow – a continuous liquid flow with entrained gas bubbles.

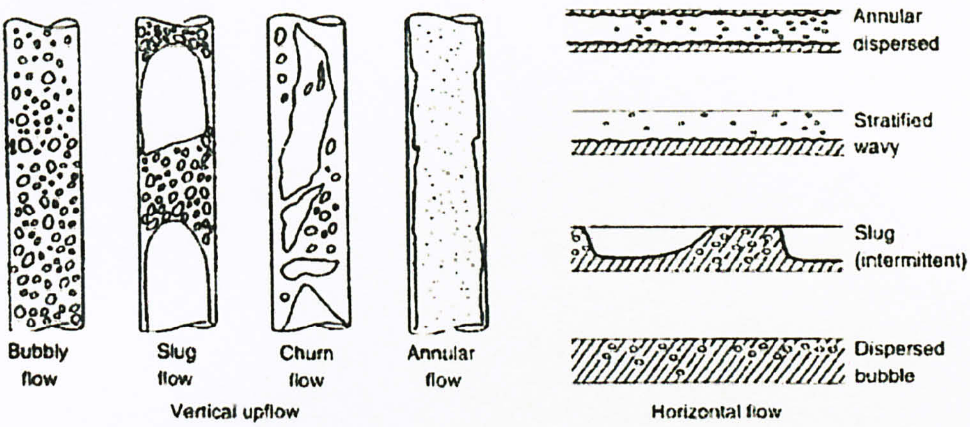


Figure 3: Flow Pattern for gas-liquid two phase flow

In most cases, the selection of flow regime is done against an experimentally constructed flow regime map. Generally the superficial liquid velocity is plotted against the superficial gas velocity (see figure 3). For given pipe diameter and inclination angle, the flow regime is a uniquely determined function of superficial gas and liquid velocities. Transitions from one regime to another are determined by series of curves, based on a variety of dimensionless parameter.

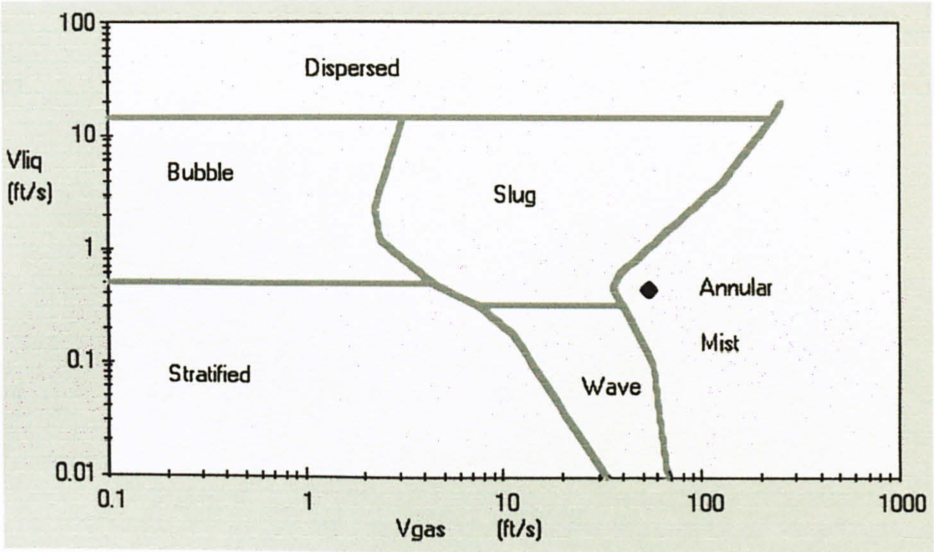


Figure 4: Typical flow regime map (Mandhane et al)

2.4 PRESSURE DROP PREDICTION

The pressure drop in a multiphase pipeline can be separated into three distinct components which are gravitational pressure gradient, frictional pressure gradient and acceleration pressure gradient.

$$\left(\frac{dP}{dZ}\right) = \left(\frac{dP}{dZ}\right)_{grav} + \left(\frac{dP}{dZ}\right)_{fric} + \left(\frac{dP}{dZ}\right)_{accel}$$

The gravitational pressure gradient for all models is given by

$$\left(\frac{dP}{dZ}\right)_{grav} = \rho_M g$$

Where

$$\rho_M = H_l \rho_l + (1 - H_l)\rho_g$$

Thus in steady-state correlation, the liquid hold-up must be calculated prior to pressure gradient determination. The frictional pressure gradient is calculated from the Moody chart (see figure 4) using the modified Reynolds number based on a combination of slip and no slip mixture properties.

