Study of Two-Phase Flow Friction Factor in EOR Injection Wellbores

by

Kanagaswarran Citalingam Mudliar

Dissertation submitted in partial fulfillment of

the requirements for the

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

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Approved by,

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May 2011

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 by unspecified sources or persons.

KANAGASWARRAN CITALINGAM MUDLIAR

ABSTRACT

Two-phase flow is defined as the flow of two phases simultaneously in a pipe and the flow patterns vary due to the density and viscosity differences between the phases which contribute to the difference in velocity of both phases. The geometry of the well is another factor which donates to the difference in flow pattern. The simultaneous flow of these two-phases creates a pressure drop which is caused by the loss due to friction, acceleration and elevation. The friction lose is due to the friction between both the phases besides the friction between the fluid and the pipe wall. This study is aimed at calculating the friction factor of two-phase flow in EOR injection wellbores based on different flow patterns. The calculation of two-phase flow has been developed by various scholars and a few mechanistic models been published. Hasan and Kabir's mechanistic model was chosen due to its accuracy and continuity. Friction factor calculated in this study is a function of temperature of the wellbore since temperature affects mixture density hence affects void fraction. I have translated the calculation method into codes using computation software of Mathematica that will perform the calculation using inputs of data. At the end, the friction factor of the EOR injection wellbore can be calculated using this program by inputting PVT data and will help to optimize the production of the well.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

A = parameter for friction-factor calculation, dimensionless

C_o = flow parameter, dimensionless

D = tubing ID, m

f_g = in-situ gas volume fraction, dimensionless

f_m = Moody friction factor, dimensionless

g = gravitational acceleration, m/sec^2

Re_m = mixture Reynolds Number, dimensionless

V_g = in-situ velocity of gas, m/sec

V_{gb} = superficial gas velocity needed for transition from bubbly to slug flow, m/sec

V_m = velocity of gas liquid mixture, m/sec

V_{sg} = superficial velocity of gas, m/sec

$V_{\infty b}$ = small bubble rise velocity, m/sec

$V_{\infty T}$ = Taylor bubble rise velocity, m/sec

x = mass quality

ρ_m = mixture density, kg/m

ρ_g = gas density, kg/m

ρ_L = liquid density, kg/m

μ_m = mixture viscosity, kg/m.sec

μ_g = gas viscosity, kg/m.sec

CHAPTER 1: INTRODUCTION

1.1 Background of study

1.1.1 Multiphase flow

The term multiphase flow refers to multiphase system of fluids while their flow variables undertake finite jumps at macroscopically observable interfaces. Multiphase flow consists of wide diversity of different kinds of flows. The main types of flows are liquid-gas, liquid-liquid, liquid-solid and gas-solid flows. Liquid-gas flows can be found in oil and gas wells, geothermal wells, field gathering systems, and pipelines. Whereas liquid-liquid flow can be seen in oil wells and gathering systems. Liquid-solid flows can normally be seen during drilling and well completion as flows of drilling mud with cuttings, cement flow and fracturing fluid carrying proppant material. Lastly gas-solid flow can be found in compressed-air-drilling systems.

Basically any fluids that have difference in flow properties can be considered as multiphase flow. Besides knowing the properties of the separate homogenous fluid it is also important to take into consideration the behavior of mixture at the hydrostatic state. The phenomenon of terminal settling velocity can be characterized by the behavior of fluids that one phase may be rising while the other phase may be settling in the other. This phenomenon depends on the properties of both the particles and the continuous phase.

Two phase with different properties tend to separate due to the difference in density. Particles tend to settle or rise which contributes to phase separation. These two different phase also tend to move with different velocities. Hence, separate velocity has to be considered simultaneously for each phase in the flow of the mixture. A simple example can be said as spherical solid particles dispersed on a Newtonian fluid at rest. Depending on the density of the particles and of the continuous fluid phase, the gravity force can cause the particles to settle or to rise.

1.1.2 Flow pattern

The term flow pattern refers to geometrical configuration of the gas and liquid phase in a pipe. In addition, the shear stress on the pipe's wall too tends to be different for each phase as a result of difference in density and viscosity.

Prominent feature of two-phase flow is the occurrence of certain characteristic flow pattern which shows how the two phases are distributed in the pipe. A usual homogenous fluid flow can be characterized simply as laminar or turbulent flow. In the case of two-phase flow in pipes, flow can be characterized by certain relative quantities and the distribution of the phases. Due to the density difference as mention previously, the flow pattern in horizontal or inclined pipes are not symmetrical with respect to the pipe axis.

1.1.3 Pressure loss

Predicting multiphase flow is of great importance. Pressure losses encountered during co-current flow enter into wide array of design calculations. Design consideration such as tubing size and operating well completion or re-completion scheme, artificial lift during either gas-lift or pump operations in a low-energy reservoir, liquid unloading in gas wells, direct input for surface flow line and equipment design calculations.

In the case of horizontal pipe flow, the energy losses or pressure drop are caused by the change in the kinetic energy and friction losses only. Since most of the viscous shear occurs at the pipe wall, the ratio of the wall shear stress to kinetic energy per unit volume reflects the relative importance of wall shear stress on the total losses. The ratio forms a dimensionless group and defines a friction factor, f. (Dale Beggs, 2003)

Economic considerations are the main reason for high injection rates, resulting in high velocities, which subsequently cause sizeable friction losses. If friction losses are neglected, any injection velocity becomes theoretically possible and hence creating a possibility of performing heat-loss and quality calculations for an injection velocity that is impossible due to excessive friction losses. (P.H. Holst and D.L.Flock, 1966)

In terms of solution of two phase flow problem, a simple approach is taken which is modeling. Modeling is approximations in which the physics of the problem is approximated and formulated in a format according to analytical or numerical means. (Yehuda Taitel, 1996). Mechanistic modeling is adopted by taking into account the important processes and neglecting the less important effects. The available models are two fluid model, drift flux model and homogenous model. There are many types of mechanistic models available and few of the examples are Beggs and Brill (1973), Hasan and Kabir(1988), and Ansari et al (1994).

1.2 Problem statement

Frictional loss plays an important role in the pressure loss gradient in two phase flow injection wells.

1.2.1 Problem Identification

In the EOR injection wells, the calculation of pressure gradient becomes complicated since it involves two phase flow. In two phase flow, friction factor is one of the factors in calculation of pressure gradient. Friction factor involves the friction between phases and friction with the wall of pipe.

1.2.2 Significant of project

The aim of this research is to study and determine the friction factor in two phase flow using appropriate model for calculation in steam injection wells.

1.3 Objectives

There are several objectives that need to be achieved when completing this project. The objectives are:

1. Identify principal flow patterns for downward two phase flow.
2. Determination of suitable model to be used for EOR injection well.
3. Calculation of friction factor in downward two phase flow.

1.4 Scope of Study

This research will involve the understanding of fluid mechanics in the perspective of petroleum engineering. Study of this project can be broken down into identification of the appropriate model for calculation in downward two-phase flow, method of calculating friction factor in EOR injection wells and effect of well configuration and fluid properties on friction factor.

1.4.1 Relevancy of the Study

This project will focus on the topic of two phase flow and friction factor. These topics are related to the course of Petroleum Production Optimization in the chapter of Flow in Pipes and Restrictions and the knowledge of Fluid Mechanics is needed to perform research for this project. This project is also related to the topic of optimization in EOR injection wellbores by calculation of friction factor hence estimating the pressure loss due to friction head in order to determine the amount of injection pressure needed.

1.4.2 Feasibility of the project within the scope and time frame

The first step in this project will be getting an introduction to the related topics by reading books, journals and research papers. Research has been done in order to understand better on the two phase flow models and friction factor calculation methods. This research took a time of approximately 1 month. Prior to understanding of the available models, the best and most appropriate model was chosen to perform the calculation of gas void fraction followed by friction factor. All the involved variables was identified and understood. That process took about 2 months to complete. Once the needed model was studied, the computation software of Mathematica was learned and the complete calculation method was translated into computer codes. 1 month was needed to perform that process and finally it took about 1 month to analysis the results obtained from the computation program.

CHAPTER 2: LITERATURE REVIEW

2.1 Analysis of References

For the study of two phase flow friction factor in EOR injection wellbores, there were several research papers that was reviewed and studied in order to understand the phenomena. The research done was divided into two categories which are friction factor and two phase flow models.

For the friction factor, the paper entitled Friction Factor for Pipe Flow published by Lewis F.Moody and N.J Princeton on 1944 was reviewed. The objective of this paper is to supply engineers with a simple way of estimating the friction factor to be used in computing of head loss in clean new pipes and in closed conduits running full with steady flow. In this paper, it was said that friction factor, f is a dimensionless quantity and at ordinary velocities it is a function of only two other dimensionless quantities- the relative roughness of the pipe surface and the Reynolds number. Under abnormal conditions, f could be affected by other dimensionless criteria such as acoustic velocity, gravity waves, and surface tension. Professor Pardoe reminds that temperature difference between the fluid and pipe wall may have a measurable effect on the shear stresses, due to ambient currents which would increase the momentum transfer in similar manner to turbulent mixing.

In studying about two phase flow model, several papers were reviewed. One of it is Advances in Two-Phase Flow Mechanistic Model by Yehuda Taitel published in 1996. Objective of this paper was to introduce the basis for some mechanistic models used in various problems of two-phase flow. Based on this paper, it can be said that there are 3 main types of model which are two-fluid model, drift flux model and homogenous model. The difference between a model and a mechanistic model was also explained in this paper. Mechanistic model was defined as to be the modeling where only the important processes are taken into consideration and the less important effects are neglected. Besides that, paper entitled Experimental Research on Downward Two-Phase Flow by Ali Hernandez, Leonor Gonzalez and Pedro Gonzalez published in 2002 was also studied. Objective of this paper is to better understand the pressure drop, flow patterns and liquid hold-up in downward two-phase flow using experiments. The experiments were performed using 2 inches diameter pipes with water and air as process fluids.

Paper entitled Void Fraction in Bubbly and Slug Flow in Downward Vertical and Inclined Systems by A.R.Hasan published in 1995 was studied. This paper was about a model that was presented on void fraction for two principal flow patterns which are bubbly flow and slug flow. A.R.Hasan applied drift flux model to calculate void fraction. The calculation for bubbly and slug flow did differ in terms of the terminal rise velocity and the difference of upward and downward flow was explained in terms of the buoyancy force. Another paper that was studied was A Basic Approach to Wellbore Two-Phase Flow Modeling by A.R.Hasan and C.S.Kabir published in 2007. This paper actually is the extended study of A.R.Hasan's paper mentioned above. This paper presented about a simplified model of two-phase flow using drift flux model for calculating liquid holdup for 4 principal flow patterns which are bubbly flow, slug flow, churn flow and annular flow. They presented a general model that differs only in the value of terminal rise velocity and flow parameter for different flow patterns.

In this study of friction factor in downward two-phase flow, the selected model was modified by including temperature as its variable in calculating liquid density, gas density, liquid viscosity, gas viscosity and surface tension. The paper of Saturated Steam Property Functional Correlations for Fully Implicit Thermal Reservoir Simulation by W.S Tortike and S.M Farouq Ali published in 1989 presented the correlation of the above mentioned parameters. In this paper, a new set of functional correlation been developed to predict the physical properties of saturated steam. The advantages of this correlation is that it gives a continuous and numerically efficient polynomial for each property, it is suitable for vector pipeline and parallel processors and computer spreadsheets, and it offers a complete selection of steam properties with choice of derived SI metric or customary units, with each correlation found separately in its own system.

