PREDICTION OF PRESSURE DROP

OF SLUG FLOW IN VERTICAL PIPES USING MECHANISTIC MODEL

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MOHAMAD FAKHROL RADZI B.ZULKELI

Thesis submitted in partial fulfilment of the requirements

for the award of the degree of

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SUPERVISOR'S DECLARATION

We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Bachelor of Chemical Engineering (Gas Technology).

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I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

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To all my friends and course mates, thank you for believing in me and helping me in completing this project. The experiences and knowledge I'm gained throughout the process of completing this Under Graduated Research Project would prove invaluable to better equip us for the challenges which lie ahead. In particular, our sincere thankful is also extends to all our lecturers and other parties who have provided assistance directly or indirectly. Their views and opinions are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. Last but definitely not least, to my family members, I'm can never thank you enough for their love and supports.

ABSTRACT

Due to the variability of flow pattern of gas liquid two-phase flow and complexity of flow mechanism,it is very difficult to seek a single model which is able to predict pressure drop and fit for any flow condition. when the existing model of two-phase flow pressure drop is used to predict the pressure of the conditions of producing gas well,a large error occurs.Therefore, it is necessary,based on the experimental data of gas-water two phase flow,to research the flow mechanism and discover the regular existing in the process of fluid property changing .On the basis of the current two-phase flow pressure drop model, it is important to explore modified pressure loss model applicable for producing gas well with water,to improve predictability of the pressure drop of gas wells,and to provide the theory and technology guidence for development of gas reservoir with water.

Underbalanced drilling (UBD) has increased in recent years because of the many advantages associated with it. These include increase in the rate of penetration and reduction of lost circulation and formation damage. Drilling of deviated and horizontal wells also increased since recovery can be improved from a horizontal or a deviated well. The drilling of deviated wells using UBD method will reduce several drilling related problems such as hole cleaning and formation damage. Prediction of flow and pressure profiles while drilling underbalanced in such wells will help in designing and planning of the well. The aim of this research is to predict the pressure drop of slug flow in the certain pressure in vertical pipes using mechanistic model and to study the behavior of the flow profile in the drillstring and the annulus under UBD conditions through the use of mechanistic two phase flow models.

Mechanistic two phase flow models is been used In this research to predict the liquid hold up for phase gas- liquid slug flow which is important for the accurate calculations of the pressure drop.In particular, its evaluation is important for the vertical pipes since the liquid hold up in the slug body is the main contributor to the hydrostatic pressure drop which quite significant for the verticals flows. Further development of mechanistic models has allowed accurate prediction of wellbore pressure. Many Underbalanced Drilling operations require the use of nitrified diesel as the drilling fluid.Thus two phase flow will exist both in the drill pipe and the annulus.

ABSTRAK

Oleh kerana kepelbagaian dalam corak aliran gas-cecair aliran dua fasa dan kerumitan mekanisme aliran, ia adalah amat sukar untuk mendapatkan model tunggal yang mampu meramalkan kejatuhan tekanan dan sesuai untuk sebarang keadaan aliran. apabila model yang sedia ada dua fasa kejatuhan tekanan aliran digunakan untuk meramalkan tekanan dengan syarat-syarat dan keadaan untuk mengeluarkan gas dengan baik, kesilapan yang besar berlaku. Oleh itu, adalah perlu berdasarkan data eksperimen gas-cecair aliran dua fasa, dengan penyelidikan mekanisme aliran dan penemuan yang sedia ada dalam proses perubahan sifat bendalir. Berdasarkan dua fasa mod kejatuhan tekanan aliran semasa, ia adalah penting untuk pengubahsuaian model kehilangan tekanan yang diguna pakai untuk telaga gas yang mengandungi air, untuk meningkatkan ketepatan ramalan penurunan tekanan telaga gas, dan untuk menyediakan teori dan teknologi untuk pembangunan takungan telaga gas yang mengandungi air.

Penggerudian Underbalanced (UBD) telah meningkat sejak kebelakangan ini kerana banyak kelebihan yang berkaitan. Ini termasuk peningkatan dalam kadar penembusan dan pengurangan kehilangan edaran dan kerosakan formasi. Penggerudian telaga terpesong dan mendatar juga meningkat kerana proses pemulihan juga boleh diperbaiki dari melintang atau menyimpang. Penggerudian telaga lencongan menggunakan kaedah UBD akan mengurangkan beberapa masalah penggerudian yang berkaitan seperti pembersihan lubang dan kerosakan formasi. Ramalan aliran dan tekanan profil semasa penggerudian underbalanced dalam telaga seumpama itu akan membantu dalam mereka bentuk dan perancangan telaga. Tujuan kajian ini adalah untuk meramalkan kejatuhan tekanan aliran lumpur dalam tekanan tertentu di dalam paip yang menegak menggunakan model mekanistik dan untuk mengkaji kelakuan profil aliran di drillstring dan anulus dalam keadaan UBD melalui penggunaan mekanistik aliran dua fasa model.

Mekanistik dua model aliran fasa telah digunakan dalam kajian ini untuk meramalkan cecair tahan untuk fasa gas-cecair di dalam aliran lumpur yang penting untuk pengiraan penurunan tekanan yang tepat. Secara khususnya, penilaian ini adalah penting bagi paip yang menegak kerana cecair tahan di dalam aliran lumpur adalah penyumbang utama kepada kejatuhan tekanan hidrostatik yang agak ketara untuk aliran menegak. Pembangunan model mekanistik telah membenarkan ramalan yang tepat tekanan lubang telaga. Banyak operasi Penggerudian Underbalanced memerlukan penggunaan diesel nitrified sebagai cecair penggerudian. maka dua aliran fasa akan wujud kedua-dua di dalam paip gerudi dan anulus.

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$\left(\frac{dP}{dL}\right)_{acc}$ Acceleration pressure gradient, (psi/ft)

$\left(\frac{dP}{dL}\right)_{el}$ Elevation pressure gradient, (psi/ft)

$\left(\frac{dP}{dL}\right)_{f}$ Frictional pressure gradient, (psi/ft)

$\left(\frac{dP}{dL}\right)_{total}$ Total pressure gradient, (psi/ft)

A_L Liquid area in pipe element (m2,in2)

A_n Bit nozzle area (m2,in2)

A_p Pipe element area, (m2,in2)

C_1 Velocity profile coefficient for slug flow

C_0 Velocity profile coefficient for bubbly flow

D_e De Equivalent pipe diameter, (m/in)

D_{ep} Equi-periphery diameter, (m/in)

D_h Hydraulic diameter, (m/in)

E_a Absolute average relative error

f_F Fanning friction factor

f_i Interfacial shear friction factor for annular flow

f_M Mixture friction factor

$f_p, F_{CA},$ Geometry parameters in calculating fanning friction factor for bubbly flow

f_{SC} Superficial core friction factor

H_L Liquid holdup

H_L^n Liquid holdup with swarm effect

$H_{L_{LS}}$ Liquid Holdup in liquid slug zone

$H_{L_{SU}}$ Liquid Holdup in a slug unit

$H_{L_{TB}}$	Liquid Holdup in Taylor bubble in a slug flow
ID	Inner diameter (m,in)
$L_{L_{LS}}$	Liquid length in liquid slug zone
$L_{L_{TB}}$	Length of slug unit
$L_{L_{TB}}$	Slug length in Taylor bubble in a slug
Mg	Gas molecular weight
N_{Re}	Reynolds Number
$N_{Re,M}$	Mixture Reynolds number
$N_{Re,SG}$	Superficial gas Reynolds number
$N_{Re,SL}$	Superficial liquid Reynolds number
OD	Outer diameter (m,in)
P_{bh}	Bottom hole pressure (Pa,psi)
P_{calc}	Calculated Pressure (Pa,psi)
P_{meas}	Measured Pressure (Pa,psi)
P_{up}	Upstream pessure (Pa,psi)
q_G	Gas flow rate (scf/m)
q_L	Liquid flow rate, (m3/s, gpm)
R	Universal Gas constant = 10.731 psia.ft3/lbm.mol.°R
T	Temperature (°K,°R)
w_g	Gas weighing factor
Z	Gas compressibility factor
β	Relative bubble length parameter in a slug flow
δ	Liquid film thickness in flow model(m,ft)
λ_L	No slip liquid holdup
μ_G	Gas viscosity, (Pa.s, cp)
μ_L	Liquid viscosity, (Pa.s, cp)

μ_M Mixture viscosity, (Pa.s, cp)

θ Inclination angle from horizontal

ρ_G Gas density, (kg/m3,ppg)

ρ_L Liquid density (kg/m3,ppg)

ρ_M Mixture density, (kg/m3,ppg)

ρ_{ML} Mixture density in liquid slug, (kg/m3,ppg)

ρ_{MTB} Mixture density in Taylor bubble in a slug, (kg/m3,ppg)

v_B Discrete gas bubble rise velocity, (m/s,ft/s)

v_G Gas velocity, (m/s,ft/s)

v_L Liquid velocity, (m/s,ft/s)

$v_{L_{LS}}$ Liquid velocity in liquid slug zone, (m/s,ft/s)

$v_{L_{TB}}$ Taylor bubble velocity in a slug, (m/s,ft/s)

v_n Nozzle velocity, (m/s,ft/s)

v_{SG} Superficial gas velocity (m/s,ft/s)

v_{SL} Superficial liquid velocity (m/s,ft/s)

v_{TB} Taylor bubble rise velocity, (m/s,ft/s)

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To all my friends especially my best friend and all my course mates, thank you for believing in me and helping me to go through the difficult time. The experiences and knowledge I gained throughout the process of completing this final project would prove invaluable to better equip me for the challenges which lie ahead. Last but definitely not least to my family members, I can never thank you enough for your love, and for supporting me throughout my studies in University Malaysia Pahang.

Chapter 1

Introduction

The Simultaneous flow of oil, gas and water in vertical pipe is encountered in many engineering installations.In petroleum,chemical process,nuclear engineering and many other chemical industries especially in tubing systems,heat exchange equipments and chemical reactor. The problems associated with simultaneous flow of two or more phases through vertical pipe have been of concern for a long time, (Olufemi et al.,2008).