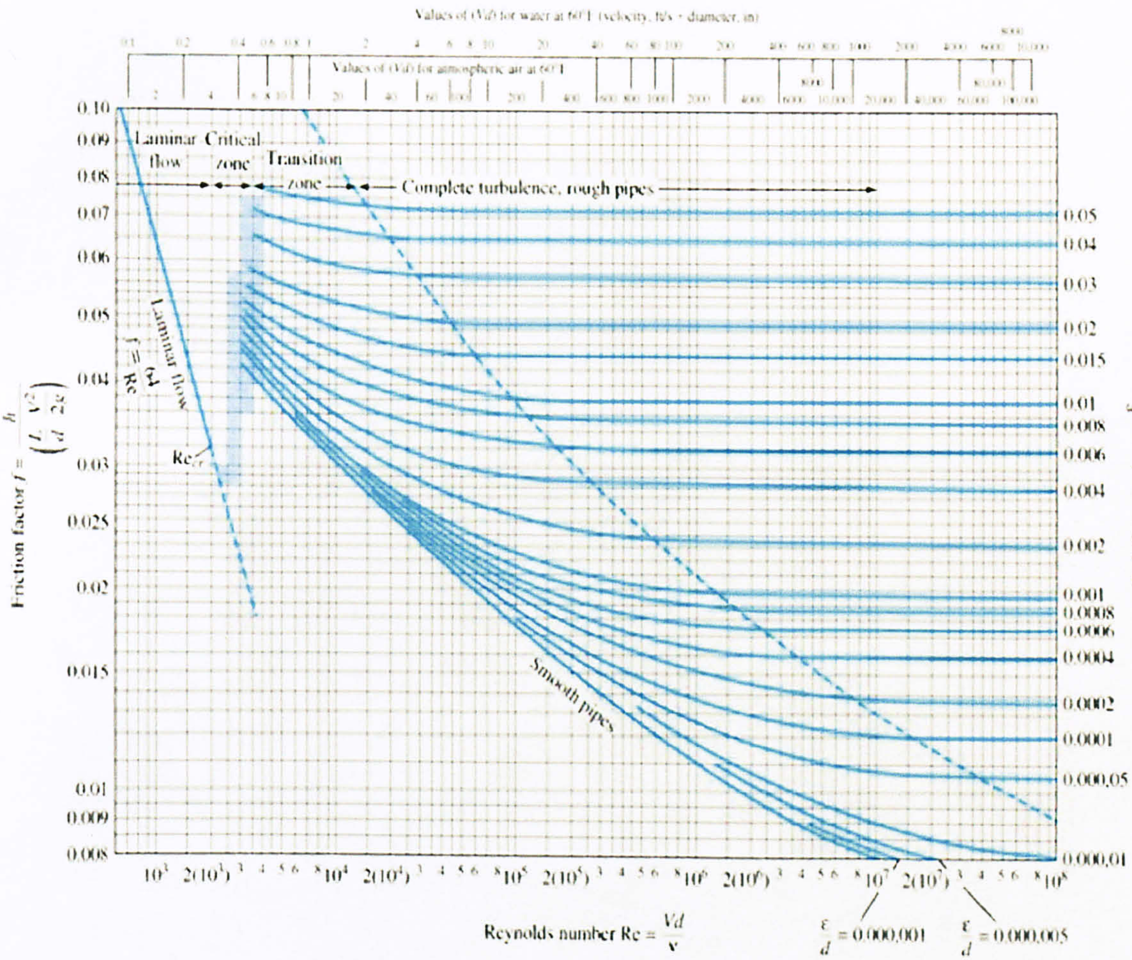


Figure 5: Example of Moody's diagram

In general, for even mildly inclined pipelines, the gravitational pressure gradient quickly exceeds the frictional pressure gradient. The acceleration pressure gradient becomes important if there is a sudden change in pipeline diameter or if the gas density is changing very rapidly, resulting in a large change in gas velocity. The acceleration of liquid into a slug can also be an important source of acceleration pressure drop, but which is presently ignored in all steady-state and transient models.[4]

METHODOLOGY

3.1 PROJECT ACTIVITIES

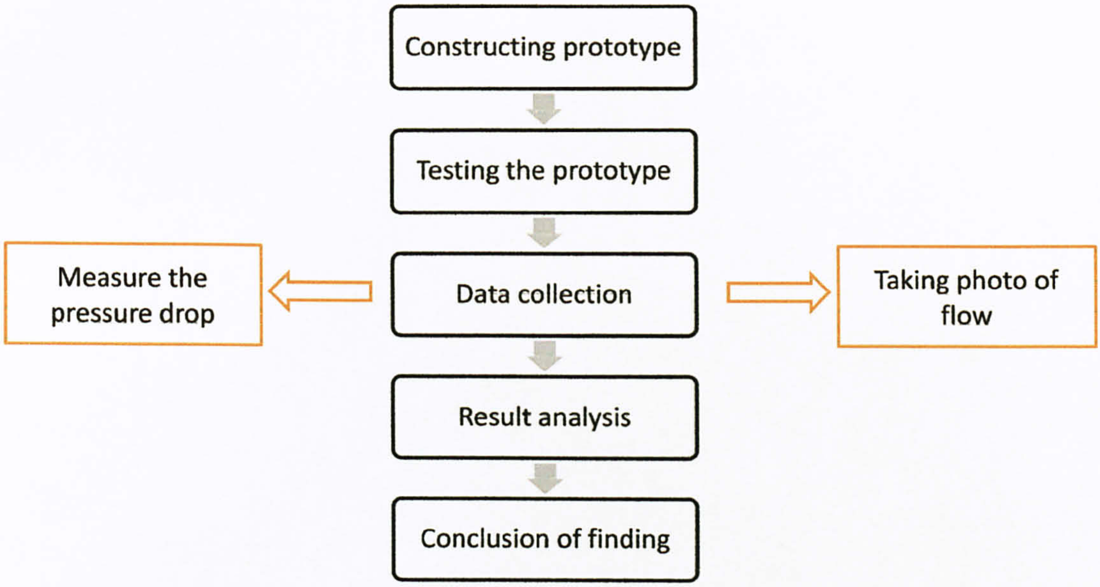


Figure 6: Experiment flow

For this project, the starting point is to designing the prototype using pump and pipes as well as relevant instrument such as pressure gauge and flowmeter. The working prototype is then tested and run to test whether it is working or not before the experiment can be conducted. The data is then collected with two different kind of measurement. The first is to take the photo of the flow pattern using high speed camera. The second experiment is to determine the pressure drop in the pipe using different flowrate of air and water. The data is then gathered and analyse before making tha conclusion of the findings. The project milestone is as follow:

No.	Detail/ Week	1	2	3	4	5	6	7	8	9		10	11	12	13	14
1	Selection of Project Topic															
2	Preliminary Research Work • Understanding project title • Identify problem • Submission of proposal															
3	Submission of Preliminary Report															
4	Project Work • Research on selected flow model • Flow assurance research and understanding • Designing the experimental work															
5	Submission of Progress Report															
6	Seminar (compulsory)															
7	Project work continues • Research ongoing • Buying the needed apparatus															
8	Submission of Interim Report Final Draft															
9	Oral Presentation															