In coming up with results in this study, calculation using a computation program was developed. In order to perform the calculation, field data was extracted from a book entitled Fluid Flow and Heat Transfer in Wellbores by A.R. Hasan and C.S. Kabir, published by Society of Petroleum Engineers in 2002. Steam PVT data and wellbore configuration data was extracted from this book. This book did also demonstrate the calculation in determining the individual pattern transition criteria in order to find the void fraction. Example of calculation procedure was also included in this book which assisted in performing the calculation.

In discussing about the results and the effect of each variable towards the friction factor few research papers have been studied. One of them is Simultaneous Flow of Gas and Liquid as Encountered in Well Tubing by N.C.J.Ros published in 1961. In this paper it was discussed about pressure gradient occurring in flowing and gas-lift wells in order to determine the optimum flow-string dimensions and to the design gas-lift installations. In this paper it was found out that a pressure gradient correlation must consist of two parts, one part being a correlation for liquid holdup and another for wall friction. In the experiment carried out, 3 flow regimes were found and the pressure gradients in those 3 regions were presented in the form of a set of correlations.

Another paper was also studied in order to discuss the results of this project. Some Practical Considerations in the Design of Steam Injection Wells by Robert C. Earlougher Jr. published in 1969 was reviewed. In this paper, a variety of examples have been given to show the effects of injection and completion details on the conditions existing in a steam injection wellbore. The conclusions of this paper is that heat loss can be reduced significantly by insulating the wellbore, well completion and injection conditions significantly affect the downhole properties of steam, pressure cannot be safely neglected in calculating heat transfer from the injected steam, it is always good to inject steam at a lower rate than anticipated steam properties caused by change in pressure in injection string.

Paper by P.H.Holst and D.L.Flock entitled Wellbore Behavior during Saturated Steam Injection published in 1960 was also studied. In this paper a mathematical model was formulated to describe the injection of saturated steam down oil well tubing under constant inlet conditions. In the study of steam injection, the steam was divided into three parts, which are the fluid, the wellbore and the formation. Each part was considered as a separate system. The analysis resulted in three equations. After the sample computer runs, it was concluded that friction had minor influences on heat loss and major effect on quality and temperature profile. The rate of heat loss may be reduced by the addition of second casing.

2.2 Theory

2.2.1 Liquid Holdup

Elemer Bobok (1938) says that in multiphase flow, density and viscosity difference occurs between phases. In this situation, the less dense phase will flow with a higher in-situ velocity. This velocity difference will affect the concentration of the phase along the length of the pipe. In the entrance section of the pipe the less mobile phase concentrates and this concentration gradually decreases in the direction of flow. This phenomenon is called holdup.

Based on H.Dale Beggs (2003), liquid holdup can also be defined as the fraction of an element of pipe that is occupied by liquid at some instant. H.Dale Beggs (2003) also mentioned that liquid holdup is important to determine in order to calculate parameters such as mixture density, gas and liquid actual velocities, effective viscosity and heat transfer. Liquid holdup can be measured experimentally by several methods such as resistivity or capacitance probes, nuclear densitometers or by trapping a segment of the flow stream between quick closing valves and measuring the volume of liquid trapped.

2.2.2 Superficial Velocity

Usually the actual distribution of the fluids in the pipe is unknown, which is why the actual velocities of the fluids are difficult to obtain. The superficial velocity of a fluid phase is defined as the velocity which that fluid phase would exhibit if it flowed through the total cross section of the pipe alone. The superficial velocity is given by the ratio of volumetric flow rate with area of the pipe.

2.2.3 Flow Patterns

Each time when two fluids with different physical properties flow simultaneously in a pipe there can be a wide range of potential flow patterns. Flow patterns are referring to the distribution of each phase in the pipe relative to the other phase. Prediction of flow patterns for horizontal flow is more difficult compared to for vertical flow. This is because for horizontal flow, the phases tend to separate due to differences in density and the effect of gravity is low causing the flow pattern to be stratified most of the time.

The determination of flow patterns is mostly carried out by direct visual observation, occasionally complemented with high-speed photography or can be determined by considering the superficial velocity. The method of using visual observation is very subjective hence the use of flow pattern diagram which is plotted in terms of superficial velocities of each phase is used. The obtained diagram is called a flow pattern map, in which certain regions correspond to characteristic flow patterns. By inserting gas at progressively increasing flow rate into a homogenous liquid flow, changing flow patterns can be distinguished. The flow patterns that can be identified are bubbly flow, slug flow, churn/froth flow and annular flow.

Bubbly flow

At the lowest gas flow rate, the liquid is continuous and small, spherical gas bubbles move upward near the pipe axis, faster than the liquid. As the gas flow rate is increased the number of bubbles increases, and because of coalescence the average bubble size increases.

Slug flow

A further increase in gas flow rate causes an increase in the volume fraction of the bubbles, up to 30 percent, while bubble coalescence leads to the occurrence of large mushroom-shaped bubbles which nearly span the entire cross-section of the pipe. These larger mushroom-shaped bubbles are followed by regions containing dispersions of smaller bubbles, and periodical bubble-free liquid plugs. With further increase in the gas flow rate, the larger bubbles become longer having a bullet shape. These bullet-shaped bubbles are called Taylor bubbles. Slug flow pattern is characterized by periodic alternating Taylor bubbles and liquid regions containing a number of smaller spherical bubbles. The liquid phase flows down the outside of the Taylor bubble as a failing film although the resultant flow of both liquid and gas is upward. In these flow patterns liquid phase is always continuous, the gas phase is dispersed.

According to <http://www.glossary.oilfield.slb.com>, 13th April 2011

Taylor bubble is defined as large bubbles of the lighter phase that form by coalescence of small bubbles under certain conditions of fluid flow. The large bubbles occur during slug flow and plug flow. The term is named after G.I. Taylor.

Churn Flow / Froth Flow

Slug flow corresponds to the increase in pressure loss. The increasing pressure gradient now tends to collapse the Taylor bubbles. Surface tension acts against this condition, but larger gas bubbles become unstable and finally collapse. At this point the interfaces between the phases become highly distorted, both phases become dispersed and froth flow pattern develops. Froth flow is highly unstable because an oscillatory upward-downward motion occurs in the liquid phase, particularly in pipes of larger diameter. This is known as churn flow. In small diameter pipes, the breakdown of the Taylor bubbles is not so abrupt since the transition is more gradual without the occurrence of churn.

Annular flow / Mist flow

As the gas flow rate is increased further an upward moving wavy annular liquid layer develops at the pipe wall, and the gas flows with a considerably greater velocity in the center of the pipe. The gas center flow may carry small fluid droplets ripped from the annular liquid layer. With a further increase of the gas flow rate the liquid film becomes progressively thinner while the number of the droplets in the core flow increases. Finally, the film will be removed from the wall and a pure mist flow occurs.

Figure 2.1 below shows the 4 principal flow patterns.

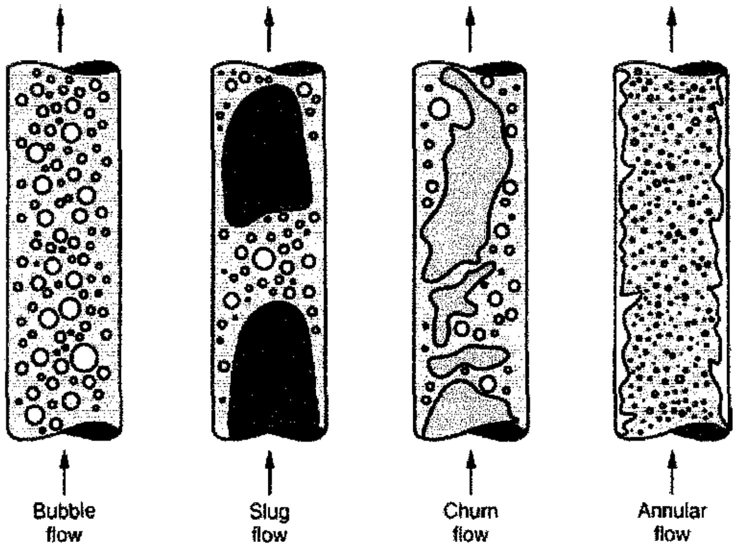


Figure 2.1: Principal Flow Patterns

2.2.4 Mechanistic Models

Mechanistic models rely more on the theory or mechanisms in multiphase flow rather than solely on experimental work. Empiricism is still used in a mechanistic approach to predict certain flow mechanisms or provide closure relationship. Closure relationship is defined as the smallest closed set containing a given set. <http://dictionary.reference.com/browse/closure>

2.2.5 Hasan and Kabir model

Since the study is concerned on downward two-phase flow, the model chosen for calculation is Hasan and Kabir model. Hasan and Kabir proposed a simplified two-phase flow model using the drift flux approach to well orientation, geometry and fluids. This model uses a single expression for liquid holdup, with flow parameters and rise velocity. This model estimates both the entrainment and the film-friction factor. Friction factor is estimated using the Chen's correlation of Moody friction factor.

2.2.6 Drift flux model

When two-phase are considered to have different velocities, the relation between void fraction and velocity is not analytically computable, but requires some empirical data which links void and velocity. A large number of empirical and semi empirical methods have been suggested over the last fifty years. The semi-empirical model which is most applicable for our problem is the drift flux model. This model has been principally developed by Zuber and Findlay, Wallis and Ishii and has been refined since that time by other researchers.

The general drift-flux expression that takes into account the effect of non-uniform flow and concentration profiles, on top of the effect of the local relative velocity between the phases was developed by Zuber and Findlay. A relationship that combines the two mechanisms is given by:

$$V_g = C_o V_m + V_d \qquad \text{......(1)}$$

Where V_g is the flow velocity of the gas phase, C_o is the profile parameter (which considers the effect of non-uniform flow and concentration profiles), V_m is the mixture velocity and V_d is the drift velocity of the gas.

The effect of the parameter on the predictions depends on the value of the mixture velocity. For high velocity flows, C_o becomes important since it multiplies the mixture velocity. However, for low velocity flow, V_d is dominant since it adds up to the product of C_o and V_m.

Gas-liquid profile parameter, C_o

The profile, C_o is in general the flow pattern dependent. For simplicity, in the drift-flux model this parameter is set to vary with liquid holdup.

According to Zuber and Findlay the value of C_o can range from 1.0 to 1.5. However, for a number of one dimensional flow correlations C_o was found to take a value of 1.2. This applies strictly in the bubble and slug flow regimes. Accordingly C_o is set to a constant value of 1.2 at low values of liquid holdup and mixture velocities. At high velocities, the system becomes more homogenous and the profile flattens out resulting in C_o approaching 1.0 such as in annular flow.

Inclination correction factor

All of the above formulations were derived for vertical systems. Hasan and Kabir developed a correlation to account for the inclination effect on the drift velocity. The correlation was initially developed for water-air system and was tuned using data from Hasan and Kabir and Runge-Wallis. It was mentioned that in gas/liquid flow, the increase in the Taylor-bubble rise velocity with increasing deviation from the vertical for near-vertical systems has been observed by a number of researches and that well deviation causes a similar total change in the shape of the droplets in oil/ water flow, causing the droplets to rise faster as the well is deviated from the vertical. Hasan and Kabir state that their correlations are valid for deviations from vertical of 70 degree or less.