Over the years,accurate prediction of pressure drop has been of vital importances in vertical multiphase flowing oil wells in order to design an effective production string and optimum production strategy selection.various scienctist and reseracher heve proposed correlations and mechanistic models for this purpose since 1950, most of which widely used in the industry.But even with recent improvements in pressure prediction techniques,most of the models fail to provide the desired accuracy of pressure drop,and further improvement is still needed.

Multiphase flow characteristics such as liquid hold up, mixture density, and flow patterns are predict by using Mechanistic models,where the modelling are know as semi-empirical models.These mechanistic models were generated based on sound theoritical approach,to outperform the existing empirical correlations.The most of these mechanistic models are those of (Ansari et al.,1994)

Slug flow is one of the basic flow patterns that characterize the gas–liquid flow in vertical pipes. It occurs over a wide range of gas and liquid flow rates. The most important characteristic of slug flow is its intermittent nature, which is due to a unique phase distribution. In view of the above phase distribution, the pressure and liquid holdup vary periodically at any given pipe cross-section. In vertical flow, the liquid hold up in the slug for prediction and accurate calculation of the pressure drop, the prediction of the liquid hold body is the main factor which contributes to the pressure drop in the piping system.

1.2 Underbalanced Drilling

Underbalanced Drilling (UBD) is the drilling process in which the circulating fluid bottomhole pressure is maintained below the formation flowing pressure. UBD can be achieved by injecting lightened drilling fluid such as gas, mist, foam, and diesel, which will create such low pressure in order not to overcome the formation pressure Many benefits are gained from using UBD operations, such as:

• Increase rate of penetration and bit life

• Minimization or elimination of differential sticking

• Minimization of lost circulation

• Reduced formation damage

• Increased well productivity

In addition, UBD operations have increased in recent years due to the following:

• Depleted reservoirs

• Awareness of skin damage

• Elimination of lost circulation

• Cost of differential sticking

• Environmental benefits

UBD techniques can be categorized into two major categories based on the fluid used, which are:

• Gaseous drilling fluid

• Gasified liquid and liquid drilling fluids

During UBD operations, a complex fluid system occurs both inside the drillstring and the annulus. Two phase flow prediction techniques are used to predict several parameters such as pressure drops (both inside the drillstring and through the annulus), flow patterns, velocities, liquid holdup, and other parameters. In order to achieve this, mechanistic two phase flow models are used.

1.3 Research Objective

The objective of this research are :

- To predict the pressure drop of slug flow vertical pipes using mechanistic model.
- To predict the behavior of the flow in the certain pressure in the vertical pipes.

1.4 Research scope

The research scope that will comply to achieve the research objectives are divided into two stages :

- Study of mechanistic steady state model using Excel Visual Basic Application (VBA) and FORTRAN 95 computer program.
- To study and predict the pressure drop in vertical pipes and the behaviour of the flow.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In recent years, mechanistic models were developed based on phenomenological approach which mass and energy conservation is been takes account. The early mechanistic model for the vertical flows, Fernandes et al.(1983) developed the semi mechanistic model to predict the liquid hold up in the slug flow body. Sylvester et. al. (1987) modified semi mechanistic for slug flow model by Fernandes, where the new correlation for the liquid holdup is been introduced.

Hasan and Kabir et al.(1992) developed a model for predicting the two phase flow in annuli upward simultaneous two phase flow In UBD operations, pressure along the wellbore length is affected by the gas and liquid injection flow rate, the flow pattern distribution and the back pressure at the wellhead. With the larger well depth, temperature and pressure in annulus increases constantly which results in the varying gas and liquid superficial velocity and gas void fraction which determines flow pattern distribution and pressure.

Ansari et al.(1994) presented the model for upward vertical two phase flow in pipes. Ansari's model improved prediction accuracy of slug flow by considering two possible conditions of slug flow, the fully developed Taylor bubble slug flow and the developing Taylor bubble slug flow.

Bijleveld et al.(1996) developed the first steady state computer program by using the mechanisitic approach,by using trial and errors to calculate the bottom hole pressure and two phase flow parameters. pattern of flow is being assumed, for the purposed of get an accurately prediction of the differences in flow parameters such as rise velocity of gas bubbles in liquid columns, flow pattern and liquid holdup.

Gomez et al.(1999) developed a comprehensive mechanistic model for predicting the flow parameters in deviated wells. Lage et al.(2000) developed a mechanistic model for predicting upward two phase flow in concentric annulus.

2.2 Multiphase Flow Concept

Multiphase flow is a generalisation modelling used in two phase flow where the two phase are not chemically related or where two or more phase are present. The most distinguished aspect of such flow during the simultaneous flow of gas and liquid, is the inconsistency of the distribution of both phases in the vertical pipes.the term flow pattern is used to distinguish such distribution,which depends on the relative magnitude of forces acting on the fluids, Brown et al. (1986).The following terms are defined in order to assist in the multiphase flow calculations.

2.2.1 Liquid Holdup

Liquid holdup (HL) is defined as the fraction of a pipe cross-section or volume that is occupied by the liquid phase,Beggs et al. (1991).The value of H_L ranges from 0(total gas) to 1(total liquid).The prediction of liquid Holdup in the slug flow body for two phase gas-liquid slug flow is important for the accurate calculations of the pressure drop.The liquid holdup is defined by

$$H_L = A_L/A_P \qquad 2.1$$

A_L = pipe area of the liquid occupied by the liquid phase

A_P = Pipe cross-sectional area

The term void fraction or gas holdup is defined as the volume fraction occupied by the gas where

$$\alpha = 1 - H_L \qquad 2.2$$

α = gas void fraction

When two fluids travel at different velocities then the flow is referred to as a slip flow. No slip flow occurs when the fluids travels at the same velocity, Hence the term no slip liquid holdup can be defined as the ratio of the volume of liquid in a pipe element that would exist if the gas and liquid traveled at the same velocity divided by the volume of the pipe element,Beggs et al.(1991).

The no-slip liquid Holdup, λ_L is defined as follows:

$$\lambda_L = \frac{q_L}{q_{L+}q_G} \qquad 2.3$$

λ_L = No slip liquid holdup

q_L = Liquid flow rate

q_G = Gas flow rate

2.2.2 Superficial Velocity

Superficial velocity is the velocity that a phase would travel at if it flowed through the total cross sectional area available for flow Beggs et al.(1991) Thus, the liquid and gas superficial velocities are defined by :

$$V_{SL} = Q_L / A_p \qquad 2.4$$

V_{SL} = Superficial liquid velocity (m/s,ft/s)

A_p = Pipe element area, (m2,in2)

and

$$V_{sg} = Q_G / A_P \qquad 2.5$$

V_{sg} = Superficial gas velocity (m/s,ft/s)

The mixture velocity can be defined as the velocity of the two phases together, as follow :

$$V_M = (Q_L + Q_G) / A_P$$

$$= V_{SL} + V_{sg} \qquad 2.6$$

The in-situ velocity is the actual velocity of the phase when the two phases travel together. They can be defined as follows :

$$V_L = V_{SL} / H_L \tag{2.7}$$

and

$$V_G = V_{sg} / H_G = V_{sg} / (1- H_L) \tag{2.8}$$

Weighting factor is introduced when water is exist because of the addition to the liquid and gas,this factor is being used to take care of the slippage that could occur between different liquid phases that exists during drilling(drilling fluid, produced oil and produced water). This factor is defined as follows:

$$f_o = q_{DF} / q_{DF} + q_o + q_w \tag{2.9}$$

where

q_{DF} = is the drilling fluid flow rate,

q_o = inflow oil flow rate, and

q_w = is inflow water flowrate.

2.2.3 Two Phase flow pattern

Multiphase flow patterns highly depend on flow rates, pipes geometry, and the fluid properties of the phases. The physical distribution of the phase that varies in the flow medium creates several flow patterns. Furthermore, because of the various pressure and temperature in the pipes it also can contribute to the change of the flow pattern. The major flow pattern that exist in multiphase flow are dispersed bubble,bubble,slug,churn and annular as shown in Figure 2.1.

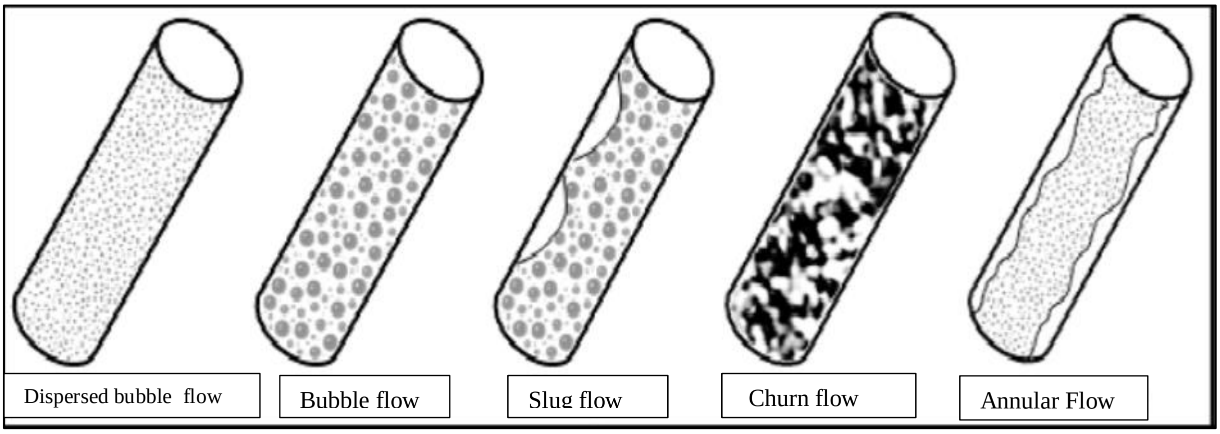


Figure 2.1 Different flow patterns in Two Phase flow

- **Dispersed bubble flow :** This flow is characterized by gas being distributed in small spherically shaped bubbles in continuous liquid phase.dispersed bubble occurs at low gas flow rates and high liquid rates.in dispersed bubble flow,both phases flow at nearly the same velocity.no slip is seen between the phases and the flow is essentially homogenous.

- **Bubble flow :** This flow characterized by a discontinuous gas phase which is distributed at discrete bubble inside a continuos liquid phase.The discrete gas bubbles tend to slightly deviate from spherical shape and exhibit slippage through the liquid phase due to buoyancy forces.This patern occurs at low to medium superficial velocites.