Table 1: Gantt Chart for FYP 1

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Project work continue														
2	Submission of Progress Report 1														
3	Project work continue														
4	Submission of Progress Report 2														
5	Seminar														
6	Project work continue														
7	Poster Exhibition														
8	Submission of Dissertation (soft bound)														
9	Oral Presentation														
10	Submission of Project Dissertation (Hard Bound)														

Table 2: Gantt Chart of FYP 2

3.1.1 EXPERIMENTAL WORK

For this project, most of the work scope will be focusing on designing the working prototype of multiphase flow in the pipe, the experimental work and the result analysis. The design flow of the experimental work is as follow:

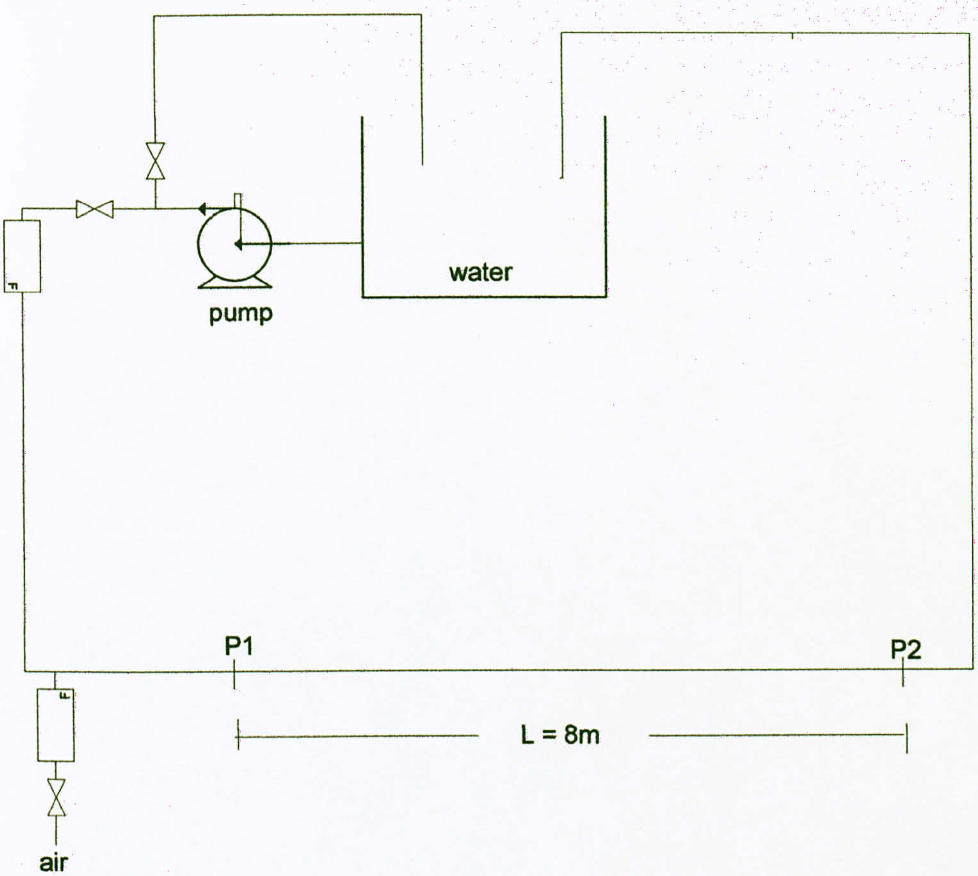


Figure 7: Design experiment

3.1.2 EQUIPMENT LIST

Before setting up the equipment, I had figure out the list that need to buy or have in order to running the experimental work. Based on the figure sketched above, the lists are:

No	Item	Remarks
1	Acrylic transparent pipe (30mm inlet diameter)	8m
2	Plastic Water tank	10 liter
3	Pressure gauge	2 pieces
4	PVC T-joint	4 pieces
5	Pump (30m max head)	1 piece
6	Pressure regulated gauge	1 piece
7	Valve (Gate valve and ball valve)	3 pieces
8	PVC Elbow (1inch diameter)	3 pieces
9.	PVC connector (1inch diameter)	4 pieces
10	PVC pipe (1inch diameter)	4 meter

Table 3: Equipment list

The setting up of equipment involving putting the desired design of experimental work into prototypes. In this project, there are two types of material involving in order to build the prototype. We are using acrylic transparent in order to study the flow pattern in the pipeline. The connector and the joint are using the

Polyvinyl Chloride or PVC where the 2m acrylic pipe is connected to these PVC pipe in order to make the pipeline system in the length of 8m. The prototype is setting in order to see the flow patterns when different water and air flow through the pipeline. In this experiment also, we would like to see the pressure drop of the flow by using pressure gauge to measure. The pressure drop is determine as the flow travel along the pipe. The length of the pipe is fixed which 8 meters but the water and the gas flowrates will be change.

3.1.4 PUMP

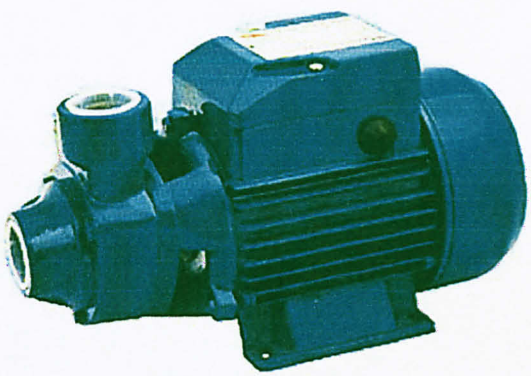


Figure 8: Pump used in the experiment

The pumping power equation is:

$$P_o = \rho\ g\ H\ Q$$

Where, P_o = output power of the pump (W)

ρ = fluid density (kg/m^3)

g = gravitational constant

Q = flowrate (m^3/s)

H = max head (m)

To find the maximum flowrate of the pump,

$$Q = \frac{P_o}{\rho g H}$$

$$Q = \frac{350}{1000 \times 9.81 \times 30}$$

$= 0.001189\ m^3/s$

$= 1.2\ L/s$

RESULT AND DISCUSSION

In this project, there are two type of studies that are been conducted. The first is to study the flow type of the flow that passed through the pipeline. The second is to measure the pressure drop of the flow with using different water and air flowrates.