CHAPTER 3: METHODOLOGY

3.1 Research Methodology

In order to achieve the objectives of this project, some researches had been done on some resources from books and journals.

The main topic that study had to be done was on the principal flow patterns. All 4 principal flow patterns were needed to be identified and the criteria to differentiate it must be known. Other research was done on determination of in situ gas velocity which is the sum of terminal rise velocity and channel center mixture velocity, next was the calculation of gas void fraction which is the ratio of in-situ gas velocity and superficial velocity, followed by determination of density and viscosity in order to determine the Reynolds number. By determination of the Reynolds number, the friction factor was able to be calculated. Once all the calculation procedure was identified, it was translated into computer codes using computation software of Mathematica.

3.2 Project Work

Project work can be divided into two categories. The first would be the method undertaken in performing the research of this study. This includes the literature studies done and selection of model used in calculation. Second would be the method of calculation that has been translated into computer codes using computation software of Mathematica.

Figure 3.1 below is the process flow of the project work. It consists of all the steps taken in completing the study on this subject.

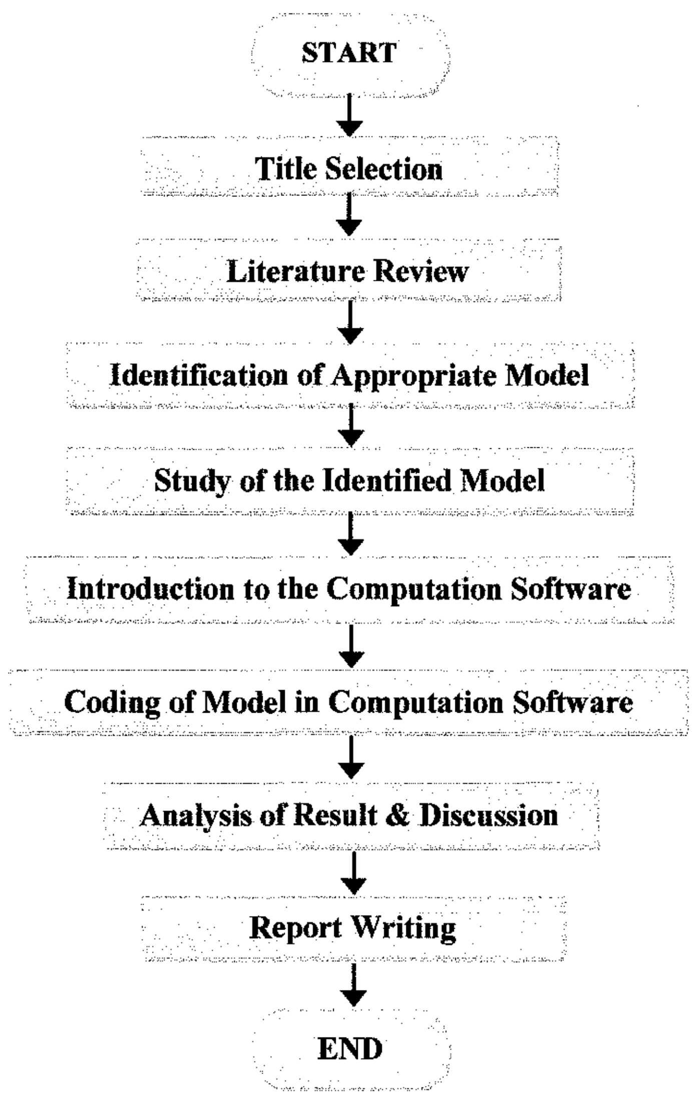


Figure 3.1: Process flow of research conducted

Figure 3.2 below is the basic process of the computation program. It starts from the input of data till the calculation of final result which is friction factor.

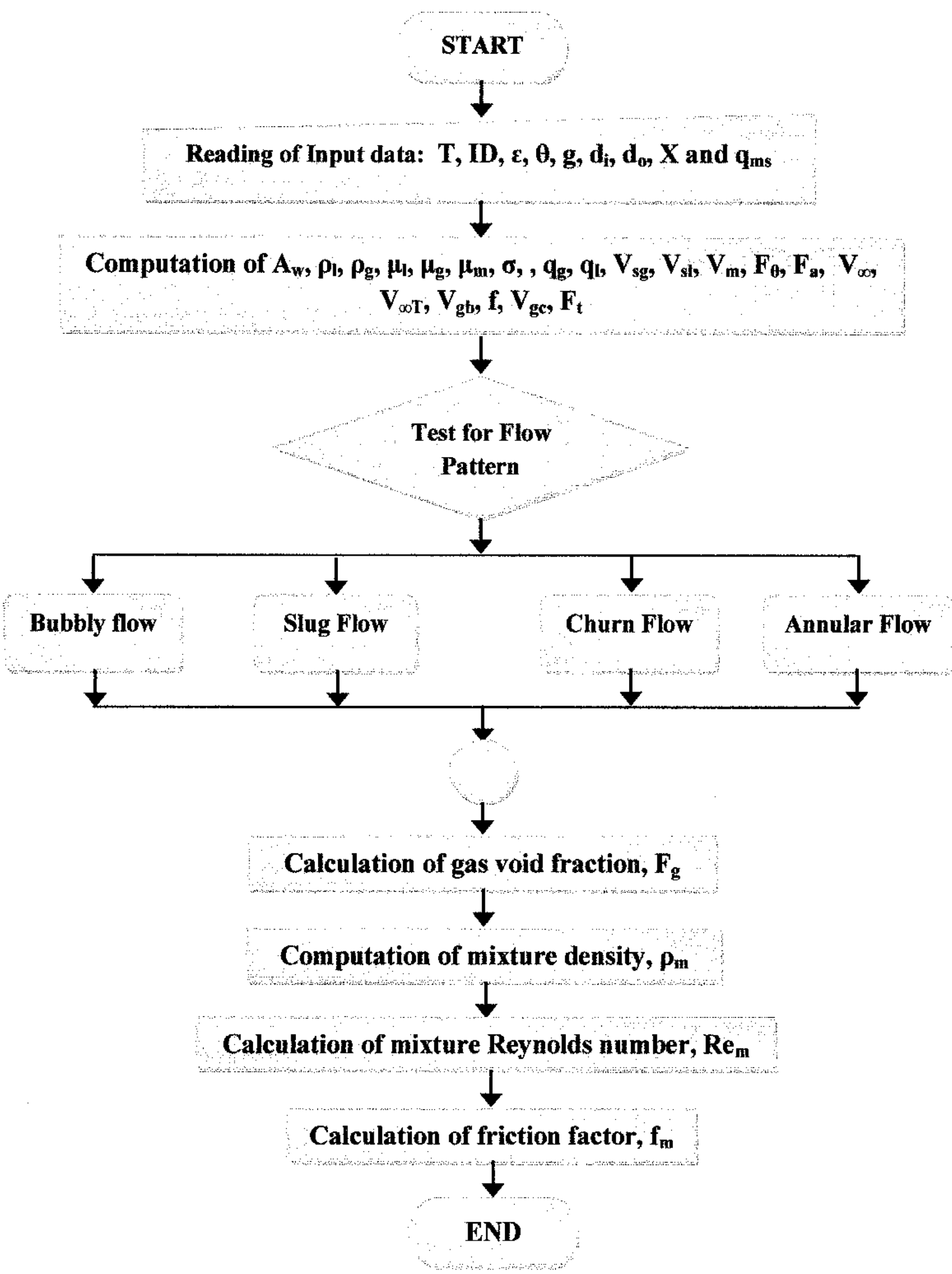


Figure 3.2: Process flow of Computation Program

3.3 Gantt Chart and Key Milestone

Figure 3.3 and 3.4 below shows the schedule and timeline of this project carried out for the period of 8 months. It consists of two parts which was divided into two semesters called Final Year Project I and Final Year Project II and was 14 weeks each.

Legend:

■ Processes

☆ Milestones

No	Detail / Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic	■	■													
2	Study on Friction factor and Downward Two-phase flow models		■	■	■	■										
3	Submission of Extended Proposal						☆		Mid Semester Break							
4	Proposal Defense										■					
5	Study on selected downward two phase flow model											■	■	■		
6	Introduction to Computation Software of Mathematica											■	■	■	■	■
7	Submission of Interim Draft Report														☆	
8	Submission of Interim Report															☆

Table 3.1: Gantt chart for the first semester project implementation

No	Detail / Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Refining the model & learning of Mathematica software	■	■	■	■	■	■	■	Mid Semester Break								
2	Submission of Progress Report									☆							
3	Coding of Model in Mathematica software									■	■	■	■	■			
4	Poster Submission												☆				
6	Submission of Dissertation (softbound)													☆			
7	Submission of Technical Paper														☆		
8	Oral Presentation															☆	
9	Submission of Dissertation (hard bound)																☆

Table 3.2: Gantt chart for the second semester project implementation

3.4 Tools required

In order to complete this project, the end result would be modeling of this friction factor in computation software. The software is needed to translate the calculation procedure into computer codes.

The software chosen was computation software of Mathematica. This software was developed by Wolfram Research. This software is the world's only fully integrated environment for technical computing. The calculation method of the model will be changed into codes using this software.

The result of the calculation using Mathematica was plotted in graphs using Microsoft Office Excel. All the obtain data was recorded in Microsoft Excel and plotted into graph to find the relation between variables and friction factor. Microsoft Excel is a commercial spreadsheet application. It features calculation, graphing tools, pivot tables, and a macro programming language called visual basic applications.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Flow Pattern Transition

In this project, the approach proposed by Hasan et al (2007) in determining the pattern transition criteria is used. In this approach, it is assumes that when gas volume fraction exceeds 25% significant increase in collisions amongst bubbles causes transition from bubbly to slug flow.

The following model shows the criteria needed for transition from bubbly flow to slug flow based on the terminal velocity.

$$V_\infty = 1.53\left[g\sigma(\rho L - \rho g)/\rho L^2\right]^{0.25} \quad \text{.......(2)}$$

$$V_{\infty T} = 0.345\left[gd(\rho L - \rho g)/\rho L\right]^{0.5}\sqrt{\sin\theta}(1+\cos\theta)^{1.2} \quad \text{.......(3)}$$

Based on the equations above, if $V\infty T < V\infty$, transition to slug flow occurs. While if $V\infty T > V\infty$, bubbly flow can exist.

Another equation on the basis of superficial gas velocity can also determine the possibility for pattern transition.

$$V_{sg} = 0.429V_{sL} + 0.357V_\infty\sin\theta \quad \text{.......(4)}$$

Based on the equation, slug flow can occur when $Vsg > 0.088m/s$.