- **Slug flow :** This flow is characterized by a series of slug units.each unit is composed of Taylor Bubble and plugs of liquid called slugs. Charateristic bullet-shaped bubbles often contains a dispersion of smaller bubbles.A film of liquid exist around the pocket flowing downward relative to the gas bubble.The liquid slug carrying distributed small gas bubbles, bridges the conduit and separates two consecutive gas bubbles.

- **Churn flow :** This flow pattern exist in upward flow only.the shape of the Taylor bubble and the liquid slugs are irregular and random.churn flow can be considered to be a transition between bubbly flow and fully developed slug flow.its characteristics oscillations is an important pattern which covering fairly wide range of gas flow rate,it rgarded as a breaking uf of slug flow with occasional bridging across the tube by the liquid phase at the lower end of the range.While at the higher range of gas flow rates it may be considered a degenerate form of annular flow with the direction of the film flow.

- **Annular flow :** This flow of pattern is characterized by the axial continuity of gas phase in the liquid flowing upward, both as a thin film along the pipe wall and as dispersed droplets in the core. A small amount of liquid is entrained in the light velocity core region. Annular flow occurs at high gas superficial velocities with relatively little liquid present.

Transition boundaries between the various flow patterns can be plotted on a flow pattern map. According to Taitel et al studied, Figure 2.2 shows a typical flow pattern map for downward vertical two phase flow. Figure 2.3 shows the flow pattern map used in the annulus which was developed by Caetano et al.(1992) Both figures are made for certain flow geometries and fluid properties.

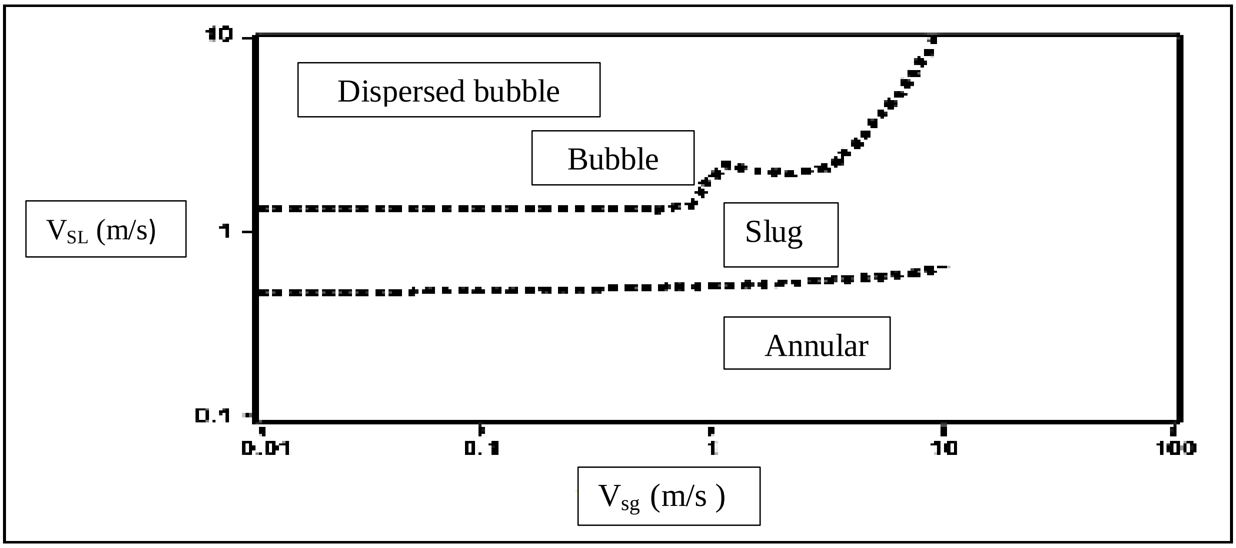


Figure 2.2: Flow pattern Map for Downward Two Phase Flow in Pipes

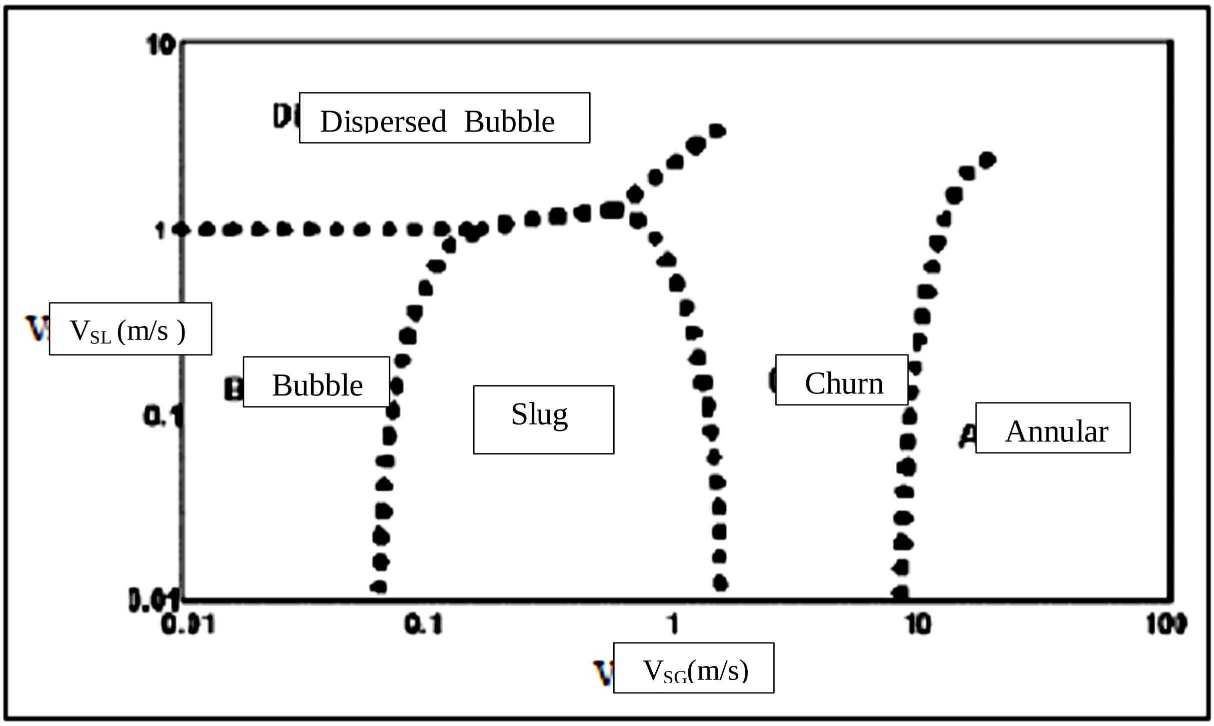


Figure 2.3 : Flow Pattern Map For Upward Two Phase Flow in Annulus

2.3 Flow Pattern Prediction Models

2.3.1 Downward Flow through the Drillstring

2.3.1.1 Bubble to Slug Transition

The transition from bubbly to slug flow occurs because of the bubble resulting from increased collision between bubbles at higher void fraction. In addition, Hasan stated that the same void fraction used for upward flow could be used for the case of downward flow. Hasan observed that this transition occurred at a void fraction of 0.25. Also, the rise velocity is unaffected by pipe inclination angle and in deviated wells, the bubbles 14 prefer to flow near the upper wall of the pipe, causing a higher local void fraction compared with the cross-sectional average value. Hasan and Kabir derived an equation for bubble to slug transition flow for upward flow in deviated wells. Hasan proposes the same equation for a downward flow using a negative terminal rise velocity. Hasan proposed the following expression for transition boundary between bubble and slug flow:

$$V_{SG} = 1 + \frac{C_o n V_{SL}\, x - V_\infty}{\left({}^{1}/_{\alpha}\right) - C_o} \sin\theta \qquad 2.10$$

Harmathy correlation is used to calculate the terminal rise velocity for upward flow in vertical channels as follows:

$$\underset{\infty}{V} = 1.53 \left[\frac{\left(\rho_{L-}\rho_G\right) g\sigma}{\rho_L^2}\right]^{0.252} \qquad 2.11$$

The velocity profile coefficient (*CO*) has been defined by Zuber and Findlay due to the effect of non-uniform flow and concentration distribution across the pipe and the effect of local relative velocity between the two phases. Table 2.1 shows the values for the velocity profile coefficientsfor different inclination angles as given by Alves

Table 2.1: Flow Coefficients for Different Inclination Angle Ranges (After Alves)

Inclination Angle (Degrees)	Co
10-50	1.05
50-60	1.15
60-90	1.25

In addition, Wallis Wallis, G.B. (1969). has proposed that the effect of single bubble rising in a swarm of bubblescan be introduced by defining a bubble swarm effect (n), thus H_L^n will be taken into consideration. Finally, Perez-Tellez et al proposed the use of the combined effect of the bubble swarm effect (n) and the velocity profile coefficient (*CO*) and introduced the following expression for the bubble slug transition.

$$V_{SL} - C_{\circ}V_m = \pi V_{\infty} H_L^n \qquad 2.12$$

Applying Equation 2.11 to Hasan approach in order to find the criteria from bubble to slug yields the following equation

$$V_{SL} = \frac{(1/\propto - C_o)V_{SG} / \sin\theta + V_{\infty} H_L^n}{C_o} \qquad 2.13$$

with a gas void fraction $\alpha = 0.25$.

2.3.1.2 Bubble or Slug to Dispersed Bubble Transition

The model which was created by Taitel et al where based on the maximum bubble diameter under highly turbulent conditions could be used to find the relationship between phase velocities, pipe diameters, and fluid properties which applicable for flow through vertical flow. The equation 2.14 which developed by Caetano as shown below was recomended by Perez-Tellez in order to calculate the homogenous fanning friction factor, and since the rise velocity for the dispersed bubble flow is very small compared to the local velocities, the no-slip holdup (λL) could be used to calculate f_F. Where ID is the inner pipe diameter.

$$V_M^{1.2}(2f_F^{0.4}/ID)^{0.4}\left[\frac{1.6\sigma}{(\rho - \rho)g}\right]^{0.5}(\rho_L/\sigma)^{0.6} = 0.725 + 4.1(V_{SG}/V_M)^{0.5} \qquad 2.14$$

2.3.2 Upward Flow through the Annuli

Taitel et al.(1980) proposed the method for predicting flow pattern, in addition to his model and coupling it with the bubble swarm effect and the velocity swarm coefficient. The flow patterns used were shown in Figure 2.3 where the transition boundaries will be calculated based on different flow geometry and properties.