4.1 COMPARISON BETWEEN EXPERIMENT DATA WITH LOCKHART-MARTINELLI THEORY

The Lockhart-Martinelli Correlation provide the assumption of the pressure drop in the multiphase flow. The experimental data is compared with the Lockhart-Martinelli Correlation to see whether the data gained is comparable with the proposed theory. The result is as below:

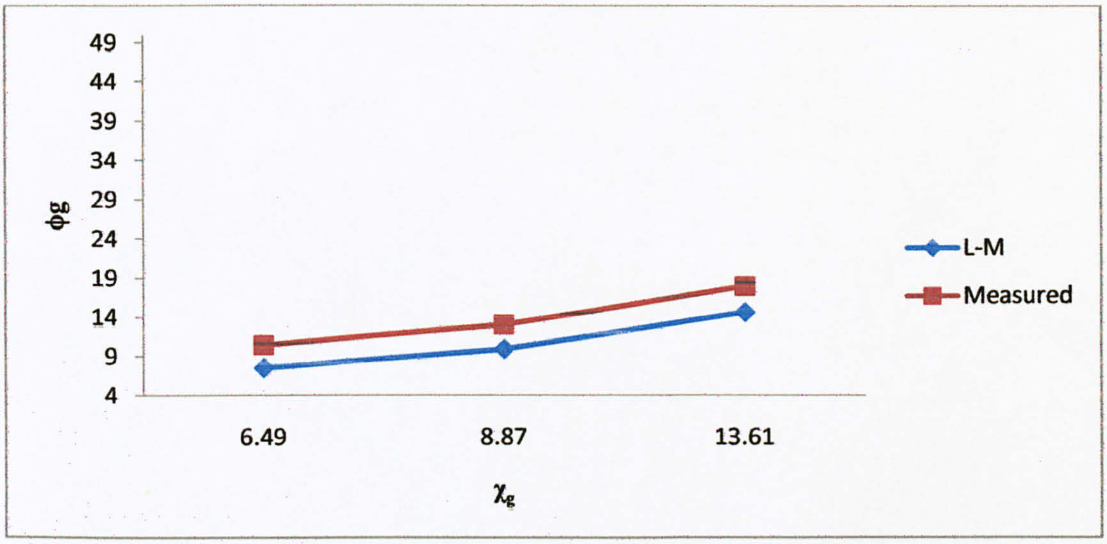


Figure 9: Comparison between measured data with theory

From the graph above, the pattern of the graph is similar only that the measured data had higher value. As per rough observation, we can conclude that the measured result is comparable and similar pattern with the theory. The comparison of the above is using the Turbulent-Laminar flow as the calculated flow of air and water show that it is Turbulent Laminar flow. So, we used the proposed equation of

Turbulent-Laminar flow to know the value of χ_g and ϕ_g (Appendix 1). The measured result is using three data from the experimental work. The data used are:

Superficial liquid velocity, V_l (m/s)	Superficial gas velocity, V_g (m/s)
0.1	0.2
0.2	0.35
0.4	0.5

Table 4: Data used in term of superficial velocity

The data had been converted to the superficial velocity of gas and liquid by the equation of:

$$\frac{F_l}{A} \; and \; \frac{F_g}{A}$$

Where A is the area of the pipe and F is the flowrate of the water and air in m^3/s.

The example detailed calculation of the experimental data is shown in Appendix IV where the final χ_g and ϕ_g calculated and theory are:

Calculated		Theory	
χ_g	ϕ_g	χ_g	ϕ_g
6.49	10.39	6.49	7.49
8.87	12.98	8.87	9.87
13.61	17.95	13.61	14.61

Table 5: χg and ϕg data for calculated and theory

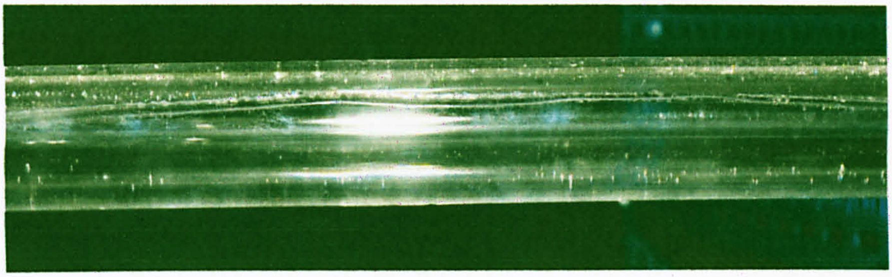
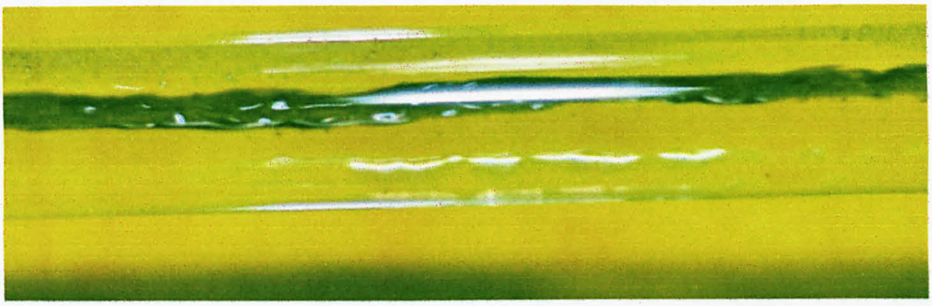
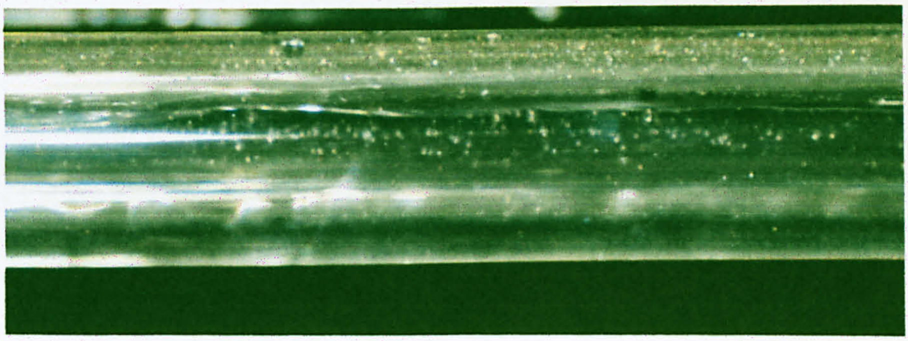
4.2 FLOW TYPES IN PIPELINE