Transition from slug to churn flow occurs due to high velocity fluid drag that breaks the Taylor bubbles. Shoham's (1982) suggestion is used in determining the transition criteria.

$$2V_{ms}^{1.2}\left(\frac{f_m}{2d}\right)^{0.4}\left(\frac{\rho_L}{\sigma}\right)^{0.6}\sqrt{\frac{0.4\sigma}{g(\rho_L-\rho_g)}} = 0.725 + 4.15\sqrt{\frac{V_{sg}}{V_m}} \quad \text{.......(5)}$$

The f_m used in the above equation is based on Blassius equation, that suggests

$$f_m = 0.32(\mathrm{Re}_m)^{-0.25} \quad \text{.......(6)}$$

and Rem which is the mixture Reynold number can be obtained by the formula of

$$\mathrm{Re}_m = DV_m\rho_m/\mu_m \quad \text{.......(7)}$$

but since the at this moment there is insufficient data to calculate mixture density which requires gas void fraction, the equation proposed by Govier and Aziz (1972) which uses liquid density and liquid viscosity in the place of mixture density and mixture viscosity can be used.

$$\mathrm{Re} = DV_m\rho_L / \mu_L \quad \text{.....(8)}$$

so, $f_m = 0.32(dV_m\rho_L / \mu_L)^{-0.25}$ .....(9)

According to Shoham's (1982) suggestion, when $Vm > Vms$, churn flow can occur. In addition to this criteria, it is also suggested that when $V_{sg} > 1.08V_{sL}$, churn flow can exist and dispersed bubbly flow cannot occur.

Transition to annular flow occurs at high gas flow rates. It is because at high gas flow rates, the shear force of the gas on the liquid will pull it upward allowing liquid to flow at the wall of the tube and the gas in the middle of the tube. A model was adopted by Taitel et al. (1989) that examine the drag force needed to keep the entrained liquid droplets in suspension. If the gas velocity is not sufficient to keep the liquid droplets in suspension, the droplets will fall back and form a bridge leading to churn and slug flow. The following equation is based on gas velocity beyond which annular flow is expected.

If

$$Vsg > 3.1\left[g\sigma(\rho L - \rho g)/\rho g^2\right]^{1/4} \quad \text{.....(10)}$$

annular flow will occur. While if

$$Vsg < 3.1\left[g\sigma(\rho L - \rho g)/\rho g^2\right]^{1/4} \quad \text{.....(11)}$$

annular flow cannot occur.

4.2 Void fraction

For all flow regimes the gas phase moves faster than the liquid because of buoyancy and its tendency to flow close to the channel center, where the velocity is higher than the average mixture velocity. Therefore, the in-situ gas velocity, *Vg* can be expressed as the sum of bubble-rise velocity and *Co* times the average mixture velocity.

$$V_g = C_o V_m - V_\infty \quad \text{.........(12)}$$

$$V_g = \frac{V_{sg}}{f_g} \quad \text{.........(13)}$$

By putting in equation (1) into equation (2), we have a relation between volume fraction and phase velocities.

$$f_g = \frac{V_{sg}}{C_o V_m - V_\infty} \quad \text{.........(14)}$$

For each flow pattern, the calculation method and flow parameters have been altered according to the flowing configuration.

4.2.2 Bubbly, Churn and Annular flow

The altered parameter is shown in Table 2.1

Flow Pattern	Flow Parameter, Co	Rise Velocity, V_∞
Bubbly	1.2	$V_{\infty b}$
Churn	1.12	$\bar{V}_\infty$
Annular	1.0	0

Table 4.1: Flow parameters and Terminal Velocity Values according to Flow pattern

Below are the equations for bubble terminal velocity and average terminal velocity.

$$V_{\infty b} = 1.53\left[g(\rho_L - \rho_g)\sigma / \rho_L^2\right]^{1/4} \quad \text{.........(15)}$$

$$\overline{V}\infty = V_{\infty b}\left(1 - e^{-0.1 v_{gb}/(v_{sg} - v_{gb})}\right) + V_{\infty T}\left(e^{-0.1 v_{gb}/(v_{sg} - v_{gb})}\right) \quad \text{.........(16)}$$

Based on the release by the International Association for Properties of Water and Steam (IAPWS) on September 1994, the following equation is used for the calculation of surface tension of the interface between the liquid and vapor phases of ordinary water. The temperature used in the units of Kelvin (K) and the critical temperature Tc = 647.096K

$$\sigma = 0.2358\left(1 - \frac{T}{Tc}\right)1.256\left[1 - 0.625\left(1 - \frac{T}{Tc}\right)\right] \quad \text{.................................(17)}$$

4.2.3 Slug flow

Flow configuration in slug flow is quite different then other flows, it is because there are two separate zones during slug flow. One is subjugated by the large Taylor bubble and other consisting of small bubbles in the liquid slug.

Based on Hasan and Kabir's (1988) approach which takes into account for the differing drift velocities in the liquid slug and Taylor bubble, model for calculating slug flow in vertical and inclined annuli for downward flow is as following.

The average void fraction is:

$$f_g = \frac{L_T}{L} f_T + \frac{L_s}{L} f_s \quad \text{..(18)}$$

Void fraction for ideal slug flow calculation is used in the Taylor bubble portion.

$$f_T = \frac{V_{GS}}{C_o V_m - V_{\infty T}} \quad \text{.....(19)}$$

Based on the data presented by Akagawa and Sakaguchi (1966), it shows that the average volume fraction of gas in the liquid slug is approximately equal to 0.1 when Vgs is greater than 0.4m/s and is equal to 0.25Vgs for lower superficial gas velocities.

When $V_{GS} > 0.4 m/s$

$$f_g = \left(\frac{L_T}{L}\right) f_T + 0.1 \quad \text{.....(20)}$$

While when $V_{GS} \leq 0.4 m/s$

$$f_g = \left(\frac{L_T}{L}\right) f_T + 0.25 V_{gs} \quad \text{.....(21)}$$

Hasan and Kabir derived the following expression for the fraction $\frac{L_T}{L}$ for gas void fraction in bubbly flow to the liquid slug.

For the condition of $V_{GS} > 0.4 m/s$ the following equation is used since

$$\left(\frac{L_s}{L}\right) f_S = 0.1$$

$$\frac{L_s}{L} = 0.1 \left(\frac{C_o V_m - V_\infty}{V_{GS}}\right) \quad \text{.....(22)}$$

For the condition of $V_{GS} \leq 0.4 m/s$ the following equation is used since $\left(\frac{L_s}{L}\right) f_S = 0.25 V_{sg}$

$$\frac{L_s}{L} = 0.25(C_o V_m - V_\infty) \quad \text{...(23)}$$

Finally the equation below is used to calculate the fraction $\frac{L_T}{L}$

$$\frac{L_T}{L} = 1 - \frac{L_S}{L} \quad \text{...(24)}$$

Hence, the void fraction for slug flow can be calculated by putting in the value obtained from equation (24) and equation (19) into equation (20) or equation (21) based on the superficial gas velocity.

4.3 Friction Factor

After obtaining the value for void fraction, friction factor can be calculated. Void fraction is a factor in determining friction factor because void fraction is a variable in the calculation of mixture density.

The mixture density is the volumetric-weighted average of the two-phase ρL and ρg and viscosity is the mass-average mixture viscosity. The mixture density and viscosity is formulated in terms of temperature. Temperature is also a variable in the calculation of liquid and gas density and liquid and gas viscosity. Equations below demonstrate the parameter of steam temperature as a factor in determining friction factor.

$$\rho_m = \rho_g f_g + \rho_L (1 - f_g) \quad \text{...(25)}$$

Calculating liquid and gas density in terms of temperature as follows:

$$\rho_L = 3786.31 - 37.2487T + 0.196246T^2 - 5.04708\times10^{-4}T^3 + 6.29368\times10^{-7}T^4 - 3.08480\times10^{-10}T^5 \quad \text{.....(26)}$$

$$\rho g = -93.7072 + 0.83394T - 0.0032080T^{2} + 6.57652\times 10^{-6}T^{3}$$

$$-6.93747\times 10^{-9}T^{4} + 2.97203\times 10^{-12}T^{5} \qquad \text{.....................(27)}$$

$$\mu m = \mu g x + \mu L(1-x) \qquad \text{.....................(28)}$$

Calculating liquid and gas viscosity in terms of temperature as follows:

$$\mu L = -0.0123274 + \frac{27.1038}{T} - \frac{23527.5}{T^2} + \frac{1.01425\times10^{7}}{T^3} - \frac{2.17342\times10^{9}}{T^4} + \frac{1.86935\times10^{11}}{T^5}$$

.............(29)

$$\mu g = -5.46807\times10^{-4} + 6.89490\times10^{-6}T - 3.39999\times10^{-8}T^{2}$$

$$+8.29842\times10^{-11}T^{3} - 9.97060\times10^{-14}T^{4} + 4.71914\times10^{-17}T^{5} \qquad \text{.........(30)}$$

In order to calculate the friction factor, Chen's (1979) correlation is used which is a factor of Reynolds number and pipe roughness. This equation can be used for all types of pipe roughness.

$$fm = \frac{1}{\left[4\log\left(\frac{\varepsilon/d}{3.7065} - \frac{5.0452}{\mathrm{Re}m}\log A\right)\right]^{2}} \qquad \text{.....................(31)}$$

Mixture Reynolds number can be obtained by finding the ratio of product of tubing diameter, mixture velocity and mixture density with mixture viscosity.

$$\mathrm{Re}_m = DV_m\rho m/\mu m \qquad \text{.....................(32)}$$

And the dimensionless parameter, A given by

$$A = \frac{\varepsilon/d^{1.1098}}{2.8257} + \left(\frac{7.149}{\mathrm{Re}_m}\right)^{0.8981} \qquad \text{.....................(33)}$$

4.4 Computation Algorithm

Calculation procedure of two phase flow friction factor done using Hasan and Kabir's model been translated into computer codes using computation software of Mathematica. A computer program has been developed to calculate the friction factor according to specific flow pattern based on input data. The input data needed to run this program are steam temperature in Kelvin, tubing inner diameter in meters, tubing outer diameter in meters, casing inner diameter in meters, well deviation from vertical in degrees, pipe roughness in meters, steam quality and mass flow rate in kilogram per second. As mentioned all computation and data input will be done in SI units.

Common parameter will be calculated first once all the needed data are being inputted. Parameters mentioned are liquid and gas density (Eq. 26 and 27), liquid and gas viscosity (Eq. 29 and 30), surface tension (Eq. 17), mixture viscosity (Eq. 28), friction factor (Eq. 9) and void fraction for Taylor bubble (Eq. 19).

Flow pattern transition criteria will be calculated in order to determine flow pattern based on input data. The computation of flow pattern is as show previously above. Once the accurate flow pattern has been identified, computation will continue with the calculation of void fraction. Void fraction calculation will follow the general equation (Eq. 14) except for slug flow will follow either Eq.20 or Eq. 21.

Final computation will be on calculation of mixture Reynolds number (Eq. 32) followed by friction factor (Eq. 31). The program's final result will show flow pattern, void fraction and friction factor based on the data inputted.