2.3.2.1 Bubble to Slug Transition

During bubble flow, discrete bubbles rise with the occasional appearance of a Taylor bubble. The discrete bubble rise velocity was defined in Equation 2.11. The presence of an inner tube tends to make the Taylor bubble sharper, causing an increase in the Taylor bubble rise velocity. As a result, Equation 2.15 was developed where the outer tube diameter should be used with the diameter ratio (OD/ID) to get the following expression for the Taylor bubble rise velocity in inclined annulus.

$$V_{TB} = (0.345+0.1*(OD/ID))\sqrt{\sin\theta}\,(1+\cos\theta)^{1.2}\sqrt{gID\,\frac{\rho L-\rho G}{\rho L}} \qquad 2.15$$

where

OD : Outside pipe diameter

ID : Inner casing diameter

g : Gravity acceleration

ρL: Liquid density

ρG: Gas density

Hasan and Kabir stated that the presence of an inner tube does not appear to influence the bubble concentration profile (*CO*) and thus the following expression could be used :

$$V_{SL} =((4 - C_O)\, V_{SG})/\sin\theta\ ) - V_{\infty} \qquad 2.16$$

where

C_O = Velocity profile coefficient for bubbly flow

θ = Inclination angle from horizontal

V_{∞} = Discrete gas bubble rise velocity, (m/s,ft/s)

2.3.2.2 Bubble or Slug to dispersed bubble transition

The flow transition from bubble or slug to dispersed bubble been defined by Equation 2.14. The hydraulic diameter (Dh) is substituted for the pipe inside diameter (ID). The hydraulic diameter of the casing-tubing annulus is given by:

$$Dh = ID - OD \qquad 2.17$$

where

ID = internal casing diameter

OD = is the outside pipe diameter.

2.3.2.3 Dispersed bubble to slug flow transition

Taitel et al. determined that the maximum allowable gas void fraction under bubble flow condition is 0.52. Higher values will convert the flow to slug, hence the transition boundary could be equated as follows

$$V_{SL} = 0.923\, V_{SG} \qquad 2.18$$

2.3.2.4 Slug to churn transition

Tengesdal et al. has developed a transition from slug to churn flow in an annulus. They stated that the slug structure will be completely destroyed and churn flow will occur if the gas void fraction equals 0.78. Thus churn flow will occur. The transition from slug flow to churn flow can thus be represented by :

$$V_{SL} = 0.0684\, V_{SG} - 0.292\sqrt{gD_{ep}} \qquad 2.19$$

where Dep is the equi-periphery diameter defined as follow

$$Dep = ID + OD \qquad 2.20$$

where

ID = is the inner casing diameter

OD = is the outer pipe diameter.

2.3.2.5 Churn to annular transition

Based on the minimum gas velocity required to prevent the entrained liquid droplets from falling back into the gas stream that would originate churn flow, Taitel et al proposed the following Equation to predict the transition to annular flow.

$$V_{SG} = 3.1\left[\frac{(\rho_G - \rho_G)g\sigma}{\rho_G}\right]^{0.25} \qquad 2.21$$

2.4 Flow Behaviour Prediction Model

After determining the required flow pattern, which either exists in the drillstring or annulus, then the following behavior prediction models are applied in order to calculate the pressure gradient and phases fractions. The total pressure gradient is calculated as follows

$$\left(\frac{dP}{dL}\right)_{total} = \left(\frac{dP}{dL}\right)_{el} + \left(\frac{dP}{dL}\right)_{f} + \left(\frac{dP}{dL}\right)_{acc} \qquad 2.22$$

Where the following are the component of the total pressure gradient

$\left(\frac{dP}{dL}\right)_{el}$ = The elevation change component

$\left(\frac{dP}{dL}\right)_{f}$ = The friction component

$\left(\frac{dP}{dL}\right)_{acc}$ = The acceleration component

2.4.1 Downward Flow through the Drillstring

Bubble Flow Model for Drillstring

The drift flux approach is used to calculate liquid holdup considering the slippage between the phases and non-homogenous distribution of bubbles. Kaya et al.13 developed an expression for the slip velocity considering inclination and bubble swarm effect. Assuming turbulent velocity profile for the mixture with rising bubbles concentrated more at the center than along the pipe wall, the slip velocity using the drift flux approach can be expressed as follows:

$$v_s = \frac{v_{SG}}{1 - H_L} C_o v_M \qquad 2.23$$

With an inclination angle θ the proposed model by Kaya et al. (1999) as shown below

$$v_s = v_\infty \sqrt{H_L \sin\theta} \qquad 2.24$$

Combining equations 2.23 and 2.24 we get the following expression

$$v_\infty \sqrt{H_L \sin\theta} = \frac{v_{SG}}{1 - H_L} C_o v_M \qquad 2.25$$

Liquid holdup can be calculated from Equation 2.25 using a trial and error procedure as follow

1. Assume an initial holdup value (HL0); a good guess is the no-slip holdup.

2. Calculate the holdup Equation 2.25 as follows :

$$H_L = 1 - \frac{v_{SG}}{v_\infty \sqrt{H_L \sin\theta} + 1.2 v_M} \qquad 2.26$$

3. Check the calculated value with the guessed one. If the two values of HL agree within an acceptable tolerance then stop. Otherwise, repeat steps 1-3 until HL converges.

After determining the holdup, mixture properties can be calculated using the following equations:

$$\rho_M = \delta_L H_L + \rho_G(1 - H_L) \qquad 2.27$$

$$\mu_M = \mu_L H_L + \mu_G(1 - H_L) \qquad 2.28$$

The elevation pressure gradient is given by

$$\left(\frac{dP}{dL}\right)_{el} = \rho_M\, g \sin\theta \qquad 2.29$$

The frictional pressure loss is given by

$$\left(\frac{dP}{dL}\right)_{f} = \frac{f_M \rho_M v_M^2}{2ID} \qquad 2.30$$

where

ID = the inner pipe diameter and

fM = is the Moody friction factor and is calculated using the following Reynolds number

$$N_{Re.M} = \frac{\rho_M v_M ID}{\mu_M} \qquad 2.31$$

Moody friction factor in AppendixB is four times the Fanning friction factor and it is calculated using the Colebrook, C.F. (1939) function and solving using a trial and error procedure using the Equation 2.32 :

$$\frac{1}{\sqrt{f_M}} = -4\log\left(\frac{0.269\varepsilon}{ID} + \frac{1.225}{N_{Re}\sqrt{f_M}}\right) \qquad 2.32$$

where

ID = inner pipe diameter

N_{Re} = Reynolds number and

ε = pipe roughness.

The acceleration pressure gradient components is calculated using Beggs and Brill J.P (1973) approach as follow

$$\left(\frac{dP}{dL}\right)_{acc} = \frac{\rho_M v_M v_{SG}}{p}\frac{dP}{dL} \quad 2.33$$

the acceleration term (Ek) is defined as follow

$$E_k = \frac{\rho_M v_M v_{SG}}{\mu_M} \quad 2.34$$

Then the total pressure drop is calculated by Equation 2.35:

$$\left(\frac{dP}{dL}\right)_{total} = \frac{\left(\frac{dP}{dL}\right)_{el} + \left(\frac{dP}{dL}\right)_{f}}{1-E_k} \quad 2.35$$

- **Dispersed bubble flow model for drillstring**

Since nearly a uniform bubble distribution in the liquid, the flow can be treated as a homogenous flow. Thus, the liquid holdup is very close to the no-slip holdup (λL). Hence, the total pressure drop is calculated using Equations 2.27-2.35.

- **Slug flow model for drillstring**

From the bubbly flow model shown above, liquid holdup for the rise velocity of a Taylor bubble in downward flow may be calculated by

$$H_{L.TB} = 1 - \frac{v_{SG}}{C_I v_M - v_{TB}} \quad 2.36$$

Hasan A.R (1993) recommended to use a value of C1=1.12. The liquid holdup is calculated by Equation 2.37 :

$$H_{LSU} = 1 - \left[\frac{L_{TB}}{L_{SU}}\left(1 - H_{L_{TB}}\right) + \frac{L_{LS}}{L_{SU}}\left(1 - H_{LS}\right)\right] \quad 2.37$$

The slug unit length can be calculated by the following expression based on the superficial gas velocity

$$L_{SU} = \frac{160(ID)v_{SG}}{C_0 v_M - v_\infty} \quad \text{for} \quad v_{SG} > 0.4\, m/sec \qquad 2.38$$

$$L_{SU} = \frac{64(ID)}{C_0 v_M - v_\infty} \quad \text{for} \quad v_{SG} \leq 0.4\, m/sec \qquad 2.39$$

Perez-Tellez31 showed that, for a fully developed Taylor bubble, the total hydrostatic and frictional pressure losses can be calculated by

$$\left(\frac{dP}{dL}\right)_{el} = \left[(1-\beta)\rho_{M,LS} + \beta\rho_{M_{TB}}\right]g \qquad 2.40$$

$$\left(\frac{dP}{dL}\right)_{f} = \frac{2f_{F_{LS}}\rho_{M_{LS}}v_M^2}{ID}(1-\beta) \qquad 2.41$$

The acceleration component in the drillstring can be calculated by using Equations 2.33-2.35. For fully developed Taylor bubble flow condition, β is given by

$$\beta = \frac{L_{TB}}{L_{SU}} \qquad 2.42$$

And $\rho_{M_{TB}} = \rho_G$

Where $\rho_{M_{LS}}$ is calculated as in Equation 2.27 with changing HL with LLS H , in addition the friction factor is calculated using the following mixture Reynolds number

$$N_{Re.M} = \frac{\rho_{M_{LS}} v_M (ID)}{\mu_L H_{L_{LS}} + \mu_G \left(1 - H_{L_{LS}}\right)} \qquad 2.43$$

2.4.2 Upward Flow through the Annulus

- **Bubble Flow Model for Annular Geometries**

For a bubbly flow the holdup is calculated as reported by Hasan and Kabir (1992) as follows

$$H_L = 1 - \frac{v_{SG}}{v_\infty - C_0 v_M} \qquad 2.44$$

CO values are based on the inclination angle as shown in Table 2.1.