In this experiment, the objective is to capture the image flow in the pipeline. The captured image is then being analyzed to know the type of flow that occurs during the flow. This experiment needed special equipment which are the camera to capture the image flow. In order to capture the image that high flow, the camera with high shutter speed is needed in order to clearly see the image. In this experiment, we are using Nikon D90 Digital Single Lens Reflex (DSLR) with the maximum shutter speed of 1/4000s. The specification of the camera used can be referred to the Appendix 3.

Figure 10: NIKON D90 [source: www.dpreview.com]

4.2.1 RESULT

The result of the flow are as below:

<table>
<tr><th>Flowrate Water (L/s)</th><th>Flowrate air (L/s)</th><th>Regime</th></tr>
<tr><td rowspan="2">0.05</td><td>0.05</td><td></td></tr>
<tr><td>0.10</td><td></td></tr>
<tr><td>0.10</td><td>0.10</td><td></td></tr>
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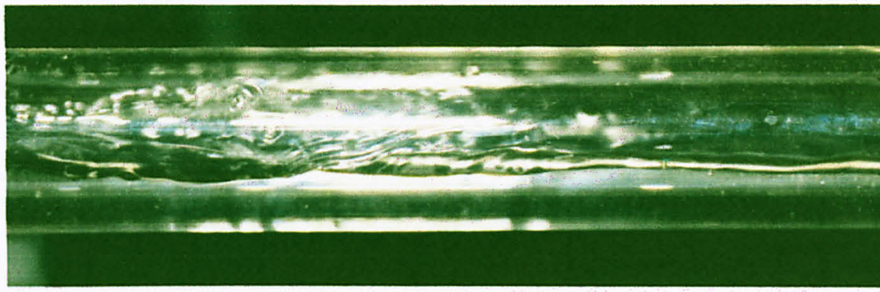
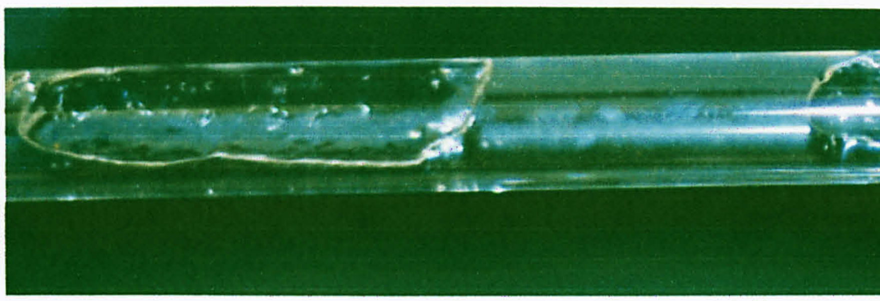
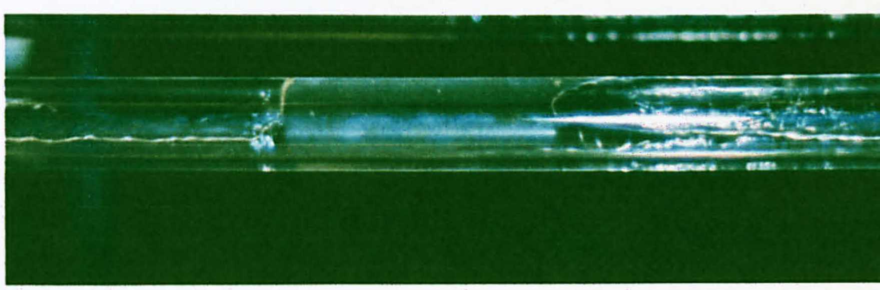
	0.18	
0.20	0.20	
	0.25	

Table 6: Result for flow pattern with different water and air flow

4.2.2 DISCUSSION

For this experiment, the water and gas flow is varied in order to see the changes of the flow pattern in the pipeline. Three different water flows which are 0.05L/s, 0.10L/s and 0.20L/s used to see the differentiation of the pattern. Every flow is taken for three times and the average is taken. For every water flow, two different air flow is taken. From the table above, for water flowrate of 0.05L/s, both result of air flow 0.05 and 0.10L/s shows the pattern is stratified flow with smooth flow in the pipe. For water flow at 0.10L/s, the pattern change from stratified to bubble flow when flowrate of 0.10L/s air is used. This is because due to the pressure drop in a liquid-phase line, resulting in gas breakout. When air flowrate change to 0.18L/s, the pattern changed to stratified wavy flow. The increasing of kinetic energy of the air rate had make the liquid surface become wavy. For water flowrate of 0.2L/s and using of air flowrate of 0.2L/s and 0.25L/s, the pattern had changed to slug. The slug flow resulting the kinetic energy of this flow changing significantly. This is resulting of the acceleration of the flow in pipe as sometime increasing and decreasing. The slug flow are formed when waves at stratified flow gain enough height to bridge the pipe. When this occur, the packet of fluid are pushed through the pipeline by the gas, hence increasing the velocity.

