Calculations of Equivalent Circulating Densities (ECDs) in Underbalanced Drilling Using Landmark WELLPLAN

by

William Liew Sin Yoong

(12467)

Dissertation submitted in partial fulfilment of

the requirement for the

Bachelor of Engineering (Hons)

(Petroleum Engineering)

MAY 2012

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan.

CERTIFICATION OF APPROVAL

Calculations of Equivalent Circulating Densities (ECDs) in Underbalanced Drilling Using Landmark WELLPLAN

by

William Liew Sin Yoong

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

Approved by,

____

(DR. REZA ETTEHADI OSGOUEI)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH PERAK
MAY 2012

CERTIFICATION OF ORIGINALITY

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

____

(WILLIAM LIEW SIN YOONG)

ABSTRACT

Underbalanced drilling (UBD) is a drilling operation where the equivalent mud weight is maintained below the open hole pore pressure. In meeting the world's rising energy demand in a sustainable manner, this technique is one of the best solutions to access challenging reservoirs and improve the recoverable reserves. However, performing underbalanced operation is not an easy task and any failure in it will cause severe damage, in most of the time, worst than conventional drilling. This project aimed to tackle one of the main challenges in underbalanced drilling which is obtaining reliable prediction of the downhole pressure or commonly expressed in terms of Equivalent Circulating Densities (ECDs). Dependable ECDs prediction method is very important as the operation window in UBD is usually very small.

The key to acquire ECDs of aerated fluid accurately, which is calculations of frictional pressure loss of two-phase flow in the annular section was studied and presented in this paper. Due to the existence of gas phase in its composition, the prediction of ECDs is much more complex and might not be perfectly done by existing drilling hydraulics simulators. By using water and air as both phases in the aerated fluid, a set of experimental pressure drop data was used to make comparisons against frictional pressure loss calculated with Beggs and Brill method and results obtained from Landmark WELLPLAN software.

The accuracy of both Beggs and Brill method and Landmark WELLPLAN software were discussed by taking into considerations effects of slip, flow pattern and inclination of well towards ECDs of drilling fluid. Results showed that WELLPLAN underestimated ECDs in all inclination sections while Beggs and Brill method is accurate for horizontal well section but less accurate for inclined sections.

ACKNOWLEDGEMENT

First and foremost, I would like to express my heartfelt gratitude to my supervisor, Dr. Reza Ettehadi Osgouei for inspiring me to take up this project and guided me throughout the journey of completing this project. In addition to that, I would like to thank him and the Department of Petroleum and Natural Gas Engineering, Middle East Technical University, for allowing me to use the results of two-phase flow experiments as comparison database of my project. The experimental results from Middle East Technical University, Petroleum and Natural Gas Department Cutting Transport facility (METU-PETE-CT) hold a very significant role in fulfilling the objectives of this project.

Next, I would like to convey my appreciation to the Department of Petroleum Engineering, Universiti Teknologi PETRONAS for the good facilities provided, especially the Landmark software laboratory. Without this, the completion of my project would not be possible.

Special thanks also to Mr. Azzumar and Mr. Aimran, the trainers from Halliburton Landmark for giving their invaluable advice and guidance to me in terms of using the software.

Finally, I would like to thank my family, friends and all others who are always by my side. Their encouragement and support had given me the strength to produce good quality of work.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

PROJECT BACKGROUND

1.1 Background of Study

Underbalanced drilling (UBD) is one of the control pressure drilling methods which is vital in commercial development of many oil and gas fields around the world. In this method, density of the drilling fluid is intentionally reduced so that the hydrostatic pressure in the wellbore is always lower than the pore pressure within the formation. Fluid flow in both conventional and underbalanced drillings is shown below.

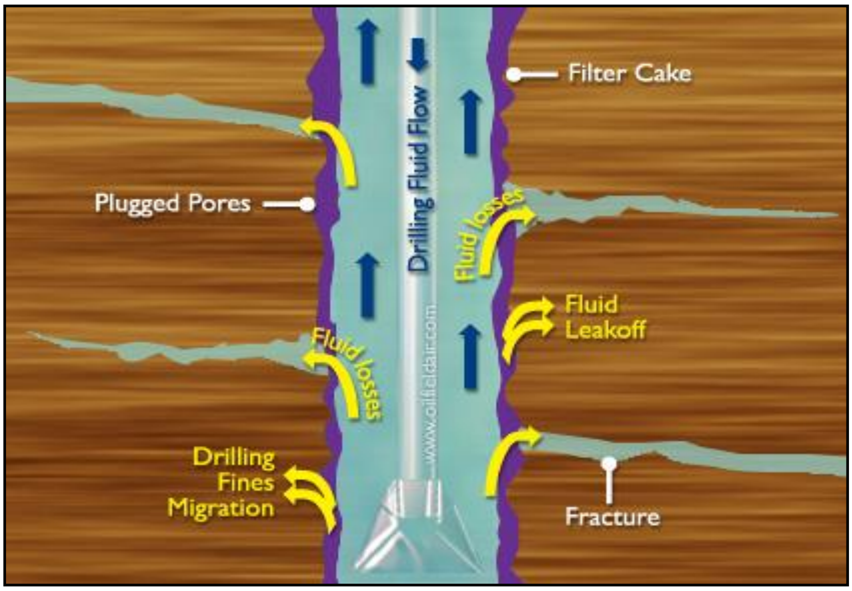


Figure 1.1: Fluid flow in conventional overbalanced drilling.

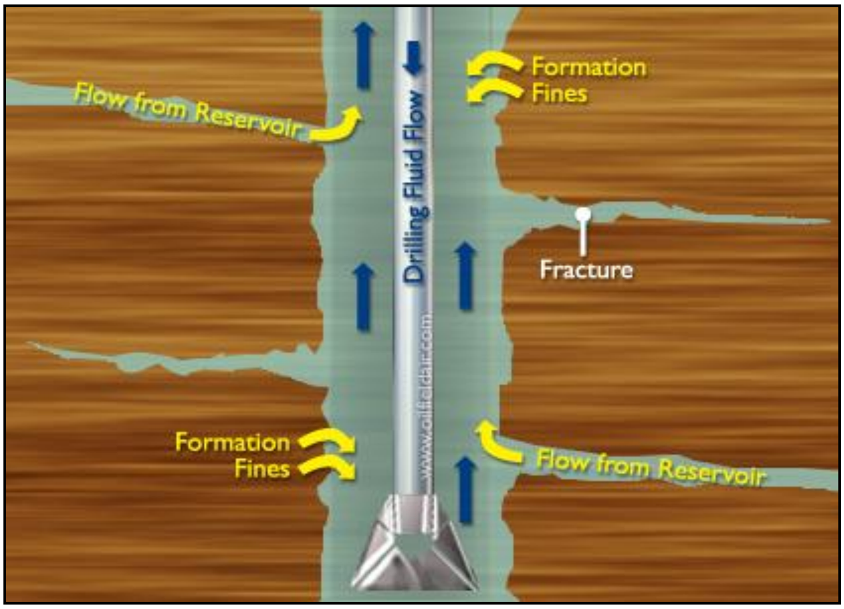


Figure 1.2: Fluid flow in underbalanced drilling.

Unlike conventional drilling method where the hydrostatic pressure is usually higher than formation pore pressure and frequently results in influx of drilling fluid into the formation, UBD offer a lot of benefits such as:

- **Improve drilling performance**

  Avoid fluid loss, increase rate of penetration, less bit wear and tripping time, and avoid differential sticking.

- **Enhancement to the ultimate recovery**

  Discovery of new zones, reduces formation damage and increase intra-zone contribution, lower abandonment pressure, increase well drainage area and accesses challenging reservoirs.

- **Allow gathering of valuable data during drilling.**

  The production while drilling data is vital for proper assessment of economical value of oil and gas in formation. They can be direct indicator of content in the formation.

1.2 Problem Statement

Although underbalanced drilling has many advantages, it is not a technique that can solve problems in all the oil and gas fields. At the same time, poor execution of UBD will results in failures. One of the main challenges in underbalanced drilling is to estimate the equivalent circulating densities (ECDs) accurately as the margin of error for this kind of operation is very small due to the narrow window between pore pressure and fracture pressure in the formation.

Kicks and blow-outs might occur if the actual ECDs of drilling fluid are lower than planned. On the other hand, higher actual ECDs of drilling fluid will results in lost circulation and formation damage. The high ECDs or drilling fluid will probably results in bottomhole pressure higher than the formation pore pressure, thus, allowing drilling fluid loss to the formation as illustrated in Figure 1.1. In the case of underbalanced drilling, this is much more severe than conventional overbalanced drilling as the drilling fluid is not designed to form mud cake around the open hole to prevent the loss. Therefore, good prediction technique of ECDs is very important to ensure the operation's success.

However, the prediction of ECDs in multiphase-flow is much more complex than single fluid flow. Heterogeneous characteristics of the flow have made the prediction of frictional pressure loss in multiphase flow more complicated. Currently, there is no hydraulic simulator that can predict the pressure gradient in two-phase flow perfectly.

1.3 Objectives and Scope of Study

- To study methods of calculating frictional pressure loss of two-phase drilling fluid in annuli and determine the most suitable method to be used to predict ECDs in underbalanced drilling.
- To develop an excel macro to calculate ECDs.
- To make comparisons between values of ECDs obtained from calculations and Landmark WELLPLAN simulation with experimental results.

Scope of study will take into considerations two important factors, slip and flow pattern which affect the two-phase-flow of Newtonian fluid in underbalanced drilling. This is important as this two-phase flow is usually heterogeneous mixture of gas and liquid. Gas in the mixture usually flows faster than the liquid, causing slippage between phases. Besides that, inclination of wells will be taken into consideration as well during the study. Inclination is another important factor as it will affect the liquid holdup and directly affect the slippage between phases.

1.4 The Relevancy of Project

This project will evaluate the best way to predict the ECDs of two-phase drilling fluid, taking into consideration the related parameters. From the results obtained, the accuracy and dependency of WELLPLAN software can be known. A good method of determining the drilling fluid ECDs will be very helpful in designing hydraulics in underbalanced drilling.

1.5 Feasibility of the Project

The project is expected to be feasible after much considerations based on the points below:

- The software needed for drilling simulation, WELLPLAN of Halliburton Landmark is readily available in the university lab.
- Research review sources such as textbooks, technical papers and journals can be obtained from university library and online sources.
- The duration of eight months in total will be sufficient to study on this subject matter.

CHAPTER 2

LITERATURE REVIEW

In the past, the world's demand for oil and gas is met by the production from easily accessible reservoirs. Currently, the oil and gas industry is facing a situation whereby exploration is difficult, the production cost is increasing, most of the existing reservoirs are pressure depleted and at the same time, oil prices fluctuating from time to time (Babajan & Qutob, 2010). Therefore, usage of new technologies is important in order to add reserves, enhance recovery, reduce cost and of course, increasing revenue. Aligned with this, underbalanced drilling is adopted in many oil and gas fields with the objectives of preventing formation damage, improving reservoir benefits, improving drilling performance and preventing conventional drilling problems (Babajan & Qutob, 2010).

Underbalanced drilling is defined as drilling operation where the drilling fluid pressure is less than the pore pressure in the formation rock in the open-hole section (Guo & Ghalambor, 2002). According to IADC Well Classification System for Underbalanced Operations and Managed Pressure Drilling, underbalanced operations (UBO) is performing operations with returns to surface using an equivalent mud weight that is maintained below the open-hole pore pressure. In this kind of operation, there are 5 type of fluid systems as classified by IADC. The descriptions are shown in the table below:

Table 2.1: IADC Classification of Fluid Systems in Underbalanced Operations

No.	Fluid System	Descriptions
1.	Gas	Gas as the fluid medium. No liquid intentionally added.
2.	Mist	Fluid medium with liquid entrained in a continuous gaseous phase. Typical mist systems have less than 2.5% liquid content.
3.	Foam	Two-phase fluid medium with a continuous liquid phase generated

		from the addition of liquid, surfactant, and gas. Typical foams range from 55% to 97.5% gas.
4.	Gasified Liquid	Fluid medium with a gas entrained in a liquid phase.
5.	Liquid	Fluid medium with a single liquid phase.

On the bright side, underbalanced drilling (UBD) provides many benefits such as increases penetration rate, minimizes lost circulation, prolongs bit life, minimizes differential sticking, improves formation evaluation, reduces formation damage, earlier oil production, discovery of new zones and accessing challenging reservoirs. Although this method of drilling is so beneficial, Alajmi and Schubert (2003) said that UBD is not a solution for all formation damage problems. Indeed, damage caused by poorly designed and/or executed UBD programs can exceed that which may occur with a well-designed conventional overbalanced drilling program.