After calculating the holdup then mixture density and viscosity are calculated from Equations 2.27 and 2.28. The elevation pressure gradient is calculated using equation 2.29. For the frictional pressure loss is calculated from equation 2.30. Caetano et. al.(1992) suggested the use of the calculation developed by Gunn and Darling et. al.(1963) for a turbulent flow as follow

$$\left[f_F\left(\frac{F_p}{F_{CA}}\right)^{0.45\,exp(-N_{Re}-3000)/10^6}\right]^{-0.5} = 4\log\left[N_{Re}\left(f_F\left(\frac{F_p}{F_{CA}}\right)^{0.45\exp\left(-\frac{(N_{Re}-3000)}{10^6}\right)^{0.5}}\right)\right]-0.4$$

2.45

where f_F is the Fanning friction factor.

Equation 2.45 has the following parameters:

F_p and F_{CA} are geometry parameters defined by the following equations

$$F_P = \frac{16}{N_{Re}} \qquad 2.46$$

$$F_{CA} = \frac{(16-k)^2}{\frac{1-K^4}{1-K^2} - \frac{1-K^2}{ln\left(\frac{1}{K}\right)}} \qquad 2.47$$

K: diameter ratio is defined below

K=OD/ID 2.48

Where OD is the pipe outer diameter and ID is the inner casing diameter.

The mixture Reynolds number is calculated using Equation 2.31 the hydraulic diameter (Dh) used instead of the pipe inside diameter (ID). The acceleration component is calculated using Beggs and Brill5 approach using Equations 2.33-2.35.

Slug Flow Model

The same model used by Perez-Tellez31 for the case of downward flow inside the drillstring is used. The hydraulic diameter is used instead of the inner tubing diameter in Equation 2.43 for calculating Reynolds number. In addition, the acceleration component can be calculated by

$$\left(\frac{dP}{dL}\right)_{acc} = \frac{H_{L_{LS}}\rho_L}{L_{SU}}\left(v_{L_{LS}} + |v_{TB}|\right)\left(v_{TB} - v_{L_{LS}}\right) \qquad 2.49$$

Finally the average holdup over the entire slug unit *LSU H* for either developed of fully developing Taylor bubble can be calculated using an equation by Perez-Téllez et.al. (2002).

$$H_{L_{SU}} = 1 - \frac{v_{SG} + \left(1 + H_{L_{LS}}\right)\left(v_{TB} - v_{G_{LS}}\right)}{v_{TB}} \qquad 2.50$$

Bit Model

Perez-Tellez developed a two phase bit model to handle the pressure drop across the bit nozzles. Using the mechanical energy balance along with the gas weighting fraction and neglecting frictional pressure drop, he formulated the following expression for calculating the pressure drop across the bit nozzles

$$\frac{V_n^2}{g_c} + \frac{(1-W_g)}{\rho_L}(P_{bh} - P_{up}) + \frac{W_g \ zRT}{M_g} ln\left(\frac{P_{bh}}{P_{up}}\right) = 0 \qquad 2.22$$

where

v_n = is the nozzle velocity

w_g = is the gas weighing factor

Pbh = is the bottomhole pressure

Pup = is the upstream pressure

Mg = is the gas molecular weight

Also using the continuity equation for the gas liquid mixture the following expression is reached to express the conservation of mass

$$\rho_M v_M An = q_L \rho_L + q_G \rho_G \qquad 2.23$$

and the nozzle velocity is calculated by

$$v_{n = }((q_L \rho_L + q_G \rho_G)/ A_n) v \qquad 2.24$$

The above three equations are solved numerically to obtain the bit nozzle upstream pressure given the bottomhole pressure

CHAPTER 3

METHODOLOGY

3.1 Computer Program Description

The mechanistic steady state model is being utilized in order to model the flow behavior of well during the operation.Therefore,the computer algorithm that was developed by Perez-Tellez were being used.the mechanistic steady state model that described before were implemented into a FORTRAN 95 computer program that performs an iterative two-phase flow analysis on a discretized wellbore. The algorithm was coded into a macro which can be run using MS EXCEL®. The macro was written in VBA (Visual Basic for Applications). Creating the code in EXCEL makes it easy to continue the analysis further into the same application or link it with other applications.

The well is divided into many axial increments and each increment is treated separately. Any increment length may be used, but 6 to 15 m (20 to 50 ft) segments provide the best results when compared to real data. An incremental procedure for calculating the wellbore pressure traverse is used by the program. Increments of depth ΔL_i with an inclination angle Θ_i from the horizontal. Figure 3.1 shows typical incremental calculations diagram in a deviated wellbore when carrying such type of pressure traverse calculations. As shows Figure 3.1, the calculations start at the annulus with a known starting pressure point (choke, surface) and then the calculations continue through the annulus taking into account different wellbore inclinations and different casing and drill pipe geometries. When the calculations reach the bottomhole, pressure drop through the bit nozzles is calculated.

Figure 3.2 illustrates a discretized wellbore and the calculation path implemented in the computer program.The pressure gradient predictions use a marching algorithm which allows calculating the flow parameters along the flow path (wellbore) after dividing it into cells.Next, calculations for downward flow in the drillstring are performed. Figure 3.3 shows a flow chart of the computer code used to carry out the pressure traverse calculations. For each length increment the inclination angle is calculated from the survey file provided or it can be input manually per the request of the user. The calculations for both the downward flow in the drillstring and upward flow in the annulus, and flow through bit nozzles. Figure 3.2 shows the flowchart for modeling the calculations of the mechanistic steady state model in a deviated well.

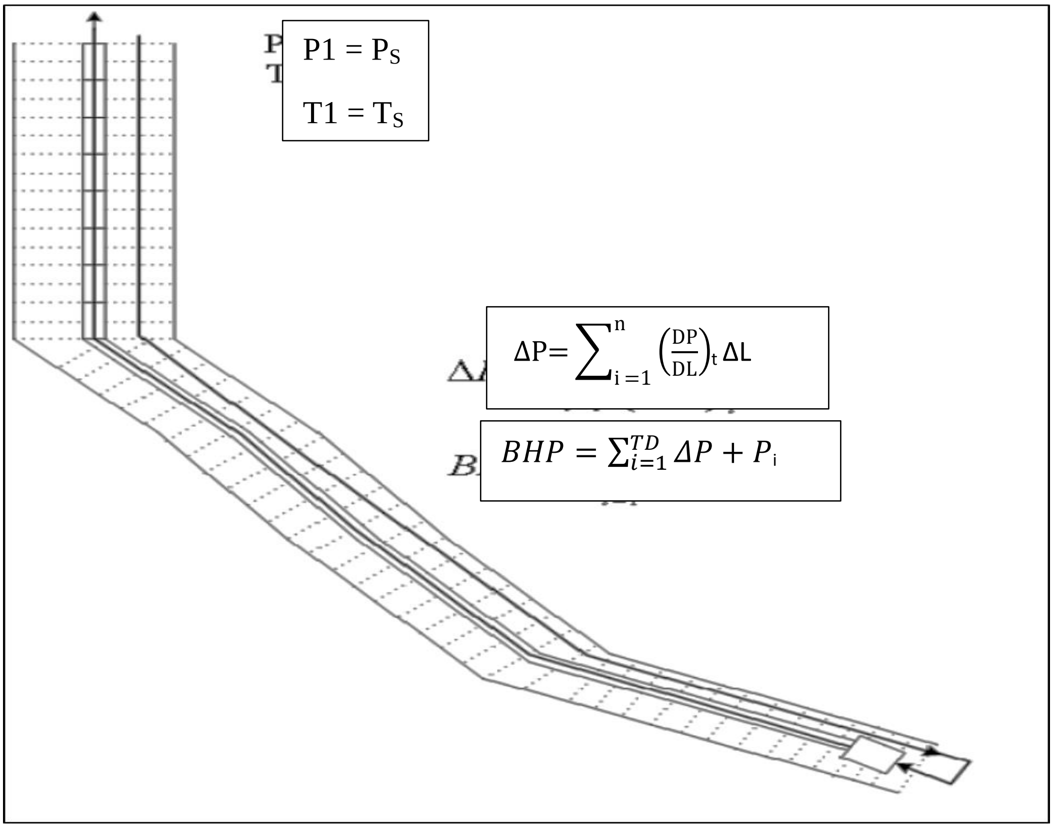


Figure 3.1 Incrimental wellbore calculations path in a deviated wellbore

3.2 Algorithm Steps

Figure 3.2 presents the computer flow diagram for the comprehensive, mechanistic steady state model to calculate flow patterns, two-phase flow parameters, and wellbore pressure along the flow path following the algorithm steps described below.