4.5 Relationship between flow pattern and friction factor

4.5.1 Bubbly flow

In most bubbly flow, the friction losses can be neglected in comparison to the hydrostatic or head pressure drop. Bubbly flow is said to exhibit a variety of bubble sizes and shapes and that those bubble characteristics are variable and depend on flow conditions, fluid properties, and how the bubbles are generated or introduced into the liquid stream. However, it has been simplified that the geometric structure of a bubbly two-phase stream by assuming that the bubbles are spherical. (Solomon Levy, 1999)

4.5.2 Slug flow

As in bubbly flow, the wall shear stress has been found negligible in several tests of vertical slug flow and it has often been neglected. In fact, if the flow direction of the liquid film in co-current vertical slug flow is examined properly, it can be found that it sometimes flows down along the walls and that the frictional pressure loss can be negative. However, at increased liquid velocities, the frictional pressure drop can be positive and important. (Solomon Levy, 1999)

4.5.3 Churn & Annular flow

Gas liquid interface in annular flow is mostly covered with waves which plays a significant role in determining the two-phase flow behavior. The occurrence of waves and their characteristics were studied starting in the early 1960s by Hewitt and Hall-Taylor. At very low liquid flows rates and high gas flows rates, the water is incapable in wetting the tube wall and a mist flow pattern exists. Above a critical gas velocity and at low liquid-flow rates, a liquid film is formed and mainly for falling films, only small surface ripples exist at the interface. Beyond a critical liquid flow rate, disturbance waves begin to appear. Initially, they are comingled with ripples waves, but as the liquid flow is raised, disturbance waves are formed primarily and they control the behavior at the interface. Annular flow below the critical gas velocity and close to the transition to slug flow, waves occur over the full range of liquid velocities. The film flow can then be intermittent and the waves are rather large and do not have smooth, steady or consistent profile. In between the waves, a liquid film exists that is decelerating and even reversing its direction before the arrival of the next wave. These waves are characteristic of churn annular flow and are referred to as flooding waves because they associated with the flooding mechanisms in countercurrent vertical flow.

In ripple wave, the interfacial friction factor is usually represented as an amplification of single-phase friction factor. An early and extensive investigation by Hall-Taylor et al. on disturbance or roll wave in vertical flow found out that roll waves are thick compared to the liquid film and that they slide atop film with a velocity of the magnitude greater than that of the film. The velocity of the waves appears to be controlled entirely by the gas flow rate, while the number of waves is governed by the liquid rate. The roll waves liquid separate from the disturbance waves and their crumble into clouds of liquid droplets in the gas core. Interface shear stress depends on the shape and number of interface waves. This fact has been recognized by many investigators, who have found that the frictional pressure drop in the gas core depends on the form and amplitude of the waves atop liquid film. For example, Chien and Ibele shown that the two-phase frictional pressure drop in annular downward two-phase is a function of superficial friction factor, mean gas superficial velocity, and waviness of the liquid film.

Levy assumed that gravitational forces could be neglected with respect to shear forces so that the relation derived for the ideal annular flow model can be used for liquid-film flow rate and its thickness. Also, he determined that the shear stress on the core side of the interface was dominated by the sharp density gradient existing at that location. (Solomon Levy,1999)

The flooding waves near the slug-to-annular flow pattern transition are even more difficult to study and predict because of the irregular and unsteady behavior. Different regions of the liquid film have been observed simultaneously to be flowing upward or downward. The waves are rather large and there are large filament shaped liquid discontinuity at the interface which are not easily representable by some kind of velocity or shear distribution. In between the waves, a liquid film exists that is decelerating behind the wave, and its deceleration can lead to flow reversal before the next wave arrives. Measurements of the interfacial friction factor carried out by Bharathan and Wallis and Abe showed that the interfacial friction factor is a lot higher than that values predicted from correlations for disturbed waves. (Solomon Levy, 1999)

4.6 Parameters analysis

Various input data have been tried and results have been obtained using the program. When one variable is changed the others were kept constant except the case when quality is changed, temperature is also changed and when tubing ID is changed, its OD is also changed. All the obtained results are plotted on the graph against friction factor to show relationship between a particular input data and friction factor.

The initial data used to perform the computation was obtained from Hasan and Kabir (2002) and the same data was presented in Satter (1965). Temperature and steam quality was extracted from the graph presented together with the data. Temperature and steam quality was plotted as a function of depth. Graph presented as per below:

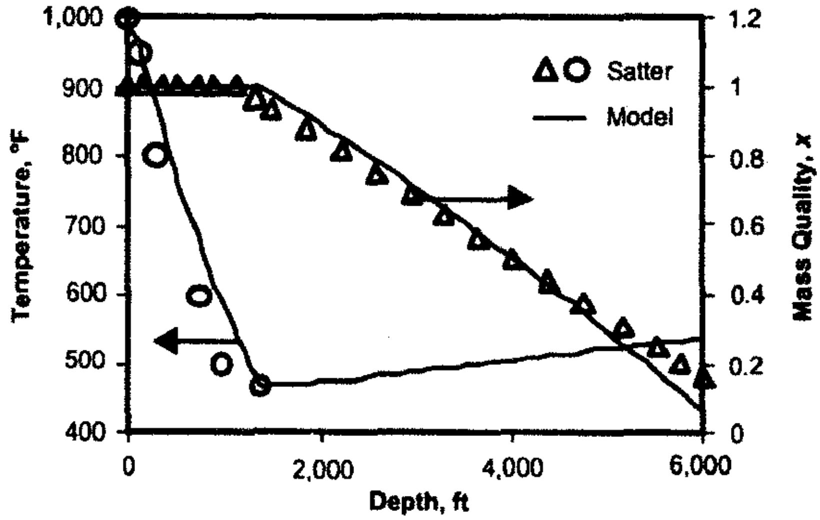


Figure 4.2 Temperature and steam quality with depth

The other data from Hasan and Kabir (2002) are

Tubing inner diameter (ID): 0.0620014 m

Tubing outer diameter (OD): 0.073025 m

Casing inner diameter: 0.1521206 m

Mass flow rate: 0.167753578 kg/sec

Well deviation from vertical: 0.0 degree

Roughness of pipe: 0.00072932 m

Roughness of pipe was obtained from Energy Resource Board, Calgary (1975) which recommends the value of 0.00072932 m (0.00005 ft) for new tubing.

All the parameters are then changed in order to find the relationship between a particular parameter and friction factor. Following will be discussion on the effect of all the variables.

4.6.1 Effect of tubing ID on friction factor.

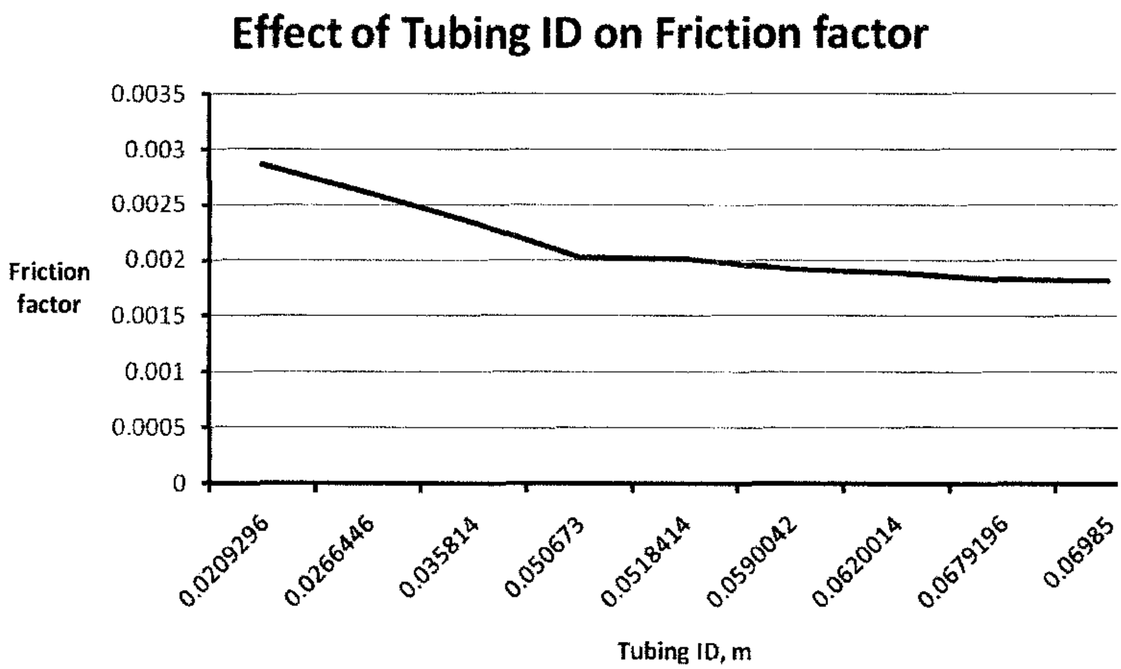


Figure 4.3 Effect of Tubing ID on Friction Factor

Based on the graph obtained by plotting various tubing size with friction factor it can be seen that as the tubing size increases, the friction factor decreases. This phenomenon can be explained by saying that if the tubing ID increases the restriction for fluid flow will decrease hence reducing the friction factor of the fluid itself.

Wall friction appears to decrease with increasing diameter, just as in the case of single-phase flow. In the high velocity ranges where the friction is dominant, the pressure gradient consequently decreases with increasing diameter. With small liquid throughputs, however, the pressure gradient will be affected only insofar as the hold-up is influenced. This is only the case at moderately high throughputs where increased diameter causes increased slip between gas and liquid, resulting in an increased in pressure gradient.

With annuli, distinction between large and small liquid throughputs must again be made. With high liquid throughputs when wall friction is great, the hydraulic diameter (that is the difference between internal casing and external tubing diameters) proves decisive, so that the pressure gradient increases with increasing tubing diameter for a given casing. When the liquid throughput is small, however, wall friction is small and the pressure gradient is nearly equal to the liquid hold-up. The latter appears to increase when the sum of the diameter of casing and tubing increases.

Tubing IDs used taken from drilling data handbook by Institut Francais du Petrole Publications based on grades and standards used in the field. All tubing selected has grade of L80.

4.6.2 Effect of temperature on friction factor

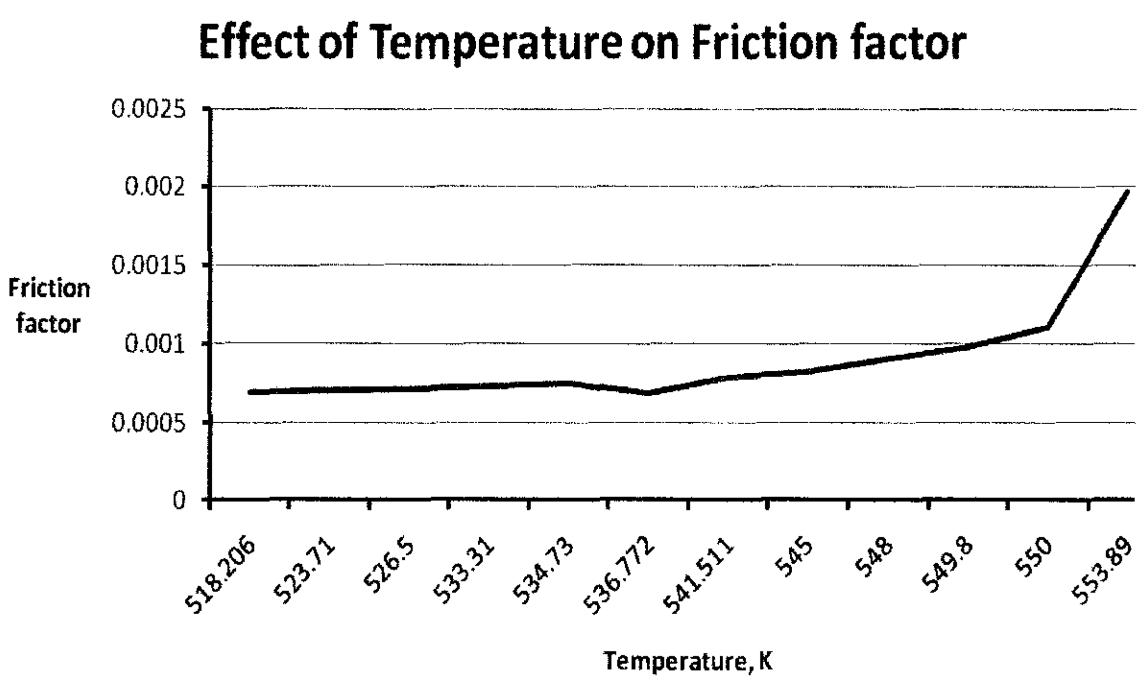


Figure 4.4 Effect of Temperature on Friction Factor

Temperature values used are extracted from the graph presented in Hasan and Kabir (2002). Based on the graph it is observed that friction factor increases as temperature increases.