Both of them also mentioned that it is generally accepted that the success of UBD operations is dependent on maintaining the wellbore pressure between the boundaries defined by the designed UBD pressure window. Therefore, the ability to accurately predict wellbore pressure is critically important for both designing the UBD operation and predicting the effect of changes in the actual operation. In this part, the ability to calculate the ECDs of drilling fluid in the wellbore accurately is very important. Any discrepancies between the ECDs calculated and the ECDs in real-time operations will lead to failure in predicting the wellbore pressure, thus, might cause operations failure. As stated earlier, underestimation of ECDs will cause problems such as formation damage and massive drilling fluid loss while overestimation of ECD will result in kick and blowout.

The equivalent circulating density of a drilling fluid can be defined as the sum of the equivalent static density (ESD) of the fluid and the pressure loss in the annulus due to fluid flow (Harris & Osisanya, 2005). In underbalanced drilling, gas is injected into the liquid at different rates to reduce the density of the resulting drilling fluid. Any of the five fluid systems as classified by IADC can be chosen, depending on the requirement of the operation. The presence of gas and liquid phases in the drilling fluid has made estimation of ECDs more difficult as we have to take into consideration the compressibility of the fluid when gas is being injected at different rates into it. Aside from that, the effects of fluid rheology, pressure and temperature have to be thought as well.

Till today, there is no method that can perfectly calculate the ECDs of drilling fluid. The complexity in simulating real borehole conditions has made it difficult to develop a perfect method. Nevertheless, there are many available methods that can be used to predict pressure-gradient in pipe flows. By assuming that the flow of drilling fluid in the annulus between drillstring and borehole is the same as flow of the fluid in pipe, these methods can be incorporated into the calculations of ECDs. The main guiding principles behind all these methods are the principles of conservation of mass and linear momentum.

According to Brill and Mukherjee (1999) in the book Multiphase Flow in Wells, early investigators treated multiphase flow as a homogeneous mixture of gas and liquid. This approach did not recognize that gas normally flows faster than liquid. The pressure drop predicted is usually lower because nonslip approach was used and as a result, volume of liquid predicted to exist in the well was too small. To improve this condition, empirical liquid-hold-up correlations were used to consider the slippage between the phases. In this case, the liquid holdup and friction effects usually rely on the flow patterns predicted by empirical flow-pattern maps. However, most of these methods still treat the fluids as a homogeneous mixture.

Brill and Mukherjee had further categorized these methods into three as stated below:

i. No slip and no flow pattern consideration.

ii. Slip considered but no flow pattern consideration.

iii. Slip and flow pattern considered.

In the first category, **“no slip and no flow pattern consideration”**, there are three methods, namely Poetmann and Carpenter, Baxendell and Thomas, and Fancher and Brown. In these three, the mixture density is calculated based on the input gas/liquid ratio by assuming both the phases travel at the same velocity and there is no difference between flow patterns. The only variation between the individual methods is the friction factor correlation used.

In the second category, **“slip considered but no flow pattern consideration”**, there are another three methods available namely, Hagedorn and Brown, Gray, and Asheim method. In order to take into account the slippage effect, a correlation is required for both liquid holdup and friction factor. Hagedorn and Brown is a generalized method developed for broad range of vertical two-phase-flow conditions while the Gray method is for vertical wells which produce condensate fluids or water. Although slip is considered, Hagedorn and Brown did not measure the liquid holdup. Instead, they developed a pressure-gradient equation by assuming a friction-factor correlation.

In the third category, **“slip and flow pattern considered”**, all the methods take into account that both gas and liquid phases have different velocities and different flow patterns exist. There are six methods available, namely the Dun and Ros, Orkiszewski, Aziz et. al., Chierici et. al., Beggs & Brill, and Mukherjee and Brill. Each method is different in terms of flow patterns prediction and for each flow pattern, how the prediction of liquid holdup, friction and acceleration pressure-gradient component is done. Compared to the other four methods, Beggs & Brill and Mukherjee and Brill is the more complete and practicable ones because they were developed for variation in angles instead of vertical upward flow only.

Brill and Mukherjee (1999) stated that **Beggs & Brill** method was the first one to predict flow behavior at all inclination angles, including directional well. By using 90 feet long, 1-inch and 1.5-inch acrylic pipes; air and water as the fluid and also variation of liquid and gas rates, Beggs & Brill experimented the flow patterns. After establishing a set of flow rates, both of them further inclined the pipes at various angles to observe the effect of angle on liquid holdup and pressure gradient. As a result from 584 measured tests at inclination of ±0°, ±5°, ±10°, ±15°, ±20°, ±35°, ±55°, ±75° and ±90°, a set of correlations were developed by Beggs & Brill. In order to calculate the pressure-gradient in inclined pipe, they proposed the following equation:

$$\frac{dp}{dL} = \frac{\frac{f\rho_n v_m^2}{2d} + \rho_s g sin\,\theta}{1 - E_k}$$

In this equation, the mixture density, ρ_s is given by:

$$\rho_s = \rho_L H_{L(\theta)} + \rho_s[1 - H_{L(\theta)}]$$

and the dimensionless kinetic-energy pressure gradient, E_k is given by:

$$E_k = \frac{v_m v_{Sg} \rho_n}{p}$$

In the equations, Beggs & Brill considered the flow pattern, liquid holdup and also friction factor. Flow patterns were actually observed in horizontal flow and a map was prepared to predict them. Figures 2.1, 2.2, 2.3 and 2.4 are the horizontal flow patterns and horizontal flow pattern map as according to Beggs & Brill.

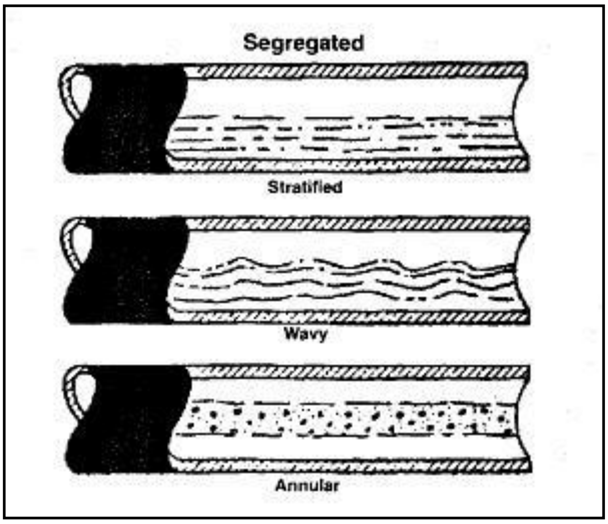


Figure 2.1: Beggs & Brill horizontal-flow patterns – Segregated.

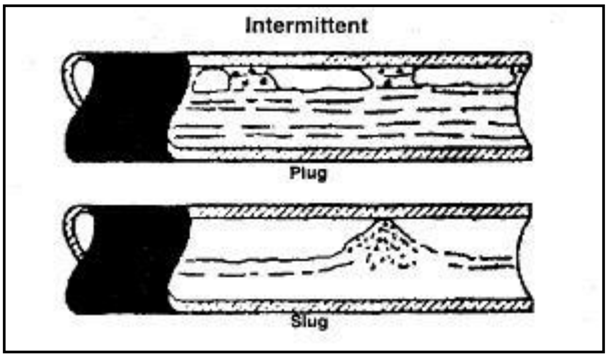


Figure 2.2: Beggs & Brill horizontal-flow patterns – Intermittent.

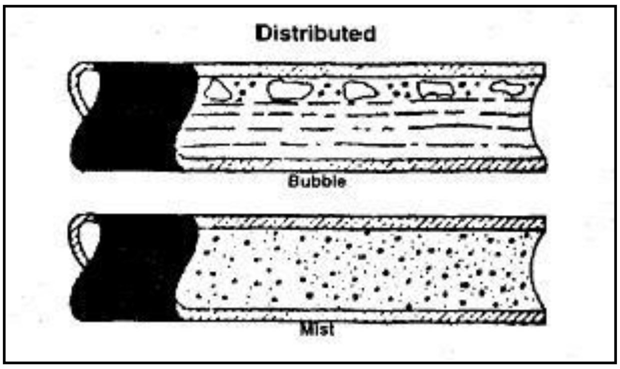


Figure 2.3: Beggs & Brill horizontal-flow patterns – Distributed.

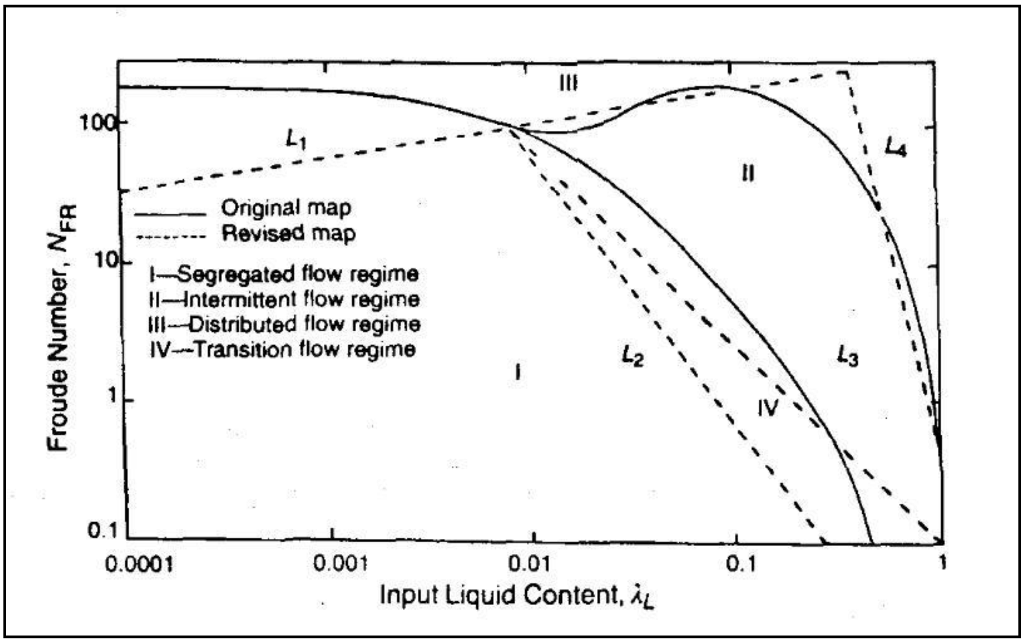


Figure 2.4: Beggs & Brill horizontal flow-pattern-map.

As the flow patterns were only considered for horizontal flow, correction has to be made when liquid holdup is predicted using Beggs & Brill method in inclined flow. From tests performed, it was found out that liquid holdup was maximum at about +50° and minimum at about -50° from horizontal. Besides that, liquid holdup was found out to be independent of the inclination angle at high flow rate, which is called the dispersed-bubble flow. Figure 2.5 shows the effect of inclination angle on liquid holdup.

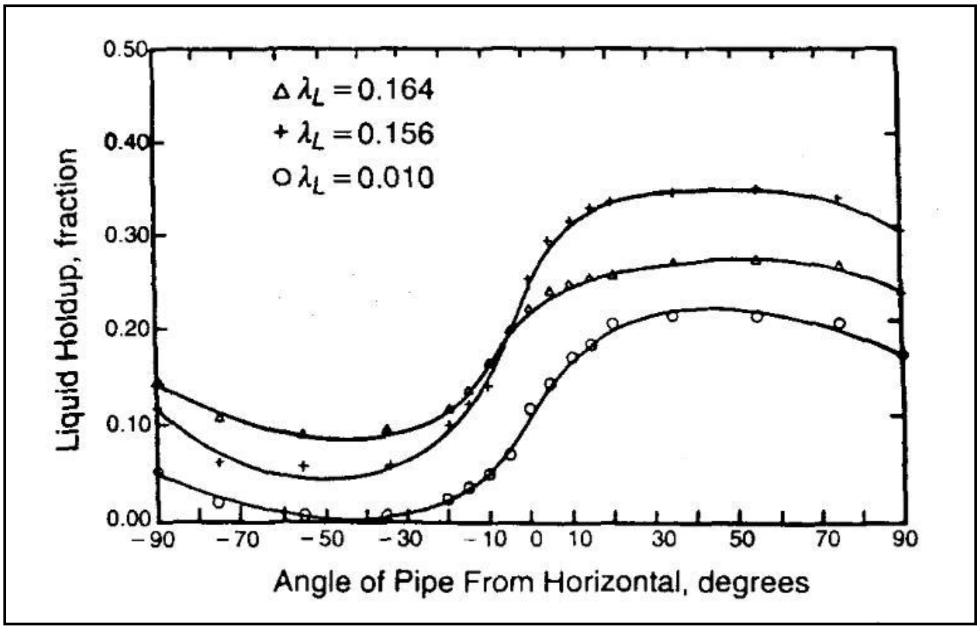


Figure 2.5: Effect of inclination angle on liquid holdup.

Although Beggs & Brill method is very practicable in predicting the pressure-gradient in vertical and inclined multiphase flows, Payne *et al.* through their experiment found out that the method underpredicted friction factors and overpredicted liquid holdup in both uphill and downhill flow. Therefore, they recommended that the normalizing friction factor, f_n be obtained from the Moody diagram for an appropriate value of relative roughness. In addition to that, they suggested few constant correction factors to improve the liquid holdup values.