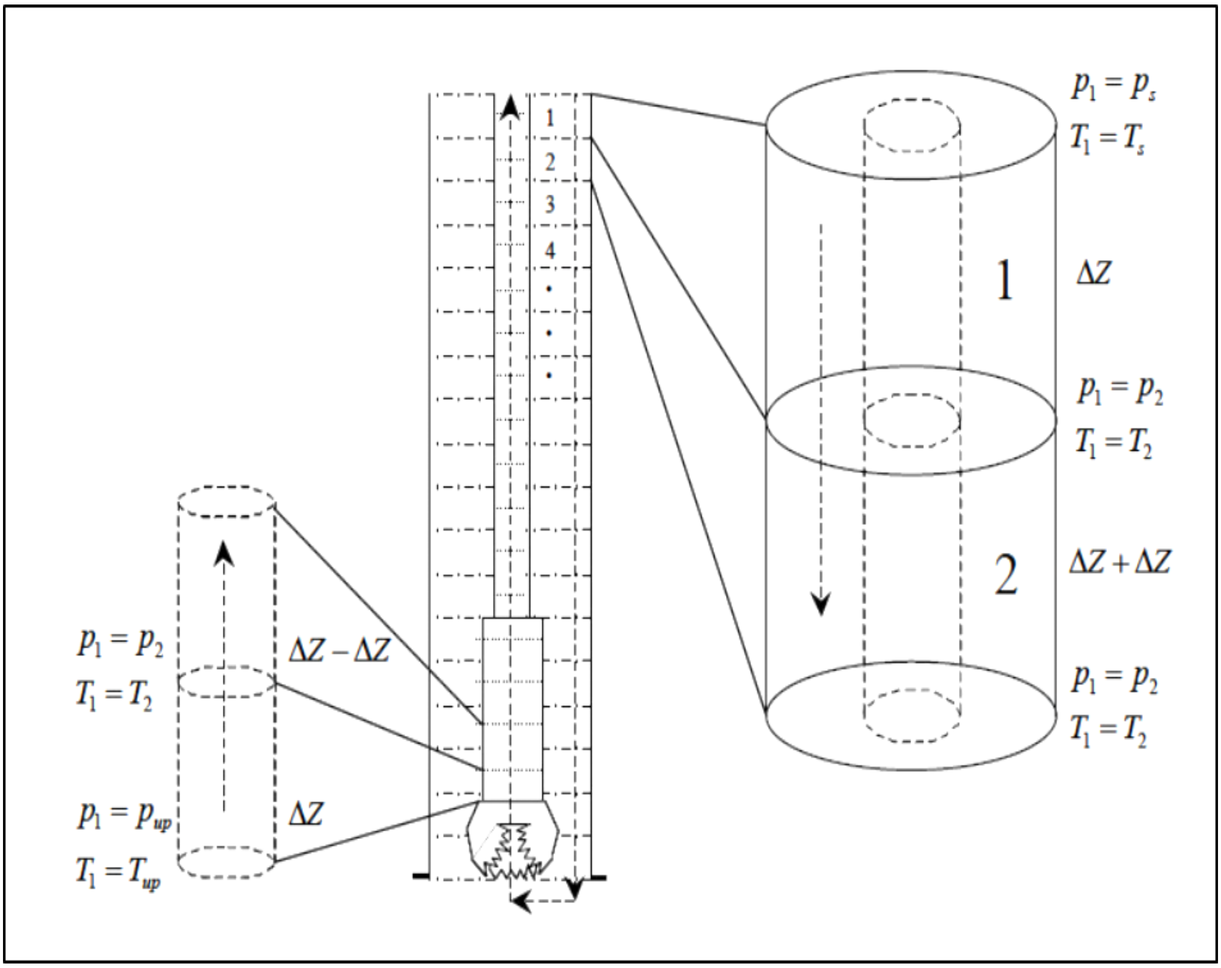


Figure 3.2 Discretized wellbore and calculation path

Firstly, the gas and liquid flow rates, fluid properties, and well geometry been input. Then select the length of the axial increments (Figure 3.2). Third step, the total pressure drop being guess corresponding to the length increment. Since the hydrostatic pressure drop accounts for approximately 80% of the total pressure drop, a good guess is the hydrostatic pressure caused by a column of the corresponding drilling fluid being used. Fourth step is to estimate the downstream temperature of the first axial increment, 2 T by using the surface temperature and geothermal gradient. Fifth, using the casing choke pressure and the guessed total pressure drop from estimate the downstream pressure of the first axial increment, 2 P .

The next step, using the surface pressure and temperature and the downstream pressure and temperature previously estimated, calculate the average pressure and temperature corresponding to the axial increment. Seventh step, estimate surface liquid and gas velocities and fluid properties at average conditions. Eight step,Program the flow pattern prediction models and with the superficial velocities estimated in, identify the flow pattern at the in-situ flow conditions.ninth step, After identifying the existing flow pattern, use the corresponding flow behavior prediction model to calculate liquid holdup, mixture density, mixture viscosity, and friction factor.

If slug flow is the existing flow pattern, the hydrodynamic parameters must be calculated as well. Calculate the gravity, friction, and acceleration pressure gradients, and then the total pressure gradient for the axial increment selected. Eleventh steps, Compare the total pressure gradient calculated against total pressure gradient that guessed in . If the difference between them is less than a tolerance (0.01 psi) continue with the next step.Otherwise, substitute the total pressure gradient guessed in step 3 for that calculated in step 10 and repeat steps 3 through 11 until convergence. When that happens, the cell downstream pressure 2 P will be the actual wellbore pressure occurring at the end of the first axial increment for the existing flow conditions.

Increase the depth by one axial increment and compare the current depth to the total depth of the first section with constant cross-section area (*DT*).Compare the current depth against *DT*. If the current depth is not equal to *DT* , repeat steps 3 through 12. If they are equal, continue the process..Using the bottom hole pressure calculated, calculate pressure drop through the bit nozzles and the nozzle upstream pressure. Considering drillstring flow pattern prediction and flow behavior models, nozzle upstream pressure and temperature, and downward pipe flow instead of upward flow in an annulus (Figure 3.2), the same flow diagram can be used for drillstring computations.This algorithm implemented in a FORTRAN 90 computer program, allows calculating the wellbore pressure and flow parameters at any position along the flow path in few seconds. Afterward, the data generated is brought to an Excel work sheet to manipulate it as we require.

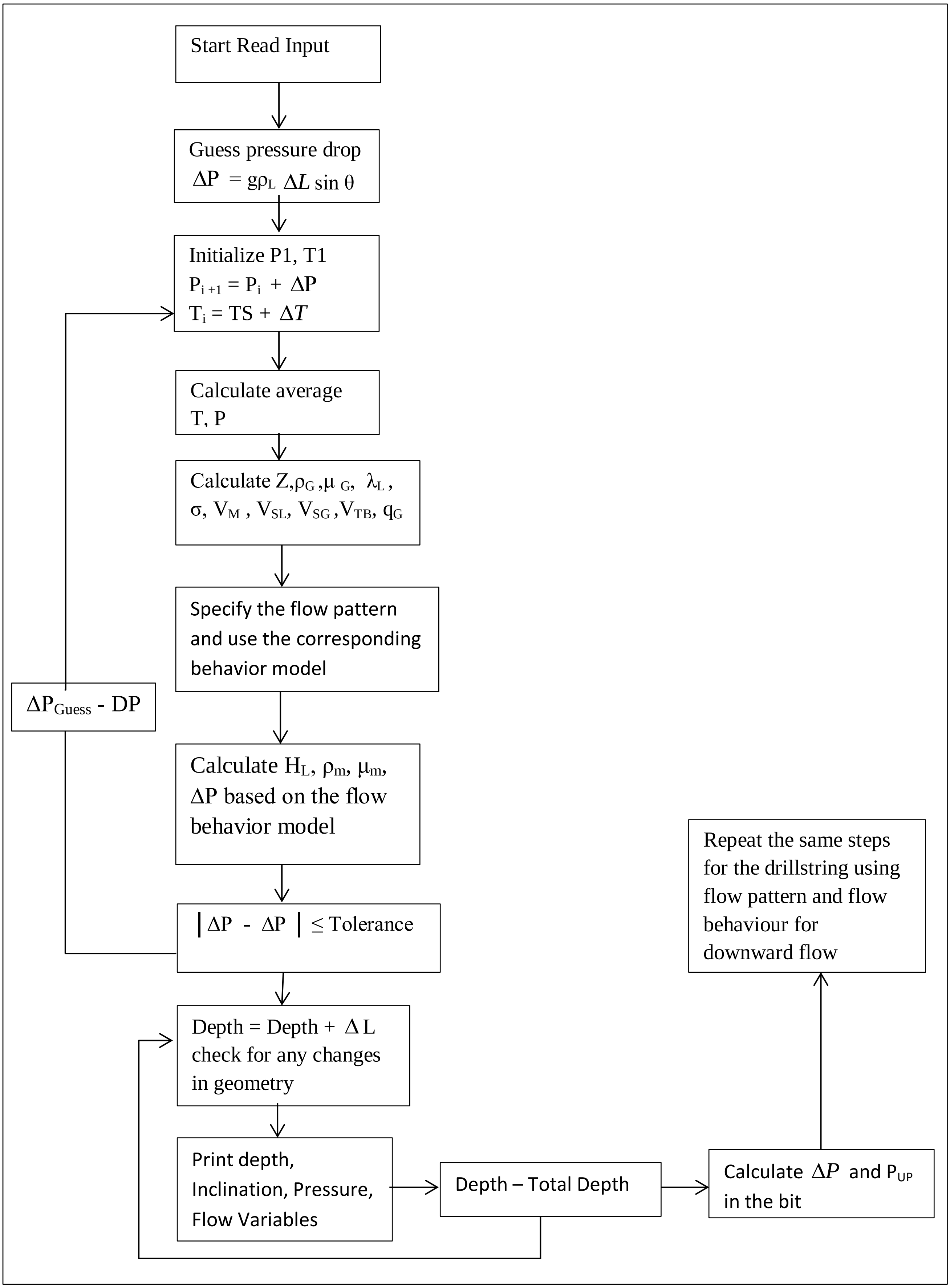


Figure 3.3 Flowchart for the Computer Algorithm used in the Mechanistic Steady State Model.

CHAPTER 4

RESULTS

4.1 Introduction

This chapter discusses the results of the pressure drop of slug flow in vertical pipes by using mechanistic steady state model. By using the model design with FORTRAN 95 computer program the pressure drop was identified.In addition, the behaviour of flow can be predicted.

4.2 Disscussion

Table 4.1 shows annular and drillstring geometries for the above two depths. And Table 4.2 shows the input given to the EXCEL VBA program. The calculation incremental length selected was taken for each 10 ft due to the sensitivity of the flow on the inclination angle. The horizontal section considered as a highly deviated section.

Table 4.1 : Drillstring and Annular Geometries at the Two Simulated Depths

Run #1				
Annulus			Drillstring	
Deptht (ft)	Casing (in)	Pipe OD (in)	Depth (ft)	Pipe ID (in)
0-6594	9.625	3.5	0-4528	2.6875
6594-6751	7	3.5	4528-5078	2.1875
6751-7547	6	3.5	5078-7478	2.4375
Pressure tool to bit			7478-7547	2.25

Run #2				
Annulus			Drillstring	
Deptht (ft)	Casing (in)	Pipe OD (in)	Depth (ft)	Pipe ID (in)
0-6594	9.625	3.5	0-4604	2.6875
6594-6751	7	3.5	4604-5154	2.1875
6751-7547	6	3.5	5154-7554	2.4375
Pressure tool to bit				2.25

The experimental data and equation adopted from the literature review will be used as a comparison with the theoritical data taken from the model.The data adopted from literature review is shown in table 4.2.