This phenomenon can be explained by looking at the viscosity of the two-phase flow and the quality of the steam at that particular temperature. Based on the previous graph on the relationship of temperature and steam quality, it can be said that the steam quality decreases as the temperature increases.

The viscosity of water is primarily determined by the temperature and the components dissolved in water. The viscosity of liquid phase decreases as the temperature increases. Unlike liquid phase, the viscosity of gas phase increases as the temperature increases. However, if we take into account that, together with the temperature, the proportion of vapor in the gas phase also increases, it becomes clear that, for thermodynamic states in the vicinity of the saturation vapor pressure curve, the viscosity is reduced again. According to the graph computed by Pruess 1987 based on a formula by Hirschfelder et al 1954, the viscosity of two-phase air-water vapor system increases as the temperature increases. (Helmig, 1997)

4.6.3 Effect of quality on friction factor

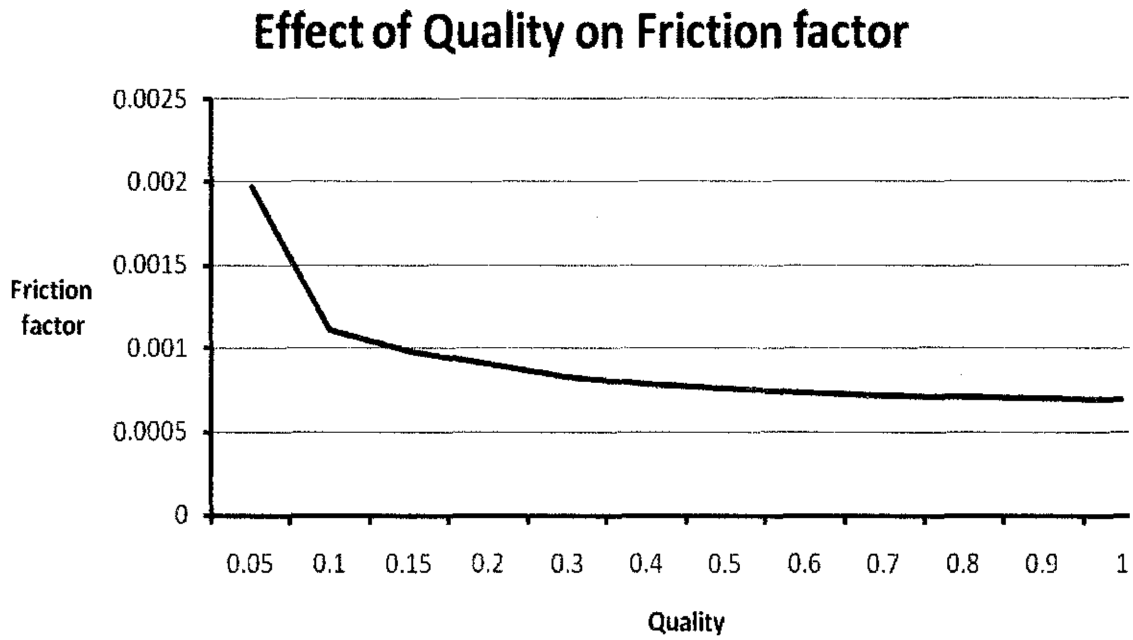


Figure 4.5 Effect of Steam Quality on Friction Factor

According to the graph plotted, the friction factor decreases as the steam quality increases. The flow pattern observed was bubbly flow for all value of quality. This is due to the change in velocity in the pipe since steam with high quality has high velocity hence increasing the mixture velocity and decreasing the void fraction. Since void fraction is the function of friction factor, the decreament of void fraction decreases the friction factor.

4.6.4 Effect of pipe roughness on friction factor

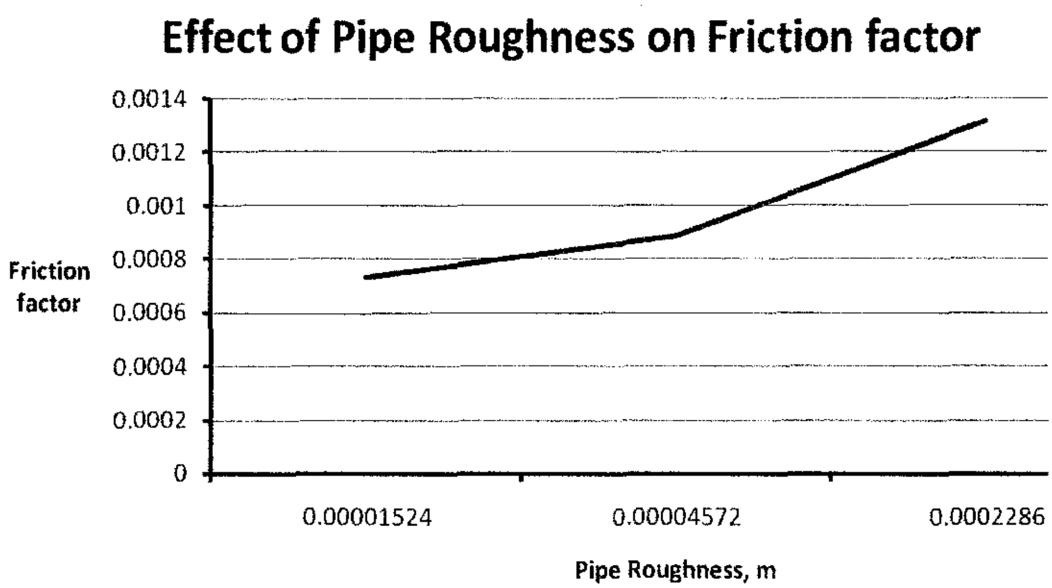


Figure 4.6 Effect of Pipe Roughness on Friction Factor

Wall roughness slightly affects wall friction, but not hold-up. The effect is noticeable when the pipe is very rough. Though with a roughness comparable to that of oil well tubing the effect is very small, it nevertheless has been incorporated in the friction correlation.

The data for pipe roughness were obtained from Energy Resource Board, Calgary (1975). Three different values of pipe roughness represent three different condition of a pipe. Value of 0.00005 ft for new tubing, 0.00015 ft for common value used in application, and 0.00075 ft for "very dirty" pipes.

Based on the graph, it can be said that friction factor increases as pipe roughness increases. This can be explained because roughness is a factor of Reynolds number and Reynolds number is a function of friction factor.

4.6.5 Effect of well inclination on friction factor

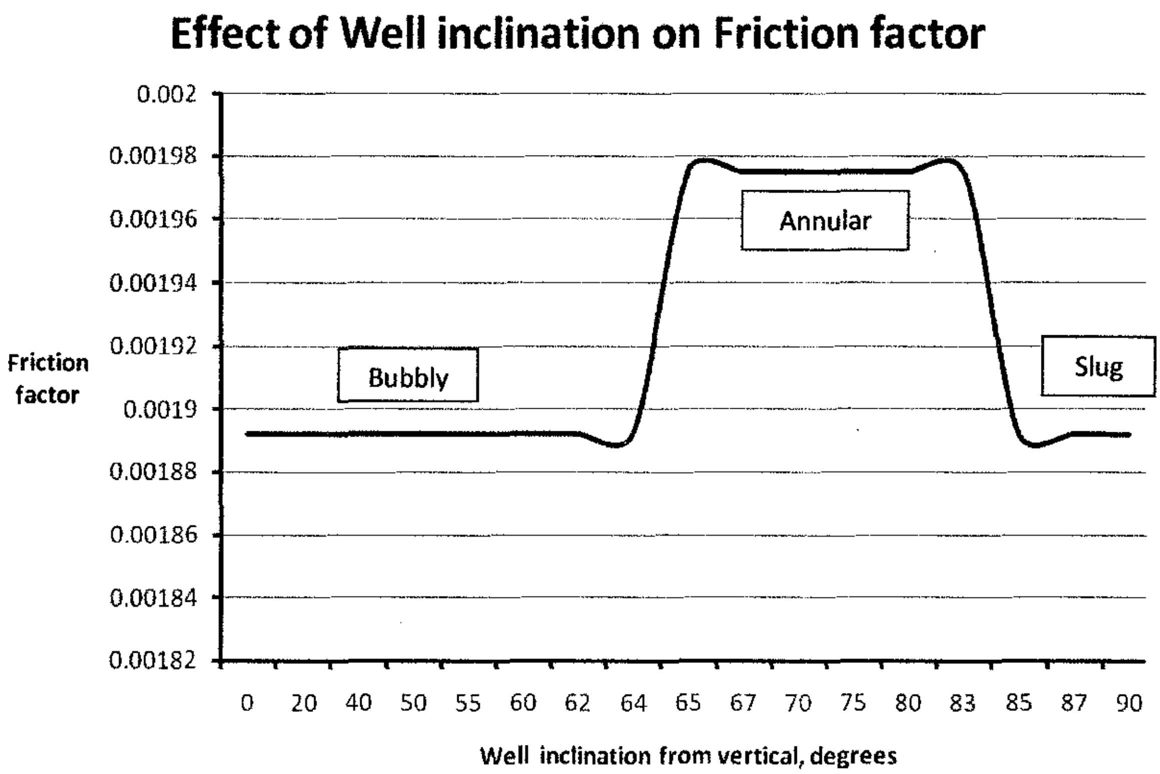
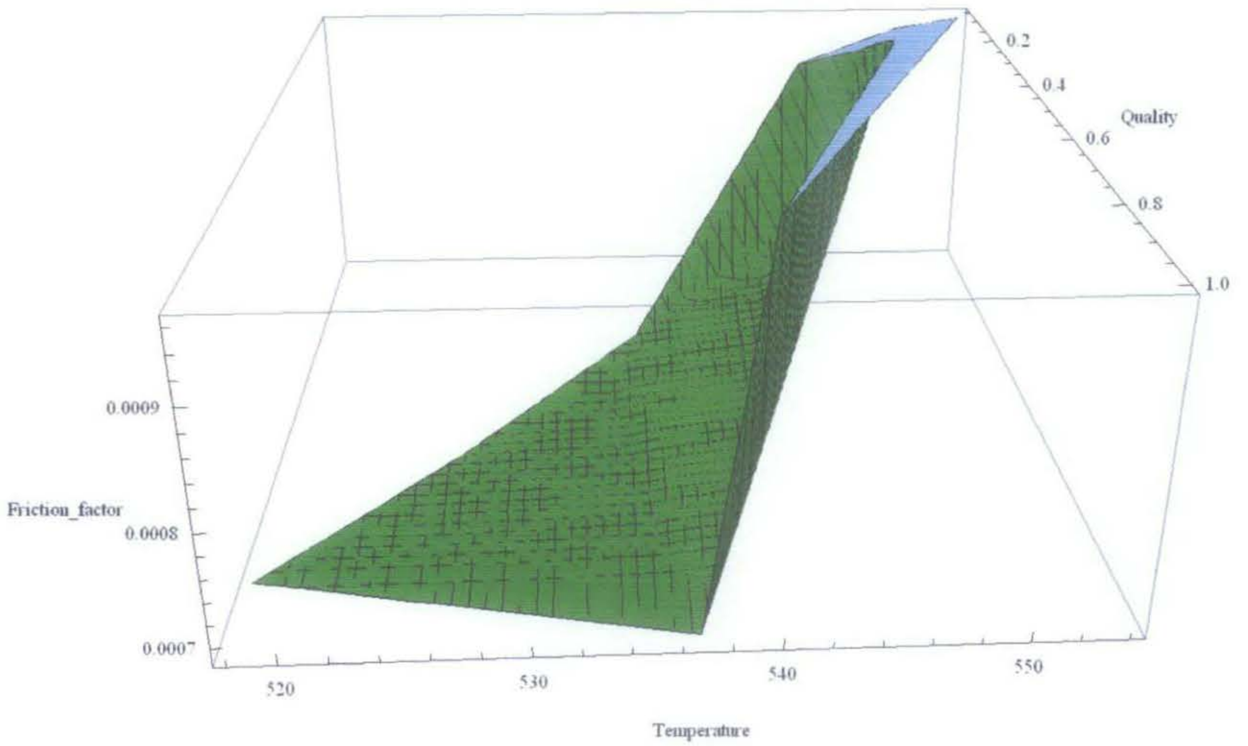