In the work by Guo *et al.* (2003), they developed a closed form hydraulics equation based on experiments on multiphase flow in an inclined well model. Then, they compared the equation with two commercial software packages (S1 and S2) using measured bottomhole pressure from another well. S2 is a simulator built with multiple correlations for two-phase flow, including Beggs & Brill methods (standard, no-slip and modified), Hagedorn and Brown methods (standard and modified), modified Dun and Ros, Dukler-Easton-Flanigan, Francher and Brown, and Gray methods. The comparison was done using measurement from a borehole with 6.13" diameter and 2,600ft deep. 3.5" drill pipe string was used and the ambient temperature was 80°F with geothermal gradient of 0.015°F/ft. During the measurement taking, there are no cuttings in the hole and water/polymer was injected at rate of 80gpm while nitrogen as the gas phase was injected at 350 scfm. A flowing bottomhole pressure of 800 psig was measured against choke pressure of 100 psig.

Comparing with the measured bottomhole pressure, the model developed by Guo *et al*. gave a pressure of 831 psig which is 3.79% higher and Simulator S1 gave a result of 766 psig which is 4.25% lower. In Simulator S2, Dukler-Eaton-Flanigan gave the nearest result which is 704 psig or 13.59% lower while Francher and Brown gave the most inaccurate result of 47.10% lower. Standard Beggs & Brill method produced the most accurate result of -17.52% as compared to modified Beggs & Brill (-38.87%) and Beggs & Brill without slip consideration (-46.24%). These results showed that the considerations of slip and flow pattern in the correlations are very important. Fancher and Brown method which has no slip and no flow pattern consideration gave the most inaccurate result. On top of that, the standard Beggs & Brill correlation was proven to be better than modified Beggs & Brill correlation in predicting the pressure gradient.

In addition to that, Ettehadi (2010) in his work entitled *Determination of Cutting Transport Properties of Gasified Drilling Fluids* found out that the original Beggs & Brill method cannot predict the pressure loss and liquid hold up in the annuli accurately. Beggs & Brill (1973) and Lockhart & Martinelli (1949) liquid holdup methods were used to determine liquid holdup in the annuli and the results were compared with identified liquid holdup during experiments performed. It was discovered that there is considerable difference between estimated liquid holdup by

Beggs & Brill (1973) model and observed liquid holdup. This is because Beggs & Brill (1973) model was developed for two-phase flow through pipes and not for flow through annuli.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

TOPIC SELECTION
Problem and objectives identifications

LITERATURE SURVEY
Preliminary research about the topic and methods of ECDs calculations

IDENTIFICATION OF ECDs CALCULATIONS METHODS
Choose a most suitable method and understand it.

PROJECT WORK
Firstly, a set of results obtained from air-water two-phase flow experiment was chosen as base data for comparison. Then, an excel macro was developed to calculate ECDs using the chosen method and at the same time, perform simulation using WELLPLAN software.

RESULTS ANALYSIS
Analyze the results obtained from excel macro and simulation and make comparison with experimental data.

CONCLUSIONS AND RECOMMENDATIONS
Make conclusions based on the project's findings and suggests future work for expansion and continuation.

Figure 3.1: Flow Chart of the Project.

In doing this project, different methods to calculate pressure-gradient in two-phase flow had been studied. Good prediction of fluid pressure loss in the annuli is essential to acquire accurate values of ECDs. Beggs and Brill method in predicting the pressure-gradient was chosen and using this method, an excel macro to calculate ECDs in underbalanced drilling was developed. Meanwhile, a set of results from air-water two-phase flow experiment was chosen as base data for comparison. Using the same parameters as in the experiment, calculations and simulations were carried out using the excel macro and Landmark WELLPLAN respectively to obtain the pressure-gradient and equivalent circulating densities.

3.1.1 Experiment Setup

The pressure loss values of two-phase flow in annuli were obtained from experiments carried out with the Middle East Technical University Petroleum and Natural Gas Engineering Department Cutting Transport Facility (METU-PETE-CT). The facility which consists of pumps, compressor, control valves, flow meters, pressure transducers, annular test section, separator and storage tanks, high speed camera and data acquisition system was modified to include gas-liquid two-phase flow. The 21 ft. long annular test section is built-up of 2.91 inch I.D. transparent acrylic casing with 1.85 inch O.D. inner drill pipe. It can be inclined at any angle from 90° (horizontal) to 10° (near vertical). In the experiments, water was first pumped at a constant flow rate into the annular test section using a centrifugal pump of 250 gpm flow capacity. The flow rate was measured and controlled using a magnetic flowmeter and a pneumatic controller respectively. Then, air was introduced with the desired rate using a compressor of 120 scfm. The rate was also measured and controlled by a mass flowmeter and a pneumatic flow controller respectively. Once both the air and water flow rates were stabilized, data such as flow rates, pressure at critical points and pressure drop inside the test section were collected. Pressure drop was measured using digital pressure transducer. At the same time, flow in the test section was recorded using high-speed camera for analysis of flow patterns and identification of gas and liquid volume fractions in dynamic conditions.

Table 3.1: Test Matrix for Gas-Liquid Two Phase Flow Tests

	Minimum	Maximum
Average Water Annular Velocity (ft/s)	1	10
Average Gas Annular Velocity (ft/s)	1	120
Average Annular Pressure (Psig)	1	13
Temperature (°C)	25	35
Eccentricity Ratio	0.623	0.623

3.1.1 Developing Excel Macro Using Beggs & Brill Method for Frictional Pressure Loss

An excel macro was developed for ECDs calculations in this project. In order to obtain the ECDs of drilling fluid in underbalanced drilling, determination of the fluid hydrostatic pressure and frictional pressure loss is very important. Beggs & Brill method is used in calculating the complex frictional pressure loss of this multiphase flow. Below are the few important steps required to obtain the pressure-gradient and then, the ECD:

Step 1: Determination of flow pattern.

- Calculate Froude number, N_{Fr}:

$$N_{Fr} = \frac{V_m^2}{gd} \qquad (3.1)$$

V_m = mixture velocity (ft/sec)

g = gravitational acceleration (32.174 ft/sec^2)

d = hydraulic diameter of annuli (ft)

- Calculate no-slip liquid holdup, λ_L:

$$\lambda_L = \frac{V_{SL}}{V_{SL} + V_{SG}} \text{.....................................} \quad (3.2)$$

V_{SL} = liquid superficial velocity (ft/sec)

V_{SG} = gas superficial velocity (ft/sec)

- Determine modified flow-pattern transition boundaries:

$$L_1 = 316\lambda_L^{0.302} \text{.................................} \quad (3.3)$$

$$L_2 = 0.000925\lambda_L^{-2.468} \text{...........................} \quad (3.4)$$

$$L_3 = 0.10\lambda_L^{-1.452} \text{...} \quad (3.5)$$

and

$$L_4 = 0.5\lambda_L^{-6.738} \text{..................................} \quad (3.6)$$

- From the N_{Fr}, λ_L and flow pattern boundaries, determine the flow pattern according to the following inequalities:

Segregated.

$\lambda_L < 0.01$ and $N_{FR} < L_1$

or

$\lambda_L \geq 0.01$ and $N_{FR} < L_2$

Transition.

$\lambda_L \geq 0.01$ and $L_2 \leq N_{FR} \leq L_3$

Intermittent.

$0.01 \leq \lambda_L < 0.4$ and $L_3 < N_{FR} \leq L_1$

or

$\lambda_L \geq 0.4$ and $L_3 < N_{FR} \leq L_4$

Distributed.

$\lambda_L < 0.4$ and $N_{FR} \geq L_1$

or

$\lambda_L \geq 0.4$ and $N_{FR} > L_4$

Step 2: Determination of liquid holdup.

- Calculate liquid holdup $H_{L(0)}$, assuming flow is horizontal:

$$H_{L(0)} = \frac{a\lambda_L^b}{N_{Fr}^c} \quad (3.7)$$

a, *b* and *c* are obtained from the Table 2, depending on flow pattern.

Table 3.2: Beggs & Brill Empirical Coefficients for Horizontal Liquid Holdup.

Flow Pattern	*a*	*b*	*c*
Segregated	0.980	0.4846	0.0868
Intermittent	0.845	0.5351	0.0173
Distributed	1.065	0.5824	0.0609

For the effect of inclination, the liquid holdup is corrected with the following formula:

$$H_{L(\theta)} = H_{L(0)} \quad (3.8)$$

whereas the factor to correct liquid holdup for the effect of inclination is given by:

$$\Psi = 1.0 + C\left[sin\left(1.8\theta - 0.333sin^3(1.8\theta)\right)\right] \quad (3.9)$$

where θ is the actual angle of the flow from horizontal and C is defined by:

$$C = (1.0 - \lambda_L)ln\left(e\lambda_L^f N_{Lv}^g N_{Fr}^h\right) \quad (3.10)$$

with the restriction that $C \geq 0$. *e, f, g* and *h* are obtained from Table 3, for the appropriate horizontal flow pattern.

Table 3.3: Beggs & Brill Empirical Coefficient for C.

Flow Pattern	e	f	g	h
Segregated uphill	0.011	-3.7680	3.5390	-1.6140
Intermittent uphill	2.960	0.3050	-0.4473	0.0978
Distributed uphill	No correction: C = 0; ψ = 1			
All patterns downhill	4.700	-0.3692	0.1244	-0.5056

- When the flow pattern falls in the transition region, the liquid holdup must be interpolated between the segregated and intermittent liquid holdup values using following formula:

$$H_{L(\theta)_{Tr}} = AH_{L(\theta)_{Seg}} + (1-A)H_{L(\theta)_{Ins}} \quad (3.11)$$

where

$$A = \frac{L_3 - N_{Fr}}{L_3 - L_2} \quad (3.12)$$

Step 3: Determination of friction factor.

- Calculate mixture density with the below equation:

$$\rho_n = \rho_L \lambda_L + \rho_G (1-\lambda_L) \quad (3.13)$$

ρ_n = mixture density (lb/ft^3)

ρ_L = liquid density (lb/ft^3)

ρ_G = gas density (lb/ft^3)

- Calculate the two-phase viscosity with the below equation:

$$\mu_n = \mu_L \lambda_L + \mu_G (1 - \lambda_L) \text{......................} \quad (3.14)$$

μ_n = two-phase viscosity (cp)

μ_L = liquid viscosity (cp)

μ_G = gas viscosity (cp)

- Calculate Reynold's number, N_{Re}:

$$N_{Re} = \frac{\rho_n v_m d}{\mu_n} \text{.....................................} \quad (3.15)$$

- Calculate normalizing friction factor, f_n:

$$f_n = \frac{1}{\left[2 \log\left(\frac{N_{Re}}{4.52231 \log(N_{Re}) - 3.8215}\right)\right]^2} \text{...............} \quad (3.16)$$

- Calculate the friction factor with the below equation:

$$f/f_n = e^s \text{..} \quad (3.17)$$

where

$$s = \frac{\ln y}{-0.0523 + 3.182 \ln y - 0.8725 (\ln y)^2 + 0.01853 (\ln y)^4}$$

$$\text{...} \quad (3.18)$$

and

$$y = \frac{\lambda_L}{\left[H_{L(\theta)}\right]^2} \text{.......................................} \quad (3.19)$$

Step 4: Determine frictional pressure loss gradient (Newtonian Model).

- Newtonian model's frictional pressure loss gradient calculation is given by the following equation:

$$\rho_f = \frac{\frac{f_f \rho_n \bar{v}_m{}^2}{2\,g\,d}}{144} \quad \text{.. (3.20)}$$

where

ρ_f = frictional pressure loss (psi/ft)

f_f = friction factor obtained from Step 3

ρ_n = mixture density (lbs/ft^3)

$\bar{v}_m$ = mixture velocity (ft/sec)

Step 5: Estimation of Equivalent Circulating Densities (ECDs).

- ECDs are estimated by using the following equation:

$$\text{ECD} = \rho_n + \frac{\rho_f}{0.052\ x\ D} \quad \text{.. (3.21)}$$

where

ρ_n = mixture density (lbs/gal)

ρ_f = frictional pressure loss gradient (psi/ft)

D = true depth (ft)

3.1.2 Predictions of ECDs Using Landmark WELLPLAN.

Among all the Landmark software, WELLPLAN is the one that is used for operation modelling and optimizations. In total, there are seven modules in this software, namely Torque Drag, Hydraulics, Surge Swab, Well Control, Critical Speed, Bottomhole Assembly and Stuck Pipe Analysis. For meeting the goals of this project, the Hydraulics Analysis module in the WELLPLAN software is used.

Prior to carrying out simulation to obtain ECDs in WELLPLAN, three well trajectories were designed using the COMPASS software (also one of the Landmark software). These three wells have different maximum inclination from vertical of 90°, 45° and 12.5° respectively. The purpose of having three different wells was to study the effect of inclination towards the predictions of ECDs. In addition to that, another case study well trajectory was designed, with combination of these three inclinations to predict the ECDs throughout the whole well.