4.3 PRESSURE DROP MEASUREMENT

In this experiment, the pressure drop is calculated and graph of pressure drop, ΔP versus the superficial liquid velocity is plotted. The measurement point start at the inlet of the acrylic pipe and the outlet of the acrylic pipe which total length is 8 meters. Two pressure gauges are used to measure the pressure inlet and outlet of the testing section of the pipe. The pressure gauge readings are both in unit of Pascal (Pa). The experiment is conduct by allowing the flow of water with different air flowrate. The results are as below:

$V_g = 0.2m/s$		$V_g = 0.35m/s$		$V_g = 0.5m/s$	
V_l, m/s	ΔP	V_l, m/s	ΔP	V_l, m/s	ΔP
0.1	0.1	0.1	0.12	0.1	0.15
0.2	0.14	0.2	0.16	0.2	0.17
0.4	0.25	0.4	0.25	0.4	0.26

Table 7: Pressure drop result from the experiment

Based on the data above, the graph of pressure drop, ΔP versus superficial liquid velocity is plotted. The graph is plotted with different superficial gas velocity as the below:

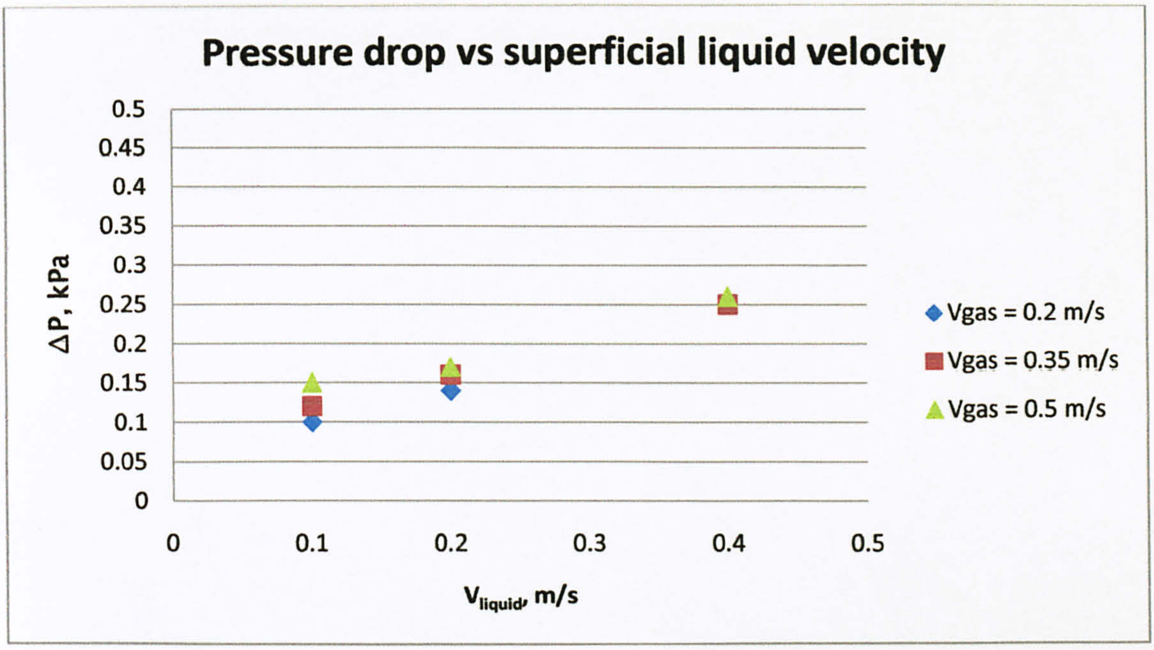


Figure 11: Graph of pressure drop versus superficial liquid velocity

From the graph above, the pressure drop is increasing with increasing of velocity of water. With the increasing of air velocity also, the pressure drop tends to increase. From this graph also, there are no significant increasing of pressure drop at $V_{gas} = 0.5$ m/s. This kind of result maybe because of reading error during the taking of the pressure at the outlet of the pipe. From this graph, we can conclude that increasing of liquid and gas velocity will increase the pressure drop in the pipe. It is because the friction between the fluid flow with the wall pipe become greater, which mean energy loss more.

The result also shows that the pressure drop is very small. This is mainly due to the friction between the pipe and the fluid is small as the surface of the pipe is very smooth. In this situation, we can neglect the pressure drop in the pipeline but must consider the pressure drop in the elbow or junction of the pipe.

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

In conclusion, the multiphase flow is a broad scope of study and the pressure drop in the pipeline will be increasing with the increasing of the fluid velocity. In the horizontal pipeline, the frictional pressure drop is the most significant contribution pressure drop. the friction is mainly from the inside wall of the pipe. The determination of the pressure drop is vital in the industry as it is to optimize the use of energy especially to design the pump with minimum energy requirement to transfer the fluid, hence reducing the cost of operation.

The in the multiphase flow, there are different flow pattern with different behaviour. The flow pattern is changing with the changing of liquid and gas velocity, depending the ratio of both fluid. The flow pattern is also important in the multiphase pipeline as it gives early and initial prediction of flow assurance.

5.2 RECOMMENDATION

For this project, there are some recommendations in order to get the more specific and reliable value and result. In order to get the clear and better image prediction, the high speed camera is needed. For example, the use of Particle Image Velocimetry (PIV) can improve the visual of the image taken as it has high speed frame rates.

Another improvement can be made is that using proper and better instrument such as digital reading pressure gauge to get accurate reading. The pump also needs to be more power that have more pumping speed where the flowrate of water that flow is large enough to have different range of data.