Figure 4.7 Effect of Well Inclination on Friction Factor

The well inclination affects the flow pattern of the fluid in the wellbore. Based on the graph above, it is clearly observed that friction factor has a constant value from the inclination of 0 to above 65 degrees and the flow regime at those values the flow pattern is bubbly flow. In the inclination of 65 till 85 degrees, the friction factor seems to be the highest and the flow pattern is annular flow. The inclination above 85 till 90 degrees, the fiction factor return to a value approximately as recorded in the inclination of 0 till 65 and the flow pattern is slug flow.

According to Solomon Levy as mentioned above, bubbly flow friction factor can sometimes be neglected as it is low and same goes to slug flow as it can sometimes be neglected or sometimes be significant. Annular flow records the highest friction factor due to the flow of liquid around the wall of the pipe.

4.6.6 Relationship between Temperature, Quality and Friction factorFigure



4.8 Relationships between Temperature, Quality and Friction Factor

Based on the 3D graph above generated by Mathematica, it can be seen that there is flat pattern in the range of temperature of 520 till 535 degrees Kelvin. In this region the quality decreases and the friction factor remains constant.

After the region of 535 onwards, the friction factor increases with respect to decrease in quality. This shows the increase in temperature decreases the quality and increases the friction factor.

4.7 Sensitivity Analysis

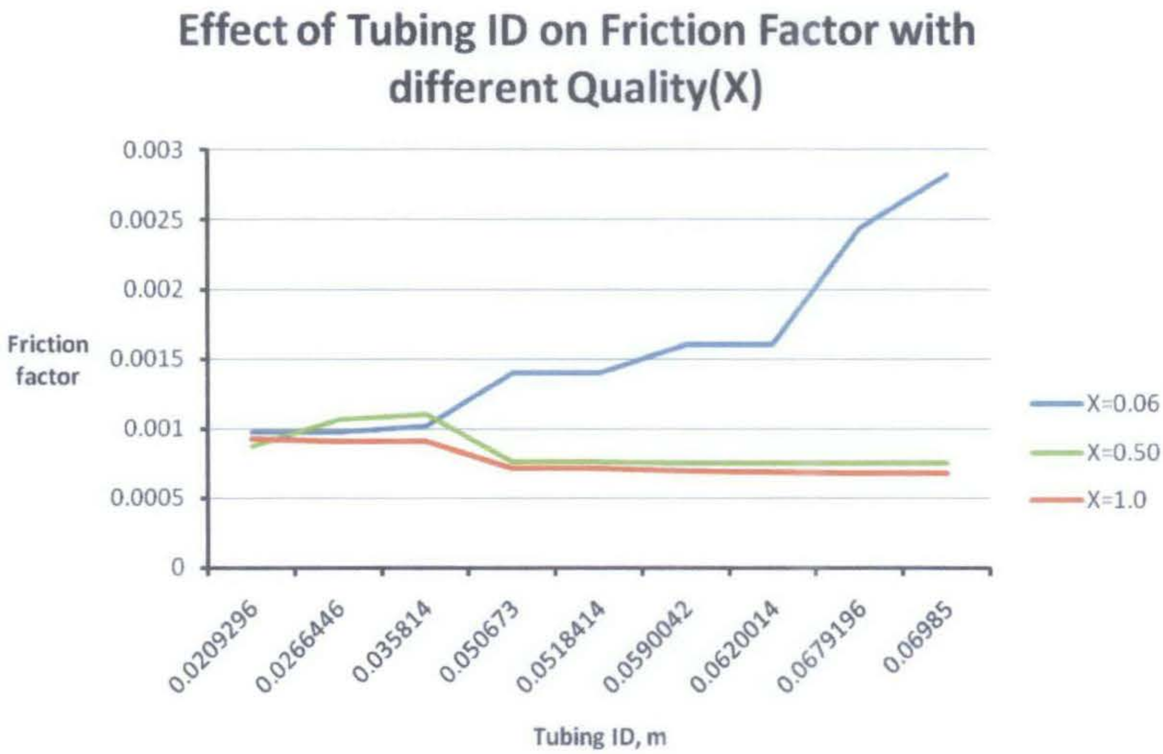


Figure 4.9 Effect of Tubing ID on Friction Factor with different Qualities

According to the graph above the friction factor decrerases as the tubing diameter increases except for the case when the quality of steam is 0.06 where the thrend is that the friction factor increases as the tubing diameter increases.

This phenomenon is because as it is shown in the previous graph, the wall friction reduces as the tubing diameter increases. So in the case of quality of 0.5 and 1.0, the friction do follow that pattern. In the graph of quality vs friction, it is shown that the increase in quality decrease the friction factor. So a steam with low quality will definetly create a large friction factor and the increment could be due to the velocity of liquid in the tubing since there will be less slip between the gas phase and the liquid phase.

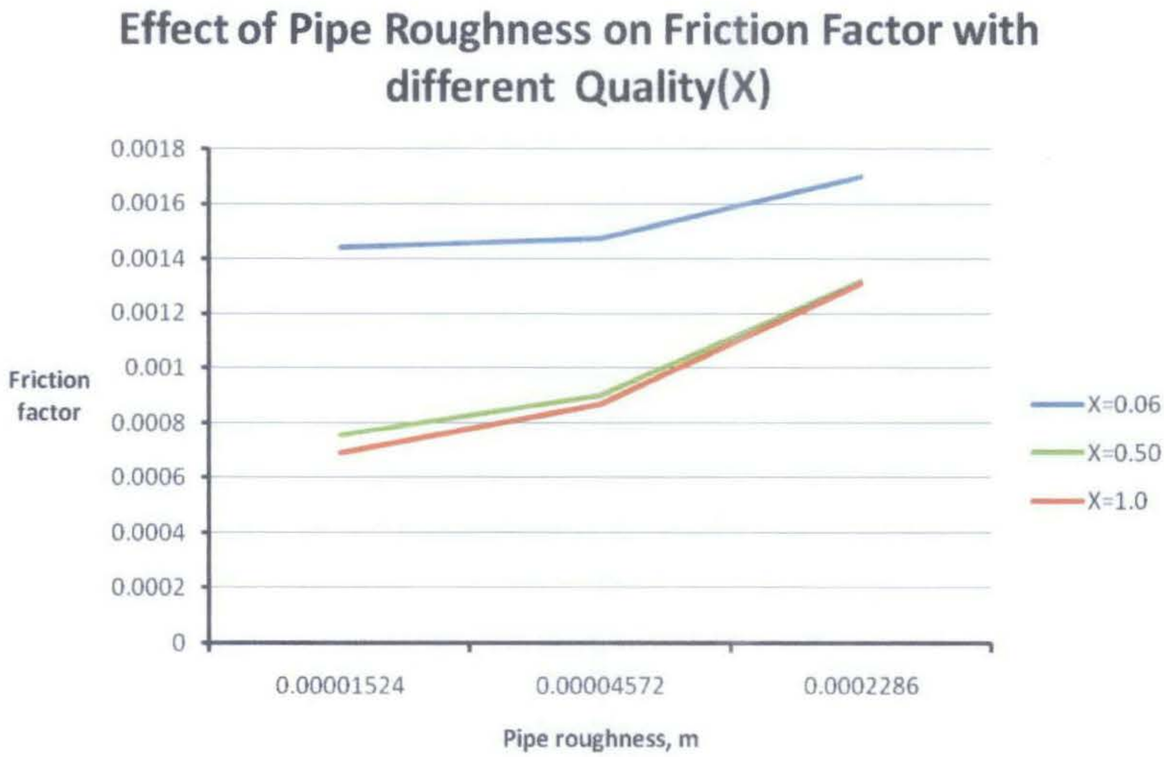


Figure 4.10 Effect of Pipe Roughness on Friction Factor with different Qualities

According to the graph above the friction factor increases as the pipe roughness increases. This phenomenon fits prefectly with the theory that friction factor increase as pipe roughness increases as explain in Figure 4.6.

In the graph of quality vs friction, it is shown that the increase in quality decrease the friction factor. So a steam with low quality will definetly create a large friction factor and the increment could be due to the velocity of liquid in the tubing since there will be less slip between the gas phase and the liquid phase.