After the well trajectories were designed, operation modelling was carried using Hydraulic Analysis module of WELLPLAN. All the parameters required to acquire prediction of ECDs were input on by one and they are shown in the following figures:

Step 1: Creating a new case.

A new case is created for the well that was earlier designed using COMPASS.

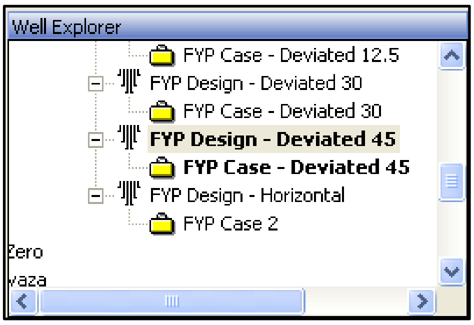
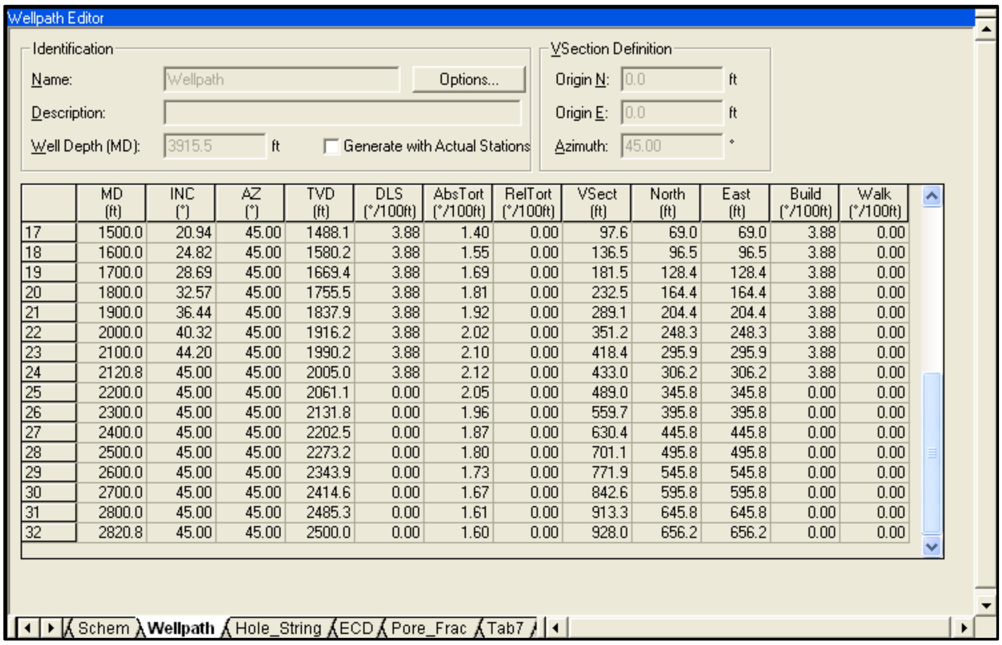


Figure 3.2: Well Explorer in WELLPLAN.

__Step 2: Review Wellpath__

Wellpath of the selected well was reviewed.


Wellpath Editor

Identification — Name: Wellpath — Options... — Description: — Well Depth (MD): 3915.5 ft — Generate with Actual Stations

VSection Definition — Origin N: 0.0 ft — Origin E: 0.0 ft — Azimuth: 45.00 °

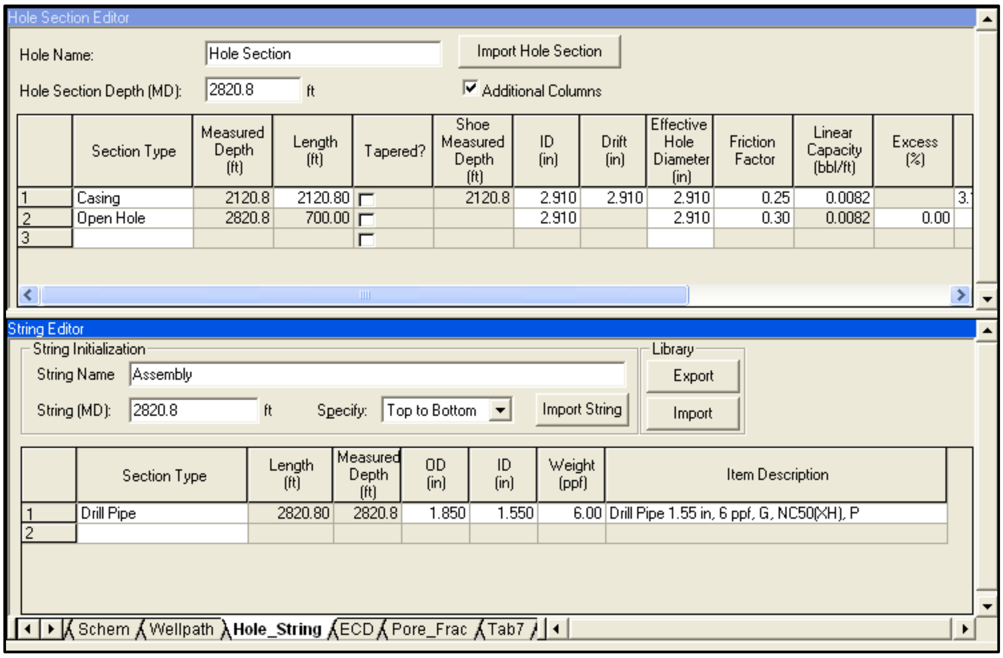
	MD (ft)	INC (°)	AZ (°)	TVD (ft)	DLS (°/100ft)	AbsTort (°/100ft)	RelTort (°/100ft)	VSect (ft)	North (ft)	East (ft)	Build (°/100ft)	Walk (°/100ft)
17	1500.0	20.94	45.00	1488.1	3.88	1.40	0.00	97.6	69.0	69.0	3.88	0.00
18	1600.0	24.82	45.00	1580.2	3.88	1.55	0.00	136.5	96.5	96.5	3.88	0.00
19	1700.0	28.69	45.00	1669.4	3.88	1.69	0.00	181.5	128.4	128.4	3.88	0.00
20	1800.0	32.57	45.00	1755.5	3.88	1.81	0.00	232.5	164.4	164.4	3.88	0.00
21	1900.0	36.44	45.00	1837.9	3.88	1.92	0.00	289.1	204.4	204.4	3.88	0.00
22	2000.0	40.32	45.00	1916.2	3.88	2.02	0.00	351.2	248.3	248.3	3.88	0.00
23	2100.0	44.20	45.00	1990.2	3.88	2.10	0.00	418.4	295.9	295.9	3.88	0.00
24	2120.8	45.00	45.00	2005.0	3.88	2.12	0.00	433.0	306.2	306.2	3.88	0.00
25	2200.0	45.00	45.00	2061.1	0.00	2.05	0.00	489.0	345.8	345.8	0.00	0.00
26	2300.0	45.00	45.00	2131.8	0.00	1.96	0.00	559.7	395.8	395.8	0.00	0.00
27	2400.0	45.00	45.00	2202.5	0.00	1.87	0.00	630.4	445.8	445.8	0.00	0.00
28	2500.0	45.00	45.00	2273.2	0.00	1.80	0.00	701.1	495.8	495.8	0.00	0.00
29	2600.0	45.00	45.00	2343.9	0.00	1.73	0.00	771.9	545.8	545.8	0.00	0.00
30	2700.0	45.00	45.00	2414.6	0.00	1.67	0.00	842.6	595.8	595.8	0.00	0.00
31	2800.0	45.00	45.00	2485.3	0.00	1.61	0.00	913.3	645.8	645.8	0.00	0.00
32	2820.8	45.00	45.00	2500.0	0.00	1.60	0.00	928.0	656.2	656.2	0.00	0.00

Schem — Wellpath — Hole_String — ECD — Pore_Frac — Tab7

Figure 3.3: Wellpath Editor in WELLPLAN.

__Step 3: Set hole and drillstring configuration.__

Hole and drillstring configuration were set to be the same as it is in the experimental setup. Hole inner diameter was 2.91" with the drillstring outer diameter of 1.85" and inner diameter of 1.55".


Hole Section Editor

Hole Name: Hole Section — Import Hole Section

Hole Section Depth (MD): 2820.8 ft — Additional Columns

	Section Type	Measured Depth (ft)	Length (ft)	Tapered?	Shoe Measured Depth (ft)	ID (in)	Drift (in)	Effective Hole Diameter (in)	Friction Factor	Linear Capacity (bbl/ft)	Excess (%)
1	Casing	2120.8	2120.80		2120.8	2.910	2.910	2.910	0.25	0.0082	
2	Open Hole	2820.8	700.00			2.910		2.910	0.30	0.0082	0.00
3											

String Editor

String Initialization — String Name: Assembly — String (MD): 2820.8 ft — Specify: Top to Bottom — Import String

Library — Export — Import

	Section Type	Length (ft)	Measured Depth (ft)	OD (in)	ID (in)	Weight (ppf)	Item Description
1	Drill Pipe	2820.80	2820.8	1.850	1.550	6.00	Drill Pipe 1.55 in, 6 ppf, G, NC50(XH), P
2							

Schem — Wellpath — Hole_String — ECD — Pore_Frac — Tab7

Figure 3.4: Hole Section Editor and String Editor in WELLPLAN.

Step 4: Key in pore pressure and fracture pressure.

A set of formation pore and fracture pressure were entered. Both sets of the pressure actually do not affect the values of resulting ECDs.

Pore Pressure

	Vertical Depth (ft)	Pore Pressure (psi)	EMW (ppg)
1	350.0	111.69	6.14
2	1476.0	629.50	8.21
3	1804.0	782.51	8.35
4	1969.0	860.22	8.41
5	2297.0	1013.07	8.49
6	2820.8	1289.51	8.80
7			
8			

Fracture Gradient

	Vertical Depth (ft)	Fracture Pressure (psi)	EMW (ppg)
1	350.0	163.64	9.00
2	1476.0	861.83	11.24
3	1804.0	1068.34	11.40
4	1969.0	1182.42	11.56
5	2297.0	1419.96	11.90
6	2820.8	1800.92	12.29
7			

Schem / Wellpath / Hole_String / ECD / Pore_Frac / Tab7

Figure 3.5: Pore Pressure and Fracture Gradient Editor in WELLPLAN.

Step 5: Adjust the density and flow rate of fluid.

Density and flow rate of fluid were varied according to records from the experimental data to study the resulting ECDs at different flow rate. As WELLPLAN limits its user to only one liquid input, the mixture densities of air-water at different velocities were used.

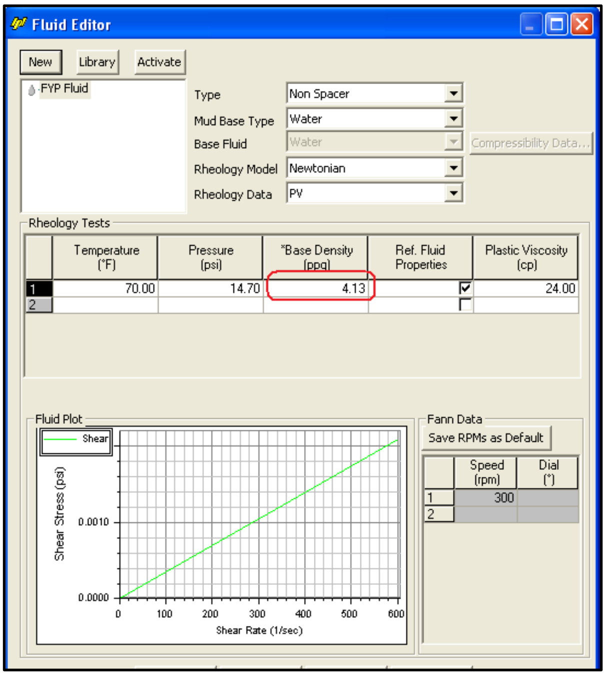


Figure 3.6: Fluid Editor in WELLPLAN.