Table 4.2 : Computer Program Input

Input	Run 1	Run 2
Depth	7573 ft	7640 ft
Gas flow rate	670 scf/min	1030 scf/min
Liquid flow rate	270 gpm	225 gpm
Liquid density:	7.910 ppg	7.910 ppg
Mud viscosity	3.00 cp	3.00 cp
Length increment (DL):	10.00 ft	10.00 ft
Bit Nozzle size	16.00 (1/32) in	18.00 (1/32) in

After running the program for the two cases, the results have a good match with the measured value where at the average absolute error *Ea* has an average value of less than 10% (about 87 psi) as shown in Table 4.3

A commercial simulator was used to compare the results of this study to the simulator output; this recent version of the simulator uses the empirical correlation that was developed by Hasan and Kabir. Table 4.3 shows the output result of the developed model in this study with the result of the simulator output.

Table 4.3 : Comparison of Absolute Average Error for the Two Simulation Runs

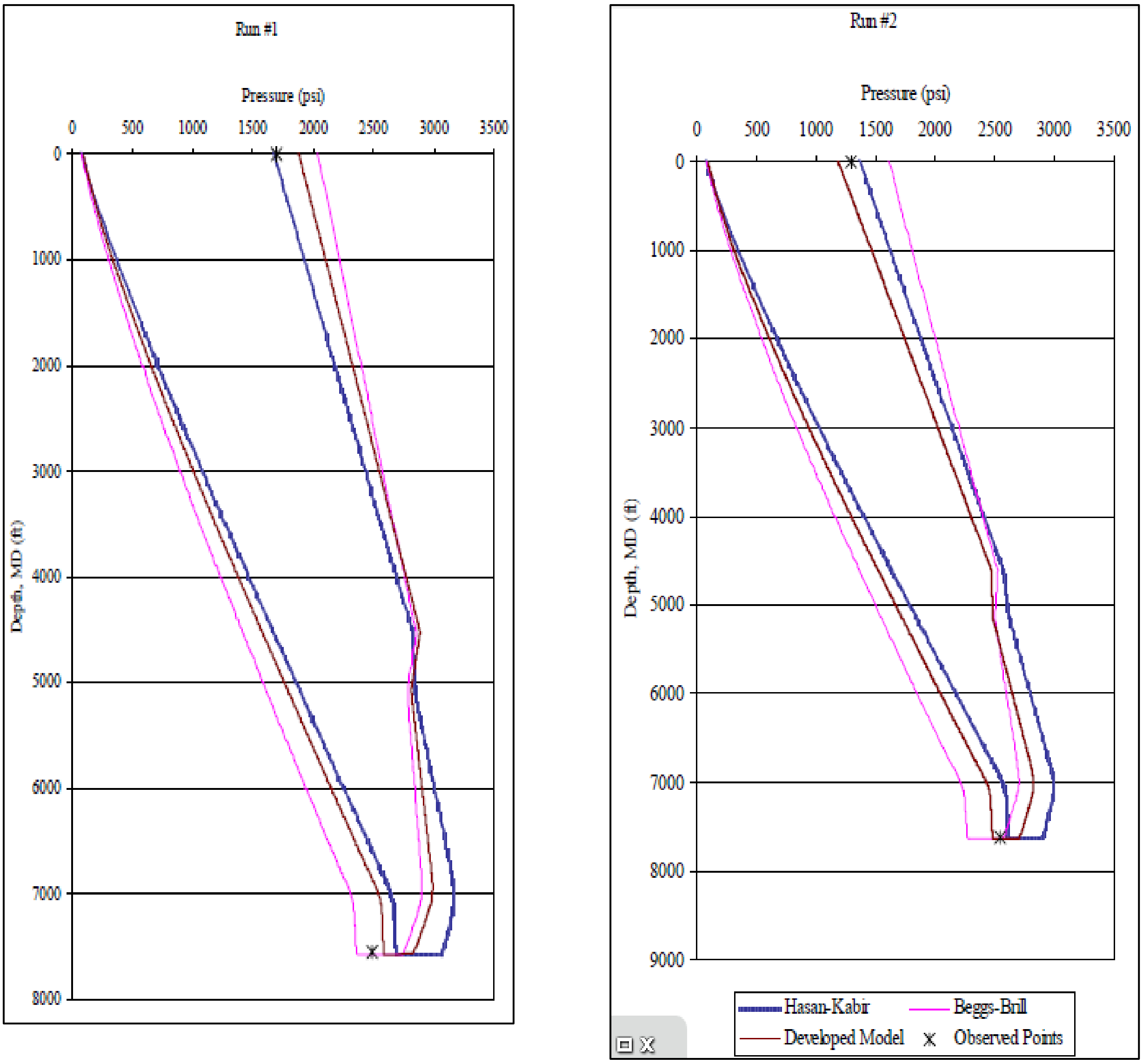
Comparison		Run #1		Run #2	
		Calc	Ea	Calc	Ea
Developed Model	BHP	2585	3.797	2494	2.564
	P_{inj}	1882	10.690	1198	7.860
Simulator-Beggs & Brill	BHP	2366	4.980	2282	6.160
	P_{inj}	2040	20.012	1614	24.185
Simulator-Hasan & Kabir	BHP	2694	8.177	2622	7.792
	P_{inj}	1675	1.476	1371	5.485

Table 4.3 shows that the developed model has a very good agreement with the observed data for both depths as shown from the absolute relative error values. The used commercial simulator is based on empirical correlations; the simulator was run using the well known Beggs-Brill and Hasan-Kabir correlations (most recent as specified by the simulator manufacturer). The results shown in Table 4.3 indicate that the simulator predict the bottomhole pressure reasonably well however the mechanistic model outperform runs both.

Also, the modified developed mechanistic steady state model shows a consistency of pressure distribution along the drill pipe and annulus for both runs, despite the fact that is appear to be Beggs and Brill correlation works well for the run at 7640 ft MD but the correlation didn't model correctly the distribution along the wellbore and gave a large injection pressure. In addition, the use of different mechanistic models shows that they can capture the behavior of the flow during different combination of flow rates and pipe geometries, unlike the empirical correlations where they reported not to work well in oil field cases, and also they were developed by production engineers to handle either upward flow during the pipe or the annulus. Another reason why such large error occurred is the fact that this well has a large horizontal section which is this case was treated as highly deviated; hence the calculations may be affected by this assumption.

Figure 4.1 shows a plot of the two simulators results with the measured data for both simulated depths. The effect of inclination is seen thoroughly in the developed model whereas the commercial simulator shows changes in the geometry where it will effect the flow behavior. Also the combination use of mechanistic steady state models has eliminated any sharp transition in the calculations, which is not the same case for commercial simulator output.

Figure 4.1 : Comparison between Field Measurements and Simulators Output at Both Runs



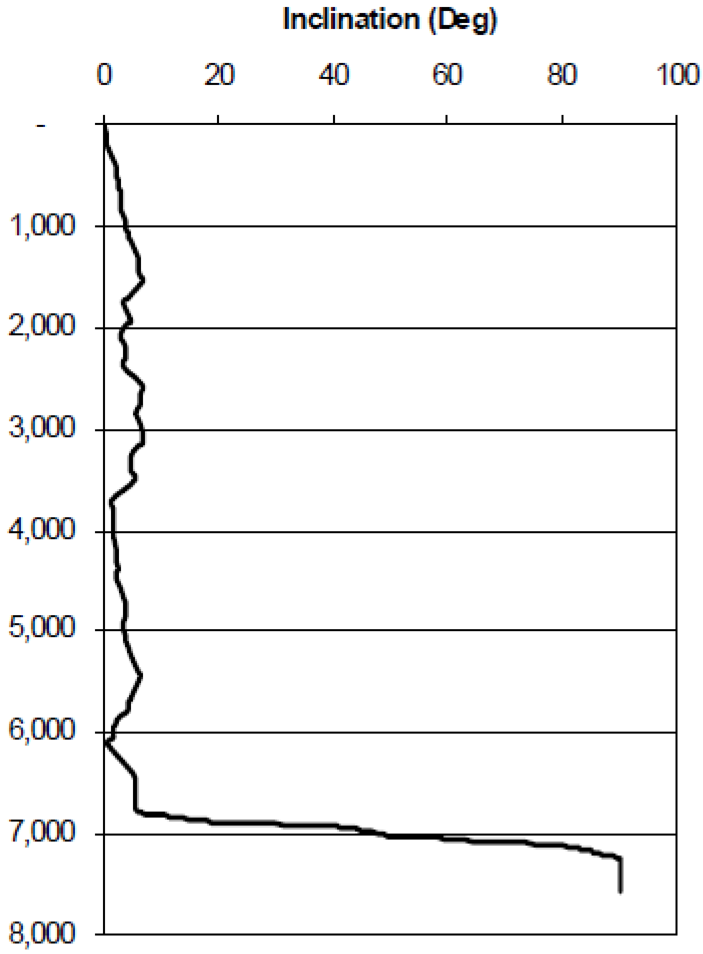


Figure 4.2:Simulation Results (HL, $\Delta P/\Delta L$) vs Depth

Figure 4.2 shows a plot of the pressure gradient, liquid holdup against measured depth. It can be seen that both the pressure gradient and liquid holdup changes with the start of the horizontal section where the pressure gradient decreased (expected in nearly horizontal flow) due to the decrease in the elevation component in the total pressure gradient computations where it has the effect shown in the figure above.

CHAPTER5

Conclusion and Recommendation

5.1 Conclusion

The developed model and the computer program is only valid to steady state conditions.The combination of flow prediction and flow behavior models has proven to effectively predict flow profile in a steady state condition but still a lot of parameters that needed to be consider for accurate calculation.The Visual Basic Application program can be used in spreadsheet calculations to carry several models and predictions.The use of the marching algorithm is recommended taking into account for selection of the appropriate length increment since if the survey data was taken alone, this will have an increase effect on the calculations. Also a simple interpolation is used in order to find the inclination angle from the horizontal at each given depth.This program can be used also to calculate the pressure drop in conditions other and than UBD operations. However, some modifications are needed in order to accommodate for variables fluid influx from the reservoir.

5.2 Recommendations

Any future development of mechanistic models should improve results by increasing accuracy in liquid holdup and pressure gradient predictions and to developing a model for a truly Vertical and horizontal increment are recommended also to enhance the calculations and create a unified model for all angle ranges.

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Appendix A: PVT Correlations

The following correlations are implemented into the computer algorithm in order to calculate fluid properties at different pressures and temperatures.