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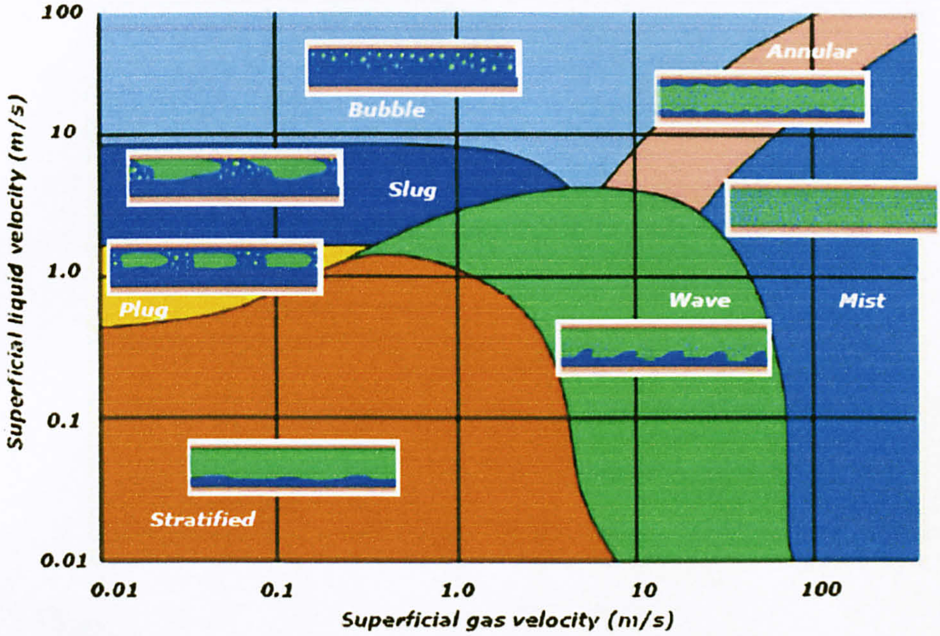
APPENDIX I

LOCKHART-MARTINELLI CORRELATION EQUATION

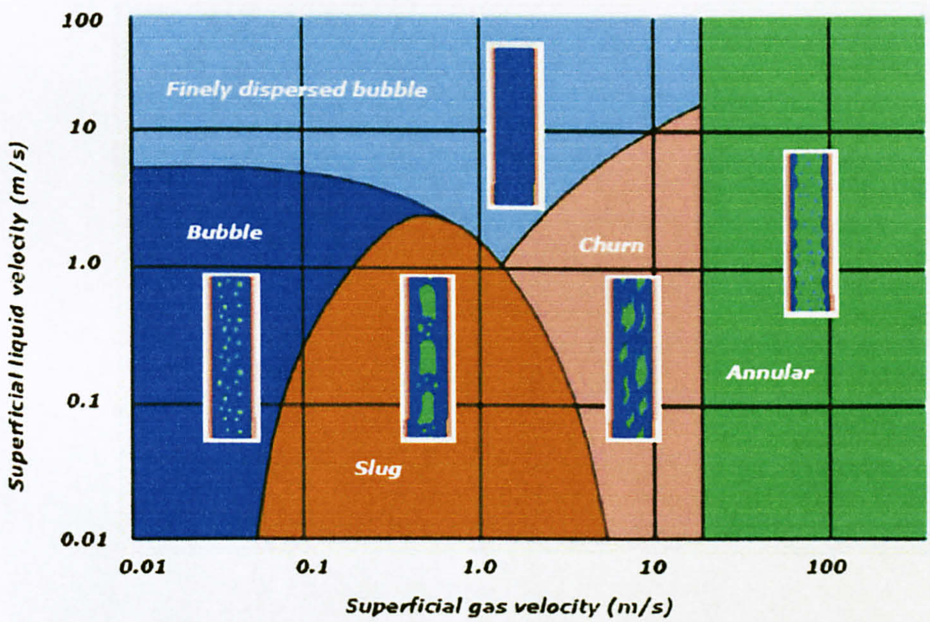
Regime	Equations	Equations
Laminar-Laminar	$\left(\frac{1}{\phi_g^{\,2}}\right)^{1/2} + \left(\frac{1}{\phi_l^{\,2}}\right)^{1/2} = 1$	$1 + \left(\chi_g^{\,2}\right)^{1/2} = (\phi_g^{\,2})^{1/2}$
Laminar-Turbulent	$\left(\frac{1}{\phi_g^{\,2}}\right)^{1/2} + \left(\frac{1}{\phi_l^{\,2}}\right)^{1/2.5} = 1$	$1 + \left(\chi_g^{\,2}\right)^{1/2.5} (\phi_g^{\,2})^{0.1} = (\phi_g^{\,2})^{1/2}$
Turbulent-Laminar	$\left(\frac{1}{\phi_g^{\,2}}\right)^{1/2.5} + \left(\frac{1}{\phi_l^{\,2}}\right)^{1/2} = 1$	$1 + \left(\chi_g^{\,2}\right)^{1/2} (\phi_g^{\,2})^{-0.1} = (\phi_g^{\,2})^{1/2.5}$
Turbulent-Turbulernt	$\left(\frac{1}{\phi_g^{\,2}}\right)^{1/2.5} + \left(\frac{1}{\phi_l^{\,2}}\right)^{1/2.5} = 1$	$1 + \left(\chi_g^{\,2}\right)^{1/2.5} = (\phi_g^{\,2})^{1/2.5}$

APPENDIX II

FLOW REGIME MAP



100
10
1.0
0.1
0.01
Superficial liquid velocity (m/s)
Bubble
Slug
Plug
Stratified
Wave
Mist
Annular
0.01
0.1
1.0
10
100
Superficial gas velocity (m/s)



100
10
1.0
0.1
0.01
Superficial liquid velocity (m/s)
Finely dispersed bubble
Bubble
Churn
Slug
Annular
0.01
0.1
1.0
10
100
Superficial gas velocity (m/s)