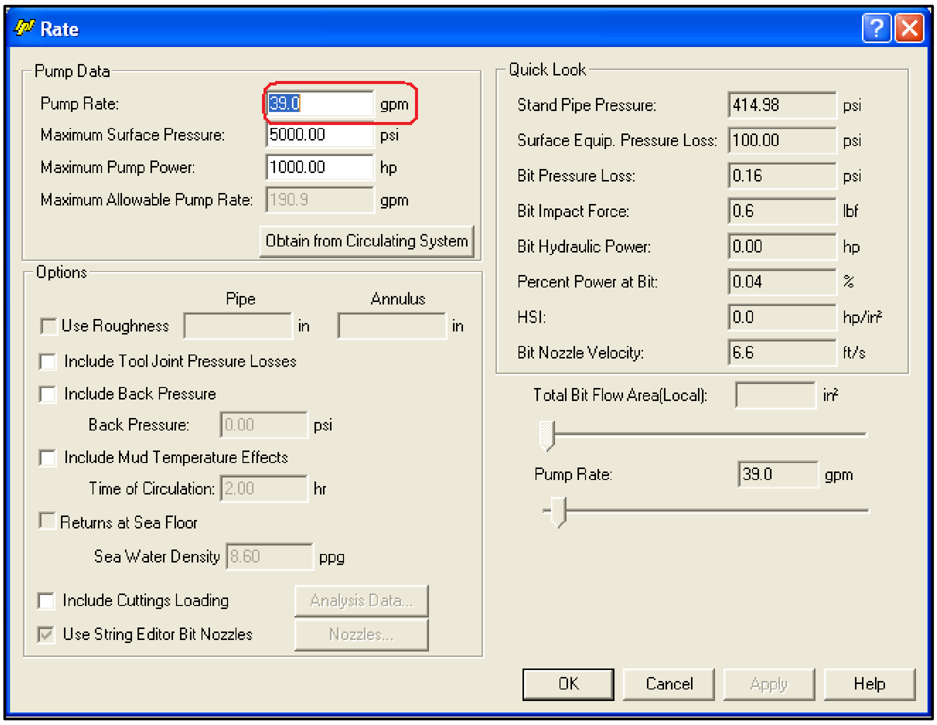


Figure 3.7: Rate Editor in WELLPLAN.

Step 6: Record ECDs predicted.

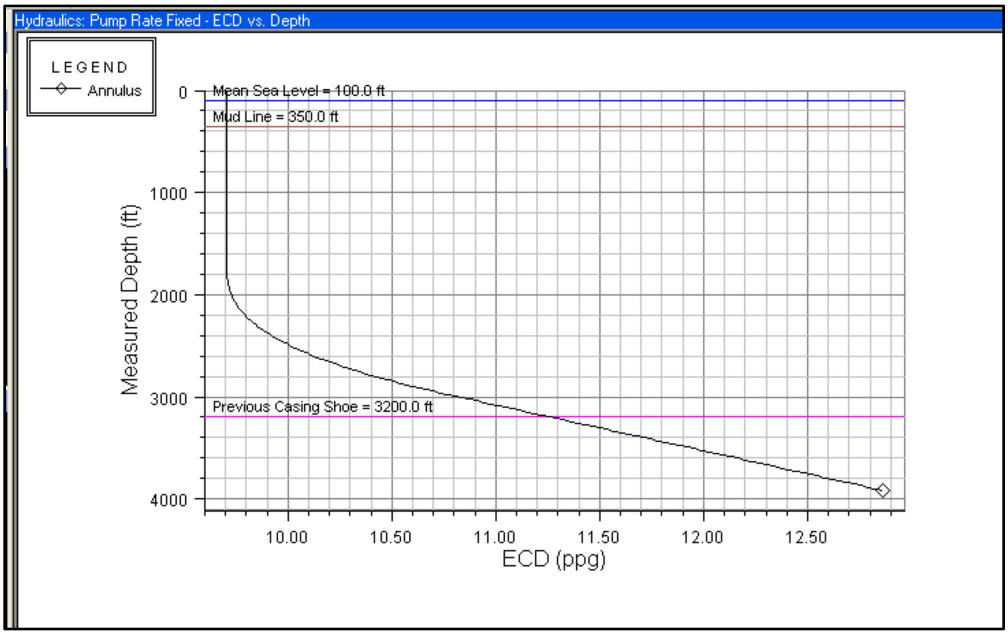


Figure 3.8: ECD vs Depth Chart in WELLPLAN.

Hydraulics: Pump Rate Fixed - ECD vs. Depth

	Annulus		Pore		Frac	
	ECD(ppg)	Measured Depth(ft)	ECD(ppg)	Measured Depth(ft)	ECD(ppg)	Measured Depth(ft)
1	5.43	0.0	6.14	350.0	9.00	350.0
2	5.43	11.3	6.22	359.9	9.08	359.9
3	5.43	22.6	6.29	369.8	9.16	369.8
4	5.43	33.8	6.36	379.8	9.23	379.8
5	5.43	45.1	6.42	389.7	9.30	389.7
6	5.43	56.4	6.48	399.6	9.36	399.6
7	5.43	67.7	6.54	409.5	9.43	409.5
8	5.43	79.0	6.59	419.5	9.49	419.5
9	5.43	90.3	6.64	429.4	9.54	429.4
10	5.43	101.5	6.69	439.3	9.60	439.3
11	5.43	112.8	6.74	449.2	9.65	449.2
12	5.43	124.1	6.79	459.2	9.70	459.2
13	5.43	135.4	6.83	469.1	9.75	469.1
14	5.43	146.7	6.87	479.0	9.79	479.0
15	5.43	158.0	6.91	488.9	9.83	488.9
16	5.43	169.2	6.95	498.8	9.88	498.8
17	5.43	180.5	6.99	508.8	9.92	508.8
18	5.43	191.8	7.02	518.7	9.95	518.7
19	5.43	203.1	7.06	528.6	9.99	528.6
20	5.43	214.4	7.09	538.5	10.03	538.5
21	5.43	225.7	7.12	548.5	10.06	548.5
22	5.43	236.9	7.15	558.4	10.10	558.4
23	5.43	248.2	7.18	568.3	10.13	568.3
24	5.43	259.5	7.21	578.2	10.16	578.2
25	5.43	270.8	7.24	588.1	10.19	588.1
26	5.43	282.1	7.27	598.1	10.22	598.1
27	5.43	293.4	7.29	608.0	10.25	608.0

Work Schem Wellpath Hole_String ECD Pore_Frac

Figure 3.9: ECD vs Depth Grid in WELLPLAN.

From the ECDs grid, frictional pressure loss can be calculated by comparing two ECDs at different point in the annulus.

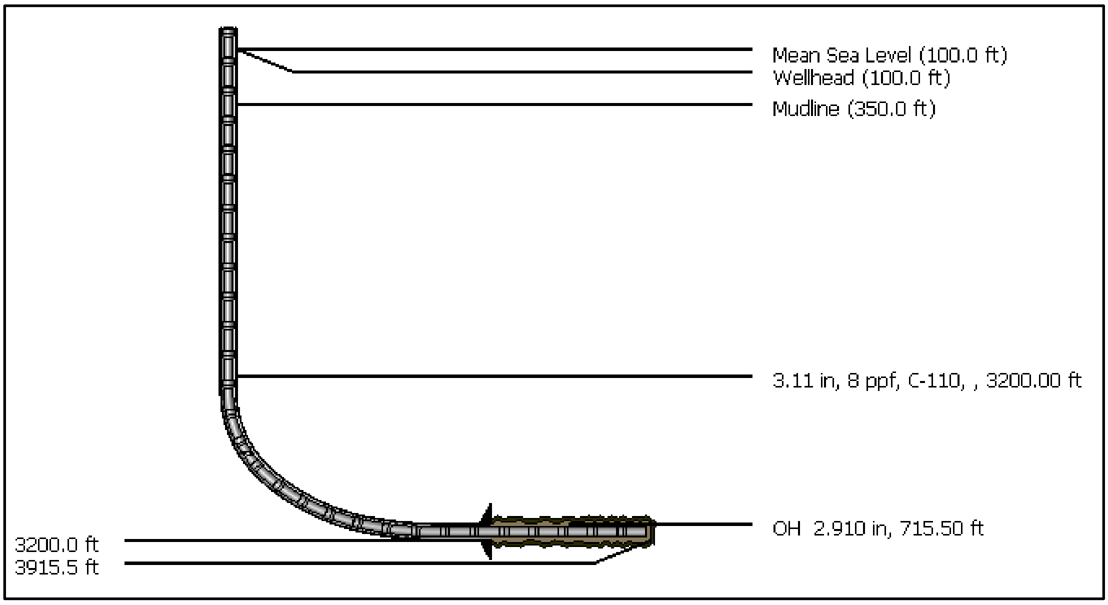


Figure 3.10: Well Schematic of Horizontal Well Used for Simulation in WELLPLAN.

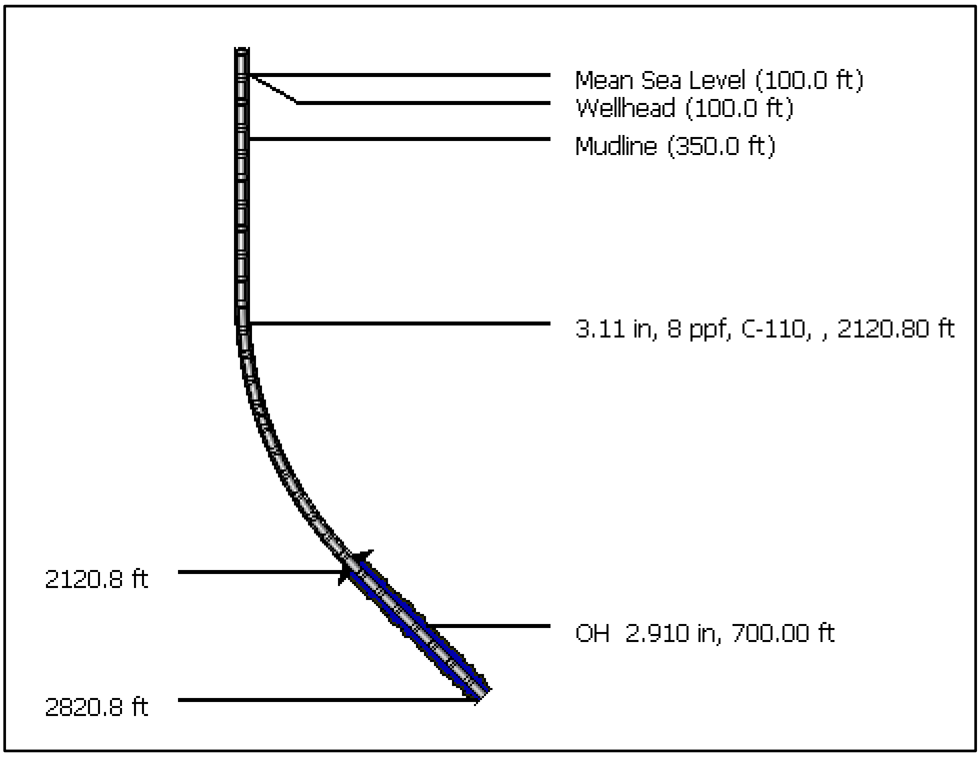


Figure 3.11: Well Schematic of Inclined 45° Well Used for Simulation in WELLPLAN.

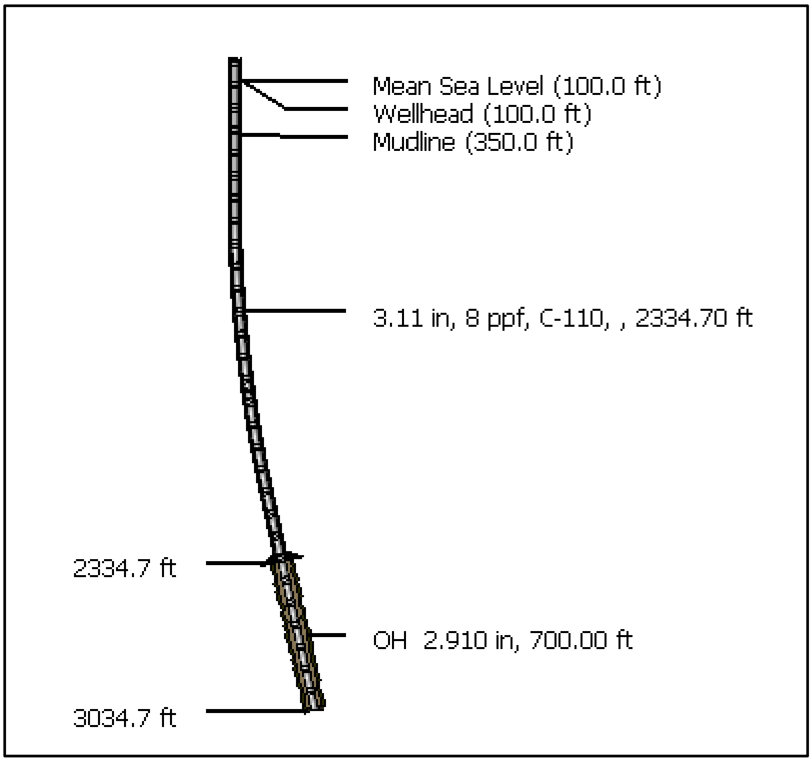


Figure 3.12: Well Schematic of Near Vertical Well (Inclined 45°) Used for Simulation in WELLPLAN.

3.2 Project Activities

- Research on the role of ECDs in underbalanced drilling.
- Research on theory and definition of ECDs.
- Research on different types of calculations method for frictional pressure loss in two-phase flow.
- Identify most suitable calculation method to be used in this project and develop an excel macro based on it.
- Familiarization with Landmark WELLPLAN software.
- Perform ECDs calculations using the excel macro.
- Perform simulation using Landmark WELLPLAN to obtain the ECDs of the specified drilling fluid.
- Compare and analyze results obtained from the excel macro and modelling in Landmark WELLPLAN with the experimental results.
- Make conclusions on the findings and also make appropriate recommendations.