Gas Compressibility Factor

Dranchak and Abu-Kassem39 correlate the Standing and Katz40 Z-Factor diagram where they reached to the following solution in which it can be solved by a trial and error procedure.

A1 to A11 are constant and shows in the table below

Table A.1 Constants Used in Dranchak and Abu-Kassem Correlation

A1 = 0.3265	A4 = 0.01569	A7 = -0.7361	A10 = 0.6134
A2 = -1.0700	A5 = -0.05165	A8 = 0.1844	A11 = 0.7210
A3 = -0.5339	A6 = 0.5475	A9 = 0.1056	

Gas Viscosity

Lee et al. developed the following equations for calculating gas viscosities at insitu temperature as follows :

$$\mu_G = Ax10^4 \exp(1000\beta\rho_G^C) \qquad \text{A.3}$$

$$\mathrm{A} = \frac{(9.4+0.02\mathrm{M_G})\mathrm{T}^{1.5}}{209} + 19\mathrm{M_G} + \mathrm{T} \qquad \text{A.4}$$

$$B = 3.5 + 0.01M_G + \frac{986}{T} \qquad \text{A.5}$$

$$\mathrm{C} = 2.4\text{-}0.2\ \mathrm{B} \qquad \text{A.6}$$

Gas Surface Tension

The following equations were used to compute the gas surface tension21 at any temperature where *T* is average temperature between surface and any given depth

$$\sigma_{w(74)} = 75 - 1.108P^{0.349} \qquad \text{A.7}$$

$$\sigma_{w(280)} = 75 - 0.1048P^{0.637} \qquad \text{A.8}$$

$$\sigma_g = \frac{\sigma_{74}(\sigma_{74}-\sigma_{280})\frac{\check{T}-T_{surf}}{T-T_{surf}}}{1000} \qquad \text{A.9}$$

Oil Viscosity

Oil viscosity is calculated using Beggs and Robinson42 equations as follows:

$$\mu_{oil} = A_{oil}(10^{x} - 1.0)^{B_{oil}} \qquad \text{A.10}$$

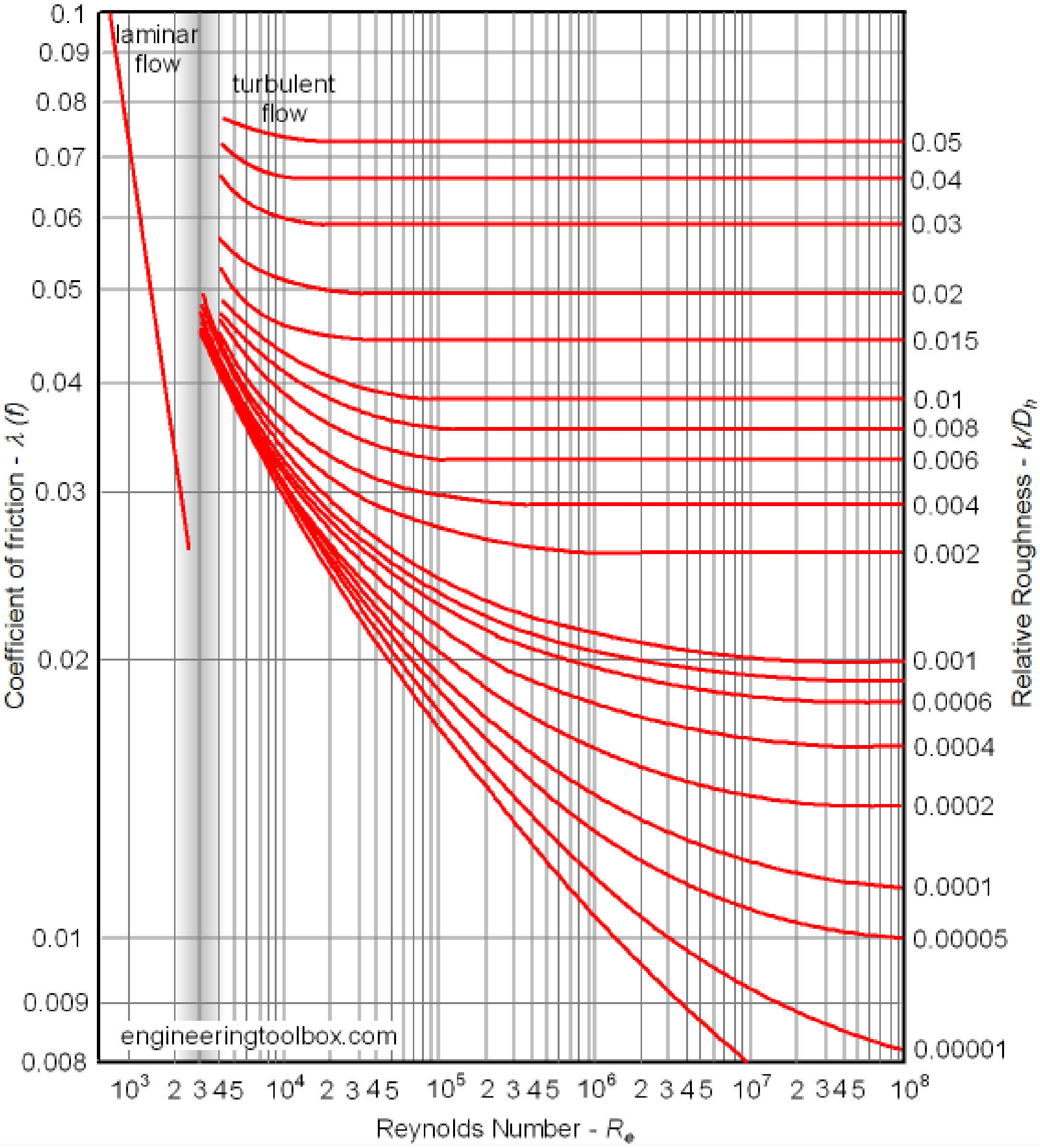
$$X = YT^{-1.163} \qquad \text{A.11}$$

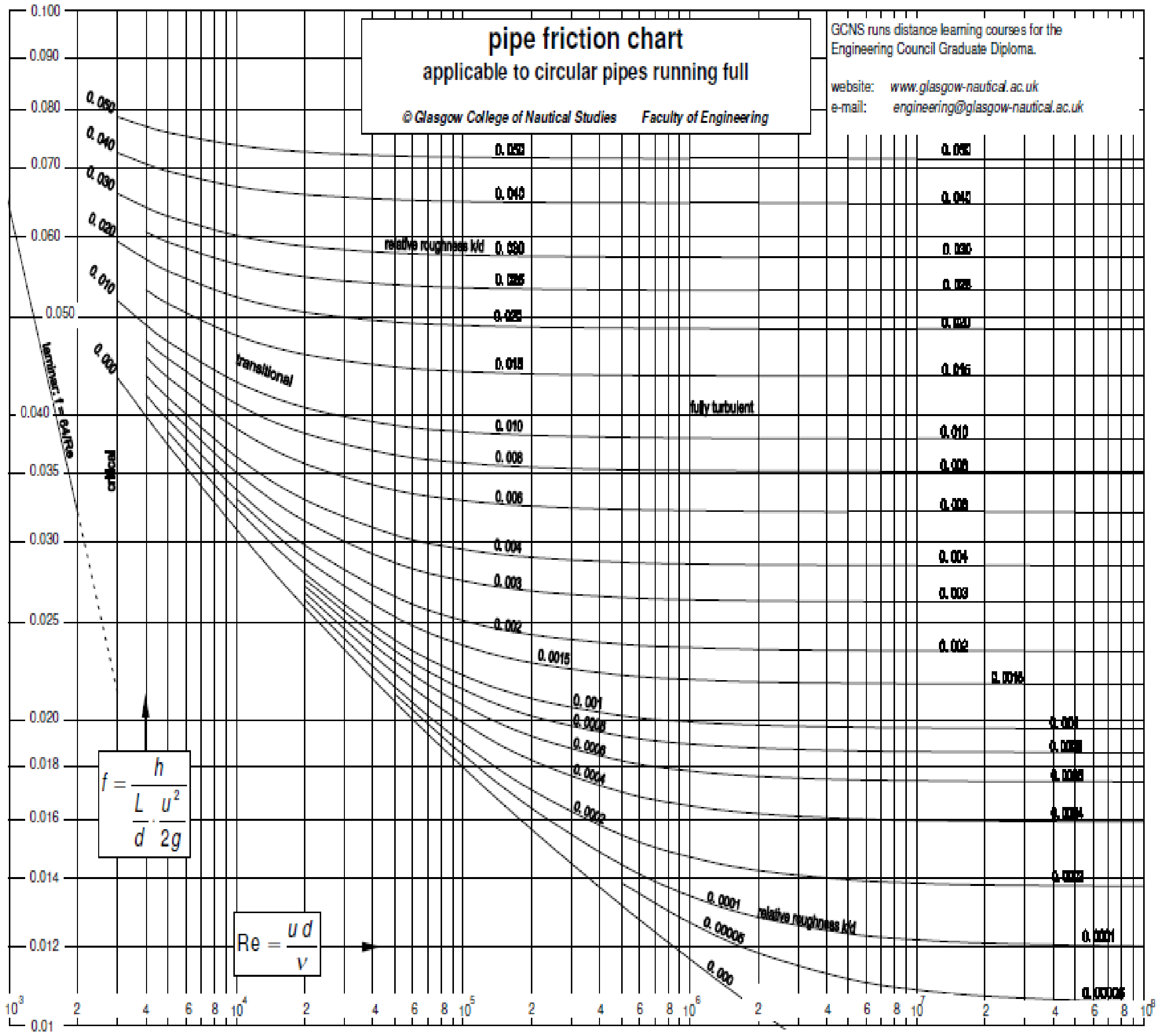
$$\text{Y} = 10^{3.0324-0.0203(API)} \qquad \text{A.12}$$

$$A_{oil} = 10.715X\,(150)^{-0.515} \qquad \text{A.13}$$

$$B_{oil} = 5.44X\,(150)^{-0.338} \qquad \text{A.15}$$

Appendix B: Moody Chart




pipe friction chart
applicable to circular pipes running full
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relative roughness k/d
transitional
fully turbulent
critical
laminar: f = 64/Re
$f = \frac{h}{\frac{L}{d}\cdot\frac{u^2}{2g}}$
$Re = \frac{u\,d}{\nu}$