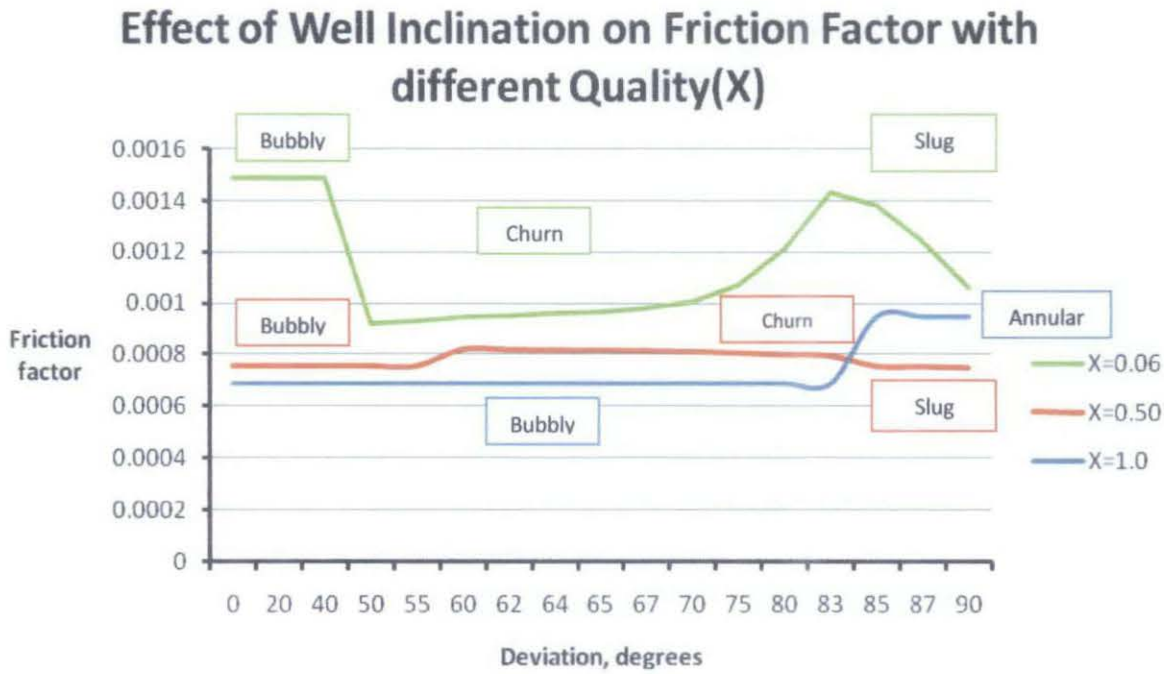


Figure 4.11 Effect of Well Inclination on Friction Factor with Different Qualities

According to the graph above the friction for the quality of 0.06 is the highest. Based on the flow pattern, annular flow records high friction factor. In the case of bubbly flow in 0.06 quality, the friction factor is high because the void fraction could be high as well.

This graph recommends that steam should be in saturated state since it gives the lowest friction factor and reducing pressure lose in the wellbore.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

As a result of the analysis of the study of two-phase flow friction factor in EOR injection wellbores, it can be concluded that:

The principal flow patterns have been identified which are bubbly flow, slug flow, churn flow and annular flow. These flow patterns are identified using the superficial velocity of gas. Individual pattern transition criteria are also identified based on Hasan and Kabir model.

Hasan and Kabir mechanistic model was chosen to be used due to the usage of drift flux model in the calculation. This model takes into account the slip velocity which considers the two phases are flowing in different velocity. This model also has been identified as the most accurate.

Friction factor is calculated using Chen's correlation of Moody friction factor. Moody friction factor is based on pipe roughness and Reynolds number and in the case of two-phase flow, the Reynolds number would be mixture Reynolds number. The calculation of the mixture density, viscosity and surface tension is done with temperature being the independent factor of the equation.

Well configurations and fluid PVT data plays a major effect in determining friction factor in EOR injection wellbores. The major contributor for friction factor would be the quality and temperature of steam.

Friction factor is the lowest in large tubing diameter, low temperature, low pipe roughness, high steam quality, and in bubbly or slug flow regime.

5.2 Recommendations

There are still further study can be done on this subject. The relationship between flow pattern and friction factor is still not very clear and more in depth research can be done to analysis the effect flow pattern on friction factor.

After all the analysis of results, it can be said that the effect of well inclination on friction factor do show an interesting trend. Further research can be done on this matter on finding the relationship between well inclination and friction factor. It is since that well inclination effect the flow pattern in the wellbore. So with different flow pattern there will be different friction factor. With the knowledge of estimating friction factor with different well inclination and flow patterns, it will surely help in reducing friction factor in the industry application and hence reducing pressure loss.

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APPENDIX A

Below are shown the codes used for the computational program that was developed using Wolfram Mathematica software.

Input data in Mathematica

```
T=536.772;              (*temperature of steam*)
ID=0.0620014;           (*tubing inner diameter*)
θ=0.0Degree ;           (*inclination from vertical*)
ϵ=0.00001524 ;          (*roughness*)
g=9.81;                 (*acceleration due to gravity*)
di=0.073025;            (*diameter of inner tube tubing OD*)
do=0.1521206 ;          (*diameter of outer tube casing ID*)
X = 1.0 ;               (*steam quality*)
qms =0.167753578 ;      (*mass flow rate*)
```

Calculation of common parameters by Mathematica

```
Aw = Abs[3.14159 (ID/2)^2]
(*Area of wellbore*)

ρl=Abs[3786.31-37.248T+0.196246T^2-5.04708×10^-4 T^3+6.29368×10^-7 T^4-3.08480×10^-10 T^5]
(*density of liquid*)

ρg=Abs[-93.7072+0.833941T-0.00320809T^2+6.57652×10^-6 T^3-6.93747×10^-9 T^4+2.97203×10^-12 T^5]
(*density of gas*)

μl=Abs[-0.0123274+27.1038/T-23527.5/T^2+(1.01425×10^7)/T^3-(2.17342×10^9)/T^4+(1.86935×10^11)/T^5]
(*viscosity of liquid*)

μg=Abs[-5.46807×10^-4+6.89490×10^-6 T-3.39999×10^-8 T^2+8.29842×10^-11 T^3-9.97060×10^-14 T^4+4.71914×10^-17 T^5]
(*viscosity of gas*)
```

μm=Abs[μg X+μl (1-X)]
(*mixture viscosity*)

q_g =Abs[q_{ms} X / ρg]
(*volumetric flow rate of gas*)
q_l = Abs[((q_g ρg)/(ρl X))-((q_g ρg)/ρl)]
(*volumetric flow rate of liquid*)

V_{sg} = Abs[q_g / A_w]
(*superficial velocity of gas*)

V_{sl} = Abs[q_l / A_w]
(*superficial velocity of liquid*)

V_m= Abs[V_{sl} + V_{sg}]
(*mixture velocity*)

σ=Abs[0.2358(1.0-T/647.096) 1.256 (1.0-0.625(1-T/647.096))]
(*surface tension*)

$F_{\theta = Abs[(\sqrt{Cos[\theta]})*((1+Sin[\theta])^{(1.2)})]}$
(*deviation factor*)

F_a=Abs[(1+(0.29d_i)/d_o)]
(*annulus factor*)

V_∞ =Abs[1.53(g(Subscript[ρ, l]-Subscript[ρ, g])σ /
Subscript[ρ, l]^2)$^{(1/4)}$]
(*terminal velocity*)

$V_{\infty b}$=Abs[1.53(g(Subscript[ρ, l]-Subscript[ρ,
g])σ/Subscript[ρ, l]^2)$^{(1/4)}$]
(*terminal bubble velocity*)

$V_{\infty Ta}$=Abs[0.35$\sqrt{g\ ID\ (\rho_l - \rho_g)/\rho_l}$ $(F_{\theta)(Fa}$)]
(*terminal taylor bubble velocity*)

V_{gb}=Abs[0.429V_{sl}+0.357$V_{\infty\ Sin[\theta]\ ]}$
(*bubble transition velocity*)

$\overline{V_\infty}_{=Abs[V\infty b}$(1-Exp[-0.1$V_{gb}$/($V_{sg}$-$V_{gb}$)])+$V_{\infty Ta}$(Exp[(-0.1$V_{gb}$/($V_{sg}$-
V_{gb}))]))]
(*average terminal velocity*)

f = Abs[0.32 (ID Subscript[V, m] Subscript[ρ, l] / Subscript[μ, l])$^{-0.25}$]
(*friction factor*)

V_{gc}=Abs[3.1(g σ (Subscript[ρ, l]-Subscript[ρ, g])/Subscript[ρ, g]^2)$^{(1/4)}$]
(*churn transition velocity*)
F_t=Abs[V_{sg}/(1.2 V_m- $V_{\infty Ta}$)]
(*taylor bubble gas void fraction*)

Testing for Flow Pattern using Rule based programming in Mathematica

Which [$V_{\infty Ta}$>V_{∞}&& Vgb< 0.088, F_g=V_{sg}/(1.2 V_m-$V_{\infty b}$),

$V_{\infty Ta}$<V_{∞}&&Vgb>0.088&&V_{sg}> 0.04, F_g= (1-(0.1((1.2 V_m - V_{∞})/Vsg)))F_t+ 0.1 ,

$V_{\infty Ta}$<V_{∞}&&Vgb>0.088&&V_{sg}< 0.04, F_g= (1-(0.25(1.2 V_m - V_{∞})))Ft + 0.25 V_{sg} ,

Abs[0.725+4.15$\sqrt{\frac{V_{sg}}{V_m}}$]>Abs[2Subscript[V, m]$^{1.2}$ (f/(2ID))$^{0.4}$ (Subscript[ρ, l]/σ)$^{0.6}$ $\sqrt{\frac{0.4\,\sigma}{g\,(\rho_l - \rho_g)}}$]&&$V_{sg}>1.08V_{sl}$, F_g= V_{sg}/(1.12 V_m- $\overline{V_{\infty}}$) ,

V_{sg}> V_{gc}, F_g=V_{sg}/(1.0 V_m)]

Which [$V_{\infty Ta}$>V_{∞}&& Vgb< 0.088,  ,

$V_{\infty Ta}<V_{\infty\&\&Vgb}>0.088\&\&V_{sg}>0.04$, ,

$V_{\infty Ta}<V_{\infty\&\&Vgb}>0.088\&\&V_{sg}<0.04$, ,

Abs[0.725+4.15 $\sqrt{\frac{V_{sg}}{V_m}}$]>Abs[2Subscript[V, m]$^{1.2}$ (f/(2 ID))$^{0.4}$

(Subscript[ρ, l]/σ)$^{0.6}$ $\sqrt{\frac{0.4\,\sigma}{g\,(\rho_l-\rho_g)}}$]&&V_{sg}>1.08V_{sl}, ,

$V_{sg}>V_{gc}$,]

Which [$V_{\infty Ta}>V_{\infty\&\&\,Vgb}<0.088$, Print [Bubbly],

$V_{\infty Ta}<V_{\infty\&\&Vgb}>0.088\&\&V_{sg}>0.04$, Print [Slug],

$V_{\infty Ta}<V_{\infty\&\&Vgb}>0.088\&\&V_{sg}<0.04$, Print [Slug],

Abs[0.725+4.15 $\sqrt{\frac{V_{sg}}{V_m}}$]>Abs[2Subscript[V, m]$^{1.2}$ (f/(2 ID))$^{0.4}$

(Subscript[ρ, l]/σ)$^{0.6}$ $\sqrt{\frac{0.4\,\sigma}{g\,(\rho_l-\rho_g)}}$]&&V_{sg}>1.08V_{sl}, Print [Churn],

V_{sg}> V_{gc}, Print [Annular]]

Calculation of Friction Factor using Mathematica

```
ρm=Abs[ρg Fg + ρl  (1- Fg)]
(*mixture density*)

Rem =Abs[ ID Vm ρm / μm]
(*mixture Reynolds Number*)

A= Abs[(ϵ/ID)^1.1098/2.8257+ (7.149/Rem)^0.8981]

fm=Abs[ 1/(4 Log [ ((ϵ/ID)/3.7065)- (5.0452/Rem)Log[A]])^2]
(*moody friction factor*)
```