3.2 Key Milestone

1) Completion of problems identification and preliminary research work.
2) Completion of detailed research work and development of methodology.
3) Completion of excel macro.
4) Completion of simulation using WELLPLAN.
5) Completion of results analysis and final report.

3.3 Gantt Chart

Final Year Project 1

NO.	DETAIL/WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic								MID SEMESTER BREAK							
2	**Preliminary Research Work**															
3	Submission of Extended Proposal Defence															
4	Proposal Defence															
5	**Detailed Research Work and Development of Methodology for Problem Solving**															
6	Submission of Interim Draft Report															
7	Submission of Interim Report															

Figure 3.13: Project Gantt Chart for FYP 1.

Final Year Project 2

NO.	DETAIL/WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	**Developing excel macro and calculations of ECDs using the developed excel macro**								MID SEMESTER BREAK								
2	**Operation modelling using WELLPLAN**																
3	Submission of Progress Report Defence																
4	**Comparison and analysis of results**																
5	Pre-EDX																
6	Submission of Draft Report																
7	Submission of Dissertation (Soft Bound)																
8	Submission of Technical Paper																
9	Oral Presentation																
10	Submission of Dissertation (Hard Bound)																

Figure 3.14: Project Gantt Chart for FYP 2.

3.4 Tools

Two main softwares are required in this project:

- *WELLPLAN of Halliburton Landmark.*
  This software will be used for drilling operation modelling to obtain the drilling fluid ECDs.

- *Microsoft Office 2007*
  Microsoft Office Word 2007 – To be used in preparing reports.
  Microsoft Office Excel 2007 – To be used in developing excel macro for calculations as well as to plot graphs.
  Microsoft Office Power Point 2007 – To be used to prepare presentation slides.

CHAPTER 4

RESULTS AND DISCUSSIONS

In this chapter, the results and findings of the project will be discussed. The project's main aim is to determine the best method of calculating equivalent circulating densities (ECDs) of two-phase flow in underbalanced drilling. As discussed earlier, accurate frictional pressure loss calculations of two-phase flow is the key to good prediction of ECDs in aerated mud drilling.

Study carried out in this project showed that there were limited researches on multiphase-flow in annuli. Instead, the work and findings on multiphase-flow in pipe are more established. Generally, there are three main category of methods to predict pressure-gradient in multiphase flows in pipe, with the first one not considering slip and flow pattern, second one considers slip but not flow pattern and third one considers both slip and flow pattern. Beggs and Brill method under the third category has been chosen to be used in this project as it consider both the slip and flow pattern, and at the same time can be used for multiphase flow in inclined wells. In fact, it is one of the only two methods available that can be used in inclined wells. By choosing this method, first objective of this project was achieved.

Next, the second objective of the project was met. An excel macro was developed to calculate ECDs in underbalanced drilling. Beggs and Brill method was used to calculate the frictional pressure loss part in the ECDs calculations.

Lastly, the results of frictional pressure loss and ECDs obtained from the excel macro and Landmark WELLPLAN were compared with experimental results to determine the accuracy of each method. Comparisons were carried out separately according to the well inclinations.

4.1 Frictional Pressure Loss and Equivalent Circulating Densities in Horizontal Well Section.

In terms of frictional pressure loss, all three set of values obtained from experiment observation, excel macro calculations and WELLPLAN modelling show increasing trend with mixture flow rate (Figure 4.1). As mixture flow rate is higher, the frictional pressure loss experienced is more.

Figure 4.2 shows the comparisons of calculated and WELLPLAN frictional pressure loss against observed frictional pressure loss. The calculated results match the observed results, with less than 5% deviation but the results obtained from WELLPLAN were deviated in around -40%.

Figure 4.3 shows the comparisons of calculated and WELLPLAN ECDs against observed ECDs. The excel macro calculated ECDs have mean error of 0.0261 ppg as compared to the observed ECDs and the standard deviation is 0.2058 ppg. However, the ECDs as modelled by WELLPLAN were more than -20% deviated from the observed values. WELLPLAN ECDs mean error is -1.1848 ppg while its standard deviation is 1.0768 ppg.

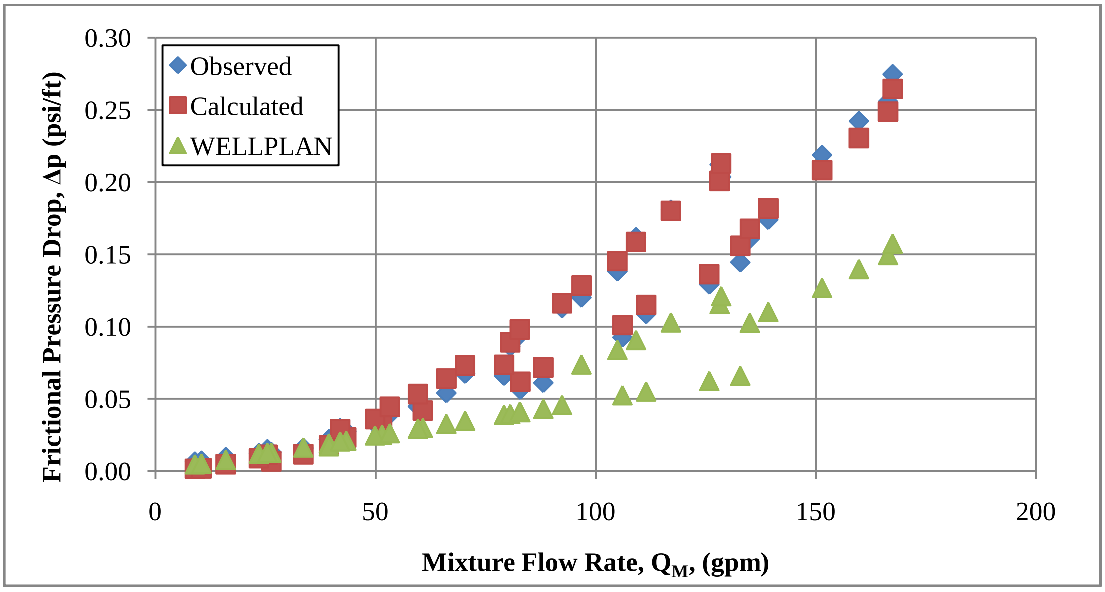


Figure 4.1 Comparisons of Observed, Calculated and WELLPLAN Frictional Pressure Loss against Mixture Flow Rate in Horizontal Well.

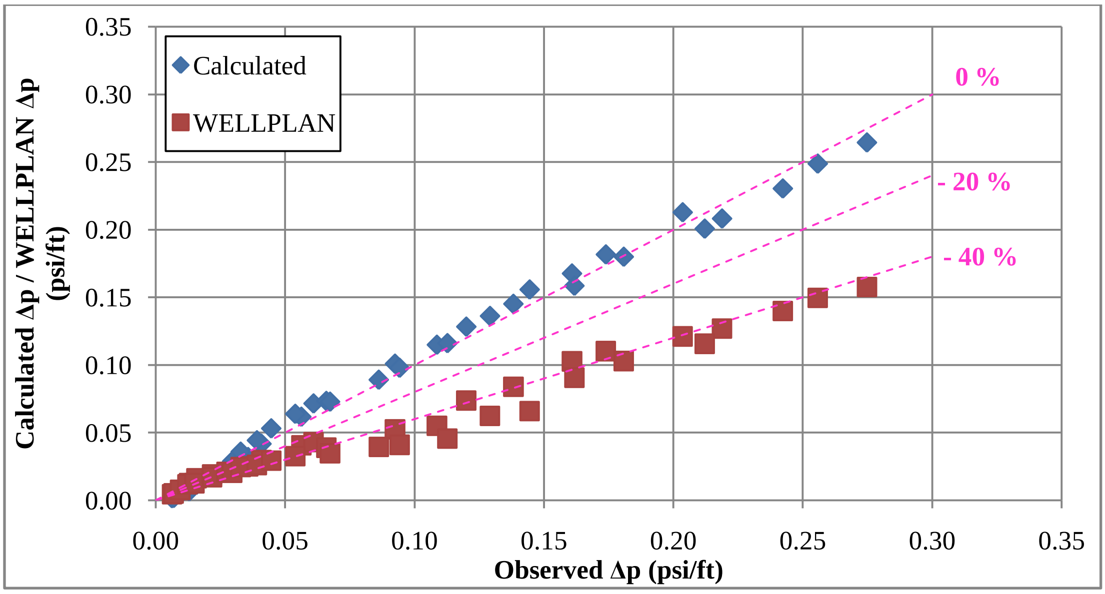


Figure 4.2 Comparisons of Calculated and WELLPLAN Frictional Pressure Loss against Observed Frictional Pressure Loss in Horizontal Well.

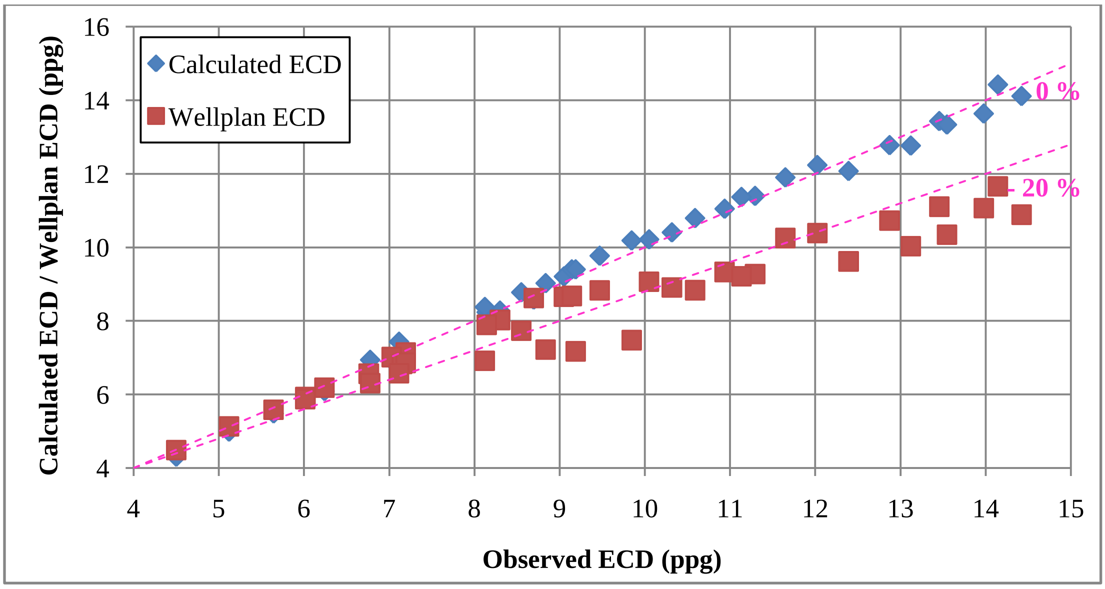


Figure 4.3 Comparisons of Calculated and WELLPLAN ECDs against Observed ECDs in Horizontal Well.

4.2 Frictional Pressure Loss and Equivalent Circulating Densities in Inclined 45° Well Section

Figure 4.4 shows all three set of values of frictional pressure loss obtained from experiment observation excel macro calculations and WELLPLAN modelling, as plotted against mixture flow rates. As mixture flow rates increase, the frictional pressure losses experienced are higher. Both observed and WELLPLAN increment can be seen to be in same trend of different magnitude but the calculated frictional pressure loss increases a little exponentially with increment in mixture flow rates.

Figure 4.5 shows the comparisons of calculated and WELLPLAN frictional pressure loss against observed frictional pressure loss. The calculated pressure losses are lower than the observed pressure losses and at the same time, WELLPLAN pressure losses are the lowest.

Figure 4.6 shows the comparisons of calculated and WELLPLAN ECDs against observed ECDs. The excel macro calculated ECDs have mean error of -1.5581 ppg as compared to the observed ECDs and the standard deviation is 0.9359 ppg. As the frictional pressure losses in WELLPLAN are much lesser, its ECDs mean error is -3.8348 ppg while its standard deviation is 0.7221 ppg.