APPENDIX III

NIKON D90 SPECIFICATION

Max resolution	4288 x 2848
Low resolution	3216 x 2136, 2144 x 1424
Image ratio w:h	3:2
Effective pixels	12.3 million
Sensor photo detectors	12.9 million
Sensor size	23.6 x 15.8 mm (3.72 cm²)
Pixel density	3.3 MP/cm²
Sensor type	CMOS
Sensor manufacturer	Sony
ISO rating	Auto, 200 - 3200 (plus 6400 with boost)
Zoom wide (W)	
Zoom tele (T)	
Digital zoom	No
Image stabilization	No
Auto Focus	Nikon Multi-CAM1000
Manual Focus	Yes
Normal focus range	
Macro focus range	
White balance override	12 positions, plus manual and Kelvin
Aperture range	
Min shutter	30 sec
Max shutter	1/4000 sec
Built-in Flash	Yes, pop-up
Flash range	17 m
External flash	Yes, hot-shoe
Flash modes	Front curtain, Rear curtain, Red-Eye, Slow, Red-Eye Slow
Exposure compensation	-5 to +5 EV in 1/2 or 1/3 EV steps
Metering	3D Matrix metering II, Center weighted, Spot
Aperture priority	Yes
Shutter priority	Yes
Focal length multiplier	1.5
Lens thread	Nikkor AF / F-mount, D-Type
Continuous Drive	Yes, 4.5 fps(CH) or 1-4 fps(CL)
Movie Clips	Yes
Remote control	Yes, Optional (ML-L3 or MC-DC2)
Self-timer	Yes, 2, 5, 10 or 20 sec
Timelapse recording	Yes, by USB cable and PC
Orientation sensor	Yes
Storage types	SD/SDHC card
Storage included	None
Uncompressed format	Yes, RAW
Quality Levels	Fine, Normal, Basic
Viewfinder	Optical (Pentaprism, 96% coverage, 0.96x magnification)
LCD	3 "
LCD Dots	920,000
Live View	Yes

USB ?	USB 2.0 (480Mbit/sec)
HDMI ?	Yes
Wireless ?	No
Environmentally sealed	No
Battery ?	Nikon EN-EL3e Lithium-Ion battery
Weight (inc. batteries)	703 g (24.8 oz)
Dimensions	132 x 103 x 77 mm (5.2 x 4.1 x 3 in)

APPENDIX IV

PRESSURE DROP CALCULATION

Physical Parameters:

Pipe diameter	0.0254m	Liquid viscosity	0.798×10^{-3} Pa.s
Liquid flowrate	0.05 L/s	Gas viscosity	1.983×10^{-3} Pa.s
Gas flowrate	0.05 L/s	Liquid density	1000 kg/m^3
Gas density	1.164 kg/m^3		

Mass Fluxes:

Cross-sectional area of pipe $\quad A := \frac{\pi \cdot D^2}{4}$

$A = 5.067 \times 10^{-4}$

Liqud mass flux $\quad G_L := \frac{w_L}{A}$

Gas mass flux $\quad G_G := \frac{W_G}{A}$

$G_L = 100$ $kg/m^2.s$

$G_G = 0.2328$ $kg/m^2.s$

Reynold Number:

Liquid Reynolds number $\quad Re_L := \frac{G_L \cdot D}{\mu_L}$

Gas Reynolds number $\quad Re_G := \frac{G_G \cdot D}{\mu_G}$

$Re_L = 3119.3$ (Turbulent flow) – Moody's Diagram to find f

$Re_G = 298.\ 2$ (Laminar flow) – use 64/Re to find f

Friction Factors:

Liquid friction factor $f_L := \text{friction}(Re_L, e)$

Gas friction factor $f_G := \text{friction}(Re_G, e)$

$f_L = 0.042$

$f_G = 0.214$

Individual Pressure Gradient:

Liquid phase pressure gradient $dPdL_L := \frac{f_L}{2} \cdot \frac{G_L^{\,2}}{\rho_L \cdot D}$

Gas phase pressure gradient $dPdL_G := \frac{f_G}{2} \cdot \frac{G_G^{\,2}}{\rho_G \cdot D}$

$$\frac{dP}{dL} liquid = 8.26\ Pa/m$$

$$\frac{dP}{dL} gas = 0.196\ Pa/m$$

Lockhart-Martinelli Factor and Total Pressure Gradient

The two-phase multiplier will be calculated using the Lockhart-Martinelli parameter and the correlations provided by Chisholm (1967).

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$$\frac{dP}{dL} gas = 0.196\ Pa/m$$

Lockhart-Martinelli Factor and Total Pressure Gradient

The two-phase multiplier will be calculated using the Lockhart-Martinelli parameter and the correlations provided by Chisholm (1967).

Lockhart-Martinelli factor $\quad X_{tt} := \sqrt{\dfrac{dPdL_L}{dPdL_G}}$

Liquid two-phase multiplier $\quad \Phi_L := \left(1 + 18X_{tt}^{-1} + X_{tt}^{-2}\right)^{0.5}$

Gas two-phase mutiplier $\quad \Phi_G := \left(1 + 18X_{tt} + X_{tt}^{2}\right)^{0.5}$

$X_{TL} = 6.49$

$\phi_G = 10.39$

Result Calculation for All Data:

Velocity, m/s		Mass Flux, kg/m^2.s		Pressure gradient, Pa/m		L-M factor		L-M from eq
V_l,	V_g	G_l	G_g	ΔP_l	ΔP_g	X	ϕ_g	ϕ_g
0.10	0.20	100	0.2328	8.26	0.196	6.49	10.39	7.49
0.20	0.35	200	0.4074	27.17	0.345	8.87	12.98	9.87
0.40	0.50	400	0.582	91.34	0.493	13.61	17.95	14.61