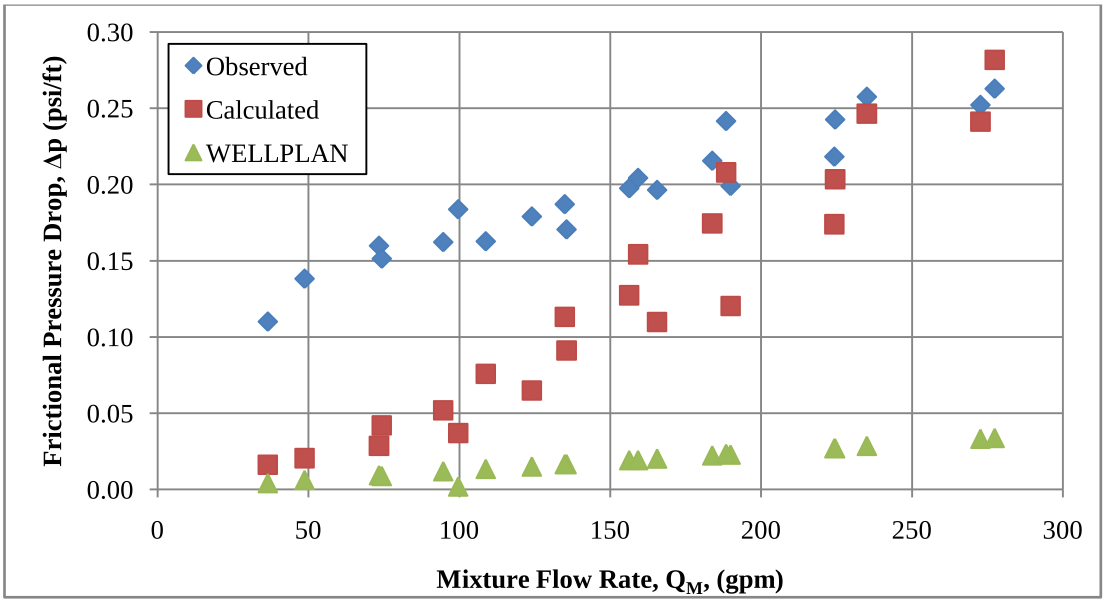


Figure 4.4 Comparisons of Observed, Calculated and WELLPLAN Frictional Pressure Loss against Mixture Flow Rate in Inclined 45° Well.

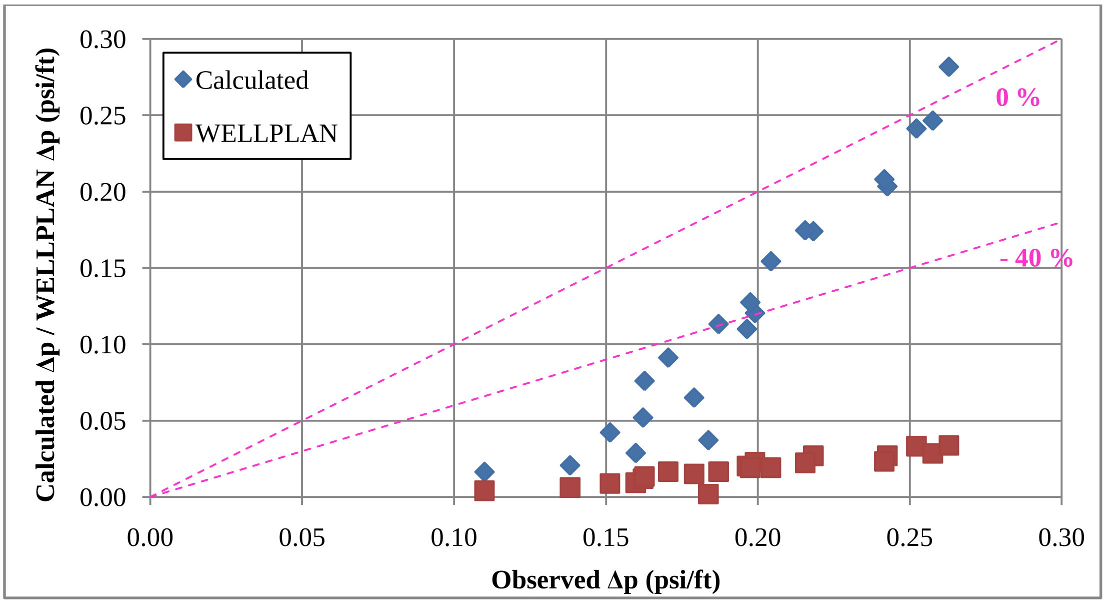


Figure 4.5 Comparisons of Calculated and WELLPLAN Frictional Pressure Loss against Observed Frictional Pressure Loss in Inclined 45° Well.

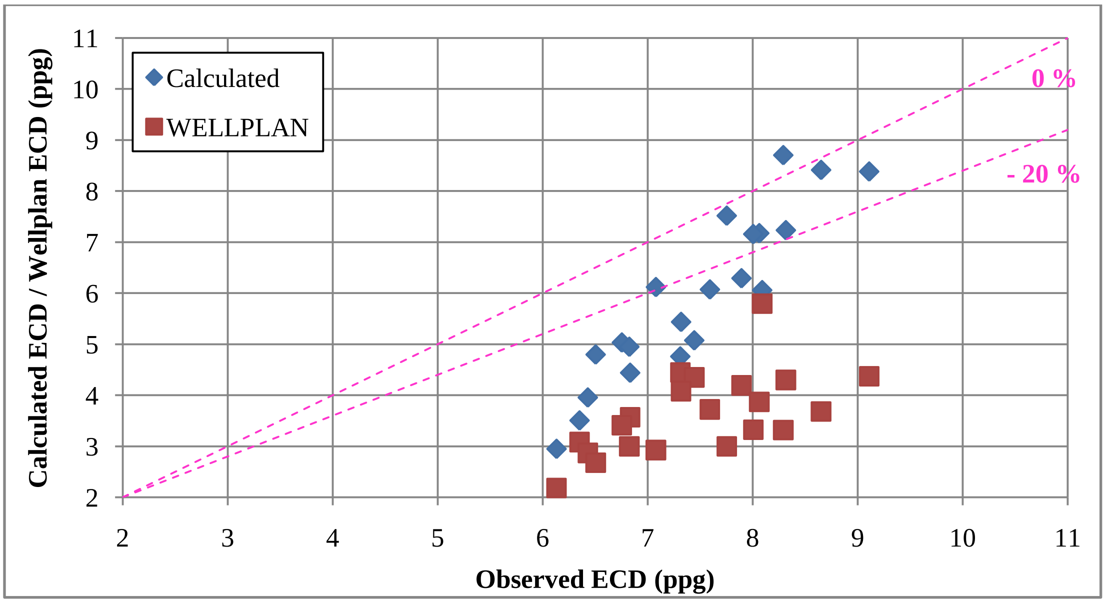


Figure 4.6 Comparisons of Calculated and WELLPLAN ECDs against Observed ECDs in Inclined 45° Well.

4.3 Frictional Pressure Loss and Equivalent Circulating Densities in Inclined Near Vertical Well Section (Inclined 12.5°)

In terms of frictional pressure loss, only values obtained from experiment observation and excel macro calculations show increasing trend with mixture flow rate (Figure 4.7). As mixture flow rate is higher, the frictional pressure loss experienced is more. However, the frictional pressure losses modelled by WELLPLAN is very small and do not show any significant trend.

Figure 4.8 shows the comparisons of calculated and WELLPLAN frictional pressure loss against observed frictional pressure loss. The calculated pressure losses are lower than the observed pressure losses and at the same time, WELLPLAN pressure losses are the lowest.

Figure 4.9 shows the comparisons of calculated and WELLPLAN ECDs against observed ECDs. The excel macro calculated ECDs have mean error of -2.0731 ppg as compared to the observed ECDs and the standard deviation is 0.5042 ppg. As the frictional pressure losses in WELLPLAN are much lesser, its ECDs mean error is -4.2578 ppg while its standard deviation is 0.8633 ppg.

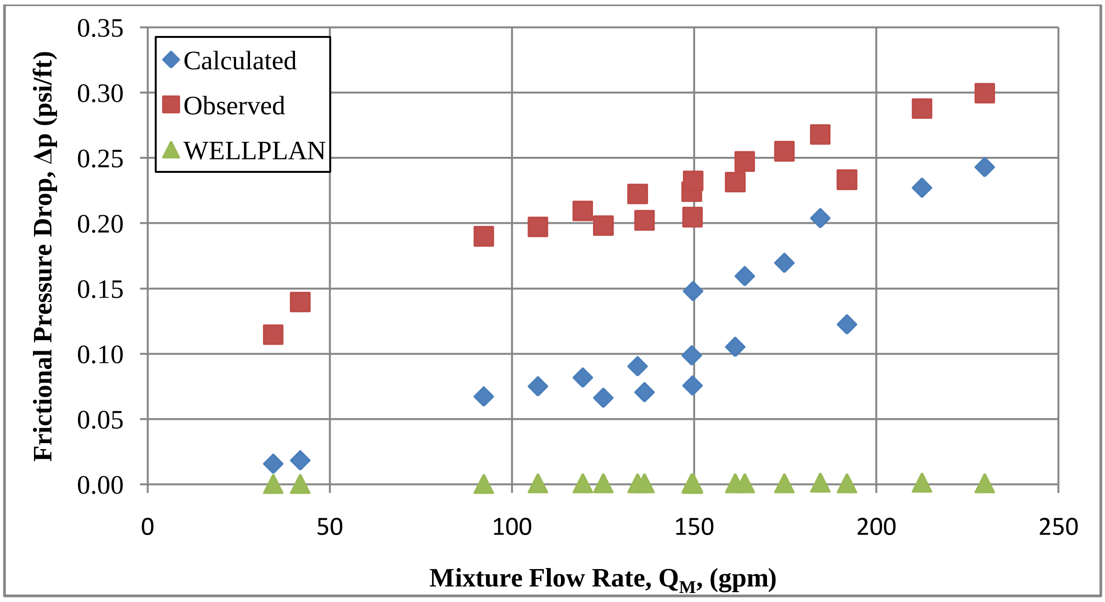


Figure 4.7 Comparisons of Observed, Calculated and WELLPLAN Frictional Pressure Loss against Mixture Flow Rate in Near Vertical Well (Inclined 12.5°).

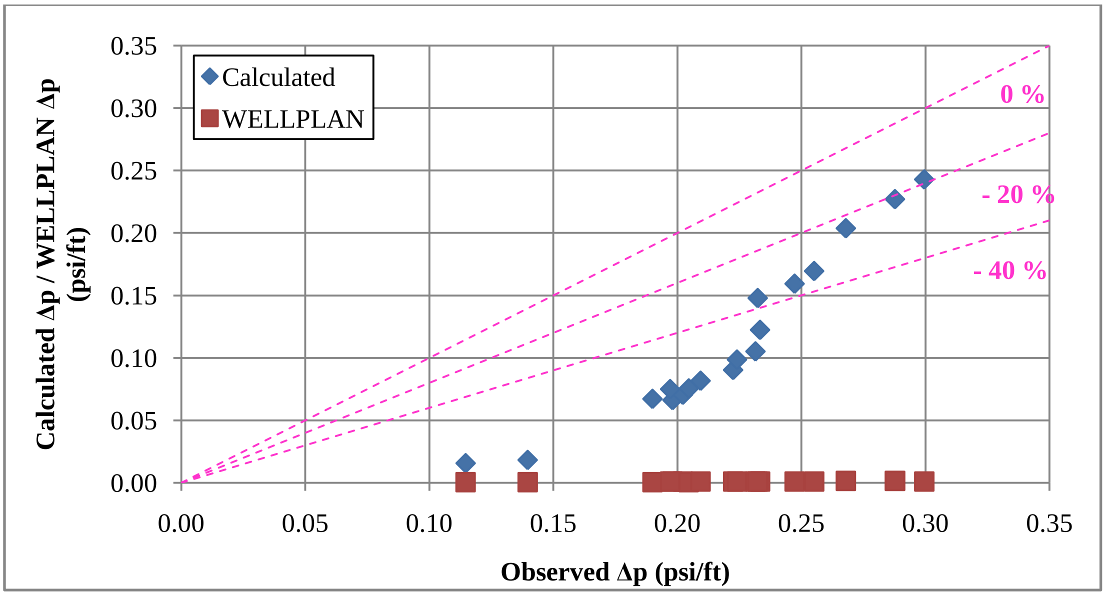


Figure 4.8 Comparisons of Calculated and WELLPLAN Frictional Pressure Loss against Observed Frictional Pressure Loss in Near Vertical Well (Inclined 12.5°).

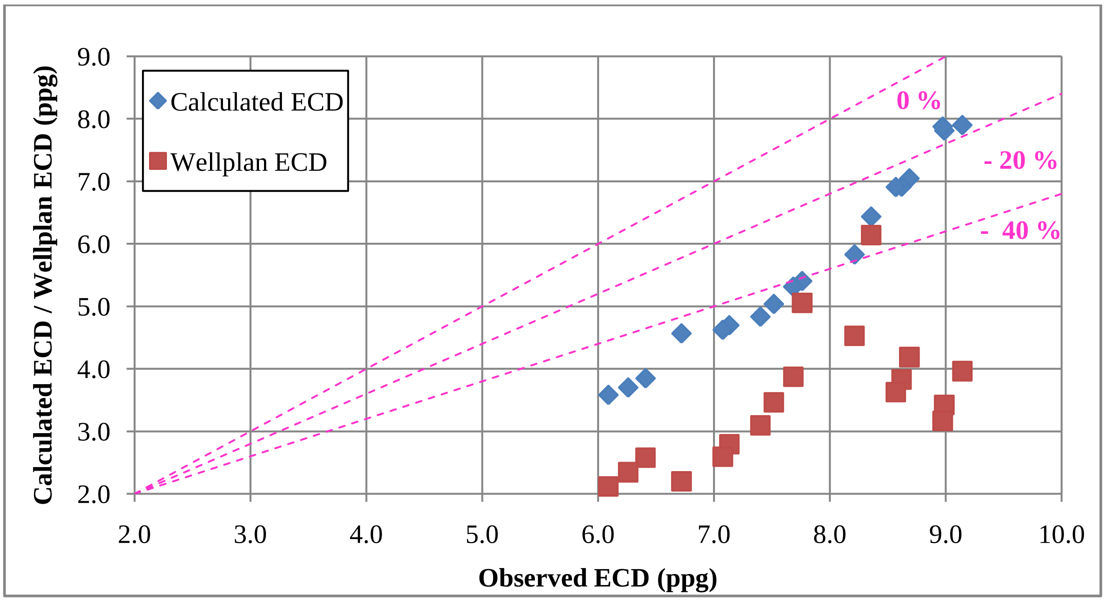


Figure 4.9 Comparisons of Calculated and WELLPLAN ECDs against Observed ECDs in Near Vertical Well (Inclined 12.5°).

4.4 Frictional Pressure Loss and Equivalent Circulating Densities in Case Study Well (Combination of Near Vertical, Inclined 45° and Horizontal Section)

Table 4.1 shows the average absolute errors and standard deviation of the calculated and WELLPLAN simulated ECDs values as compared to experiment observed values. Calculated ECDs using the excel macro developed gave the lowest average absolute error in all three well sections and lowest standard deviation in horizontal and near vertical sections. However, in inclined 45° section, the standard deviation of ECDs obtained from WELLPLAN is smaller than the calculated one.

Comparisons between the three sections prove that the results obtained for horizontal section are most accurate, followed by inclined 45° section and the near vertical section. The developed excel macro can be used in horizontal well section with very small absolute error and standard deviation.

Table 4.1 ECDs Error Statistics.

Horizontal Section		
Method	**Average Absolute Error (ppg)**	**Standard Deviation (ppg)**
Excel Macro Calculations	0.0261	0.2058
WELLPLAN	-1.1848	1.0768
Inclined 45° Section		
Method	**Average Absolute Error (ppg)**	**Standard Deviation (ppg)**
Excel Macro Calculations	-1.5581	0.9359
WELLPLAN	-3.8348	0.7221
Near Vertical Section (Inclined 12.5°)		
Method	**Average Absolute Error (ppg)**	**Standard Deviation (ppg)**
Excel Macro Calculations	-2.0731	0.5042
WELLPLAN	-4.2578	0.8633

Figure 4.10 shows the ECDs in case study well from experimental results, calculations and WELLPLAN. Calculated ECD is less than the observed ECD and WELLPLAN ECD recorded the least value among the three.

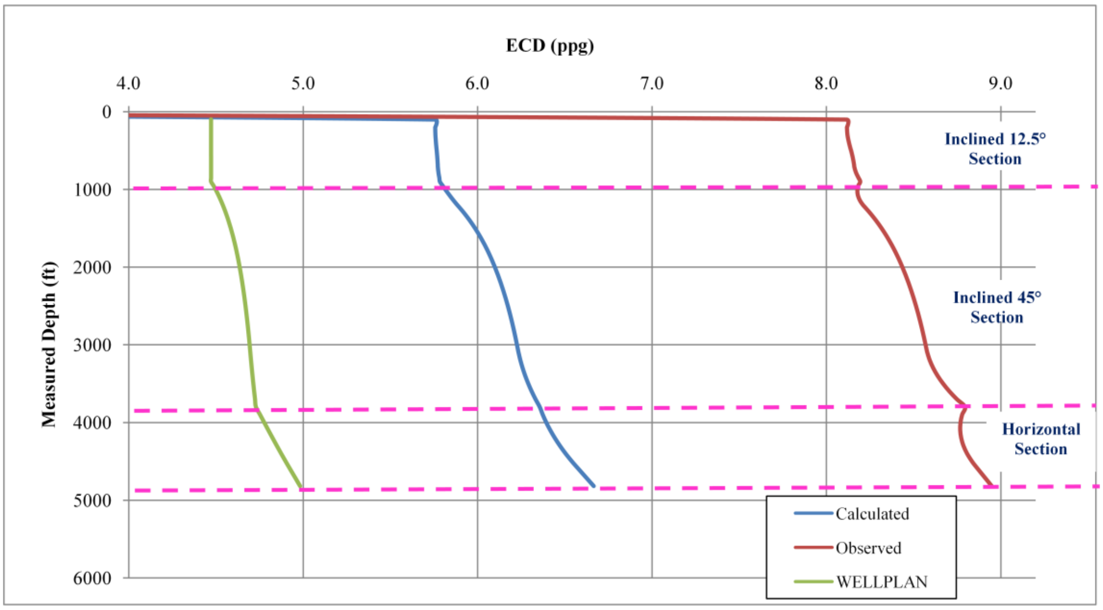


Figure 4.10 Comparisons of Calculated and WELLPLAN ECDs against Observed ECDs in Case Study Well (Combination of Near Vertical, Inclined 45° and Horizontal Section).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The project's main aim is to make comparison between calculations method and WELLPLAN modelling with experiment observations in predicting ECDs of aerated mud in underbalanced drilling. Study have been carried out and the literature findings showed that Beggs and Brill method is most suitable to be used to calculate frictional pressure loss of two-phase flow, hence, to predict the ECDs of aerated mud. The excel macro developed using the Beggs and Brill method was proved to be able to calculate the ECDs of aerated mud in underbalanced drilling.

Comparisons of the ECDs values between excel macro, WELLPLAN and experiment observation showed that WELLPLAN has underestimated ECDs in all three well sections (horizontal, inclined 45° and inclined 12.5°). This is most likely caused by the fact that WELLPLAN only allows its user to use single fluid input. In order to simulate the density in two-phase flow, the mixture density was used during the operation modelling, assuming both the phases are homogeneous with each other. However, this assumption has ignored slippage and flow pattern effects of the two-phase flow. Two-phase flow such as air-water is not homogeneous in reality and they do travel at different velocity due to the differences in fluid properties, notably, the densities. Therefore, slippage effect and different flow patterns were created. With slippage effect and higher liquid holdup, the frictional pressure loss is definitely higher, hence, resulting in higher ECDs.

In addition to that, it was also noted that Beggs and Brill method is only accurate in predicting ECDs in horizontal well section. In inclined well sections, the method also underestimated the ECDs as compared to experimental observation, but better than WELLPLAN results. This might be due to the fact that Beggs and Brill method was originally developed to predict pressure loss in pipe. It might not be as accurate when used to predict pressure loss in annuli. Furthermore, this method was initially developed using observation of liquid holdup in horizontal section. Correlations were made in later stage for multiphase flow in inclined sections. The correlations made for multiphase flow in pipe might not be suitable for flow in annuli.

In conclusions, the objectives of the project were met. The results of this study proved that Landmark WELLPLAN is not able to predict equivalent circulating densities in underbalanced drilling accurately. The ECDs predicted are lower than the observed ECDs. This difference should be considered by the software users when using it to simulate underbalanced drilling operation using aerated mud.

5.2 Recommendations

Based on the study and results, the following recommendations were made:

- Landmark WELLPLAN software should be enhanced to allow multi-fluid input in the hydraulics module. In doing this, the slippage, flow pattern and inclination effects on the multiphase-flow should be considered.
- The Beggs and Brill method correlations should be modified for multiphase-flow in annuli. The current correlations are not suitable for predicting pressure-gradient in annuli.
- Further comparisons can be done using field data instead of experimental results. The scale of annuli in experiment are not the same as the real borehole, thus, might not be the most suitable to be used as database for comparisons.
- Comparisons done in this project is based on Newtonian fluid model. Further work shall include rheological parameters of non-Newtonian fluid.

REFERENCES

Abdollahi, J., Carlsen, M., Mjaaland, S., Skalle, P., Fafiei, A. & Zarei, S. (2004). Underbalanced Drilling as a Tool for Optimized Drilling and Completion Contingency in Fractured Carbonate Reservoirs. SPE/IADC Paper 91579 presented at SPE/IADC Underbalanced Technology Conference and Exhibition, Houston, Texas.

Alajmi, S.E. & Schubert, J.J. (2003). SPE/IADC Paper 85322 presented at SPE/IADC Middle East Drilling Technology Conference and Exhibition, Abu Dhabi, United Arab Emirates.

Babajan, S. & Qutob, H. (2010). Underbalanced Drilling Technology adds Reserves and Enhances Ultimate Recovery. SPE Paper 136117 presented at the SPE Production and Operations Conference and Exhibition held in Tunis, Tunisia.

Brill, J.P. & Mukherjee, H. (1999). *Multiphase Flow in Wells* (pp. 28-48). Texas: Society of Petroleum Engineers.

Charles, R., & Tian, S. (2008). Sometimes Neglected Hydraulic Parameters of Underbalanced and Managed Pressure Drilling. SPE/IADC Paper 114667 presented at Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition, Abu Dhabi, UAE.

Eck-Olsen, J., & Vollen, E. (2004). Challenges in Implementing UBO Technology. SPE/IADC paper presented at SPE/IADC Underbalanced Technology Conference and Exhibition, Houston, Texas, U.S.A.

Ettehadi, R.O. (2010). *Determination of Cutting Transport Properties of Gasified Drilling Fluids*. (Doctor of Philosophy Dissertation, Middle East Technical University, 2010).

Guo, B., & Ghalambor, A. (2002). *Gas Volume Requirements for Underbalanced Drilling* (pp. 1-18). Oklahama. PennWell Corporation.

Guo, B., Sun, K., Ghalambor, A. (2003). SPE Paper 81070 presented at SPE Latin America & Caribbean Petroleum Engineering Conference.

Harris, O.O. & Osisanya, S.O. (2005). SPE Paper 97018 presented at SPE Annual Technical Conference and Exhibition, Dallas, Texas, U.S.A.

Luo, S. et. al. (2000). A New Drilling Fluid for Formation Damage Control Used in Underbalanced Drilling. SPE Paper 59261 presented at the IADC/SPE Drilling Conference held in New Orleans, Lousiana.

Rehm, B., Schubert, J., Haghshenas, A., Paknejad, A.S., Hughes, J. (2008). *Managed Pressure Drilling*. Houston, Texas. Gulf Publishing Company.

Vieira, P., Larroque, F., Al-Saleh, A.M., Ismael, H., Qutob, H.H. & Chopty, J.R. (2007). Kuwait Employs Underbalanced Drilling Technology to Improve Drilling Performance While Simultaneously Evaluating the Reservoir. SPE Paper 106672 presented at Offshore Europe 2007 held in Aberdeen, Scotland, U.K.

WELLPLAN™ Software, Release 5000.1 Training Manual (2010). Huoston, Texas. Halliburton Landmark.

APPENDICES

DEVELOPED MACRO EXCEL

Appendix 1 Developed Excel Macro to Calculated Frictional Pressure Loss and Equivalent Circulating Densities in Horizontal Well Section.

```
Sub BeggsBrill()

Application.ScreenUpdating = False
Sheets("Beggs & Brill").Select

For i = 1 To 40

'Landa
   Cells(16 + i, 7).Value = Cells(16 + i, 1).Value / (Cells(16 + i, 1).Value + Cells(16
+ i, 2).Value)

'Mixture Density
   Cells(16 + i, 8).Value = (Cells(4, 2).Value * Cells(16 + i, 7).Value) + (Cells(5,
2).Value * (1 - Cells(16 + i, 7).Value))

'Mixture Velocity
   Cells(16 + i, 9).Value = Cells(16 + i, 1).Value + Cells(16 + i, 2).Value

'Mixture Flow Rate
   Cells(16 + i, 10).Value = Cells(16 + i, 9).Value * (2.448 * ((Cells(9, 2).Value ^ 2)
- (Cells(8, 2).Value ^ 2)))

'Mixture Viscosity
   Cells(16 + i, 11).Value = (Cells(6, 2).Value * Cells(16 + i, 7).Value) + (Cells(7,
2).Value * (1 - Cells(16 + i, 7).Value))
```

```
'Froude Number
    Cells(16 + i, 12).Value = (Cells(16 + i, 9).Value ^ 2) / ((Cells(10, 2).Value / 12) * Cells(12, 2).Value)

'L1
    Cells(16 + i, 13).Value = 316 * Cells(16 + i, 7).Value ^ 0.302

'L2
    Cells(16 + i, 14).Value = 0.000925 * Cells(16 + i, 7).Value ^ -2.469

'L3
    Cells(16 + i, 15).Value = 0.1 * Cells(16 + i, 7).Value ^ -1.452

'L4
    Cells(16 + i, 16).Value = 0.5 * Cells(16 + i, 7).Value ^ -6.738

'Reynold's Number
    Cells(16 + i, 17).Value = (1488 * Cells(16 + i, 8).Value * Cells(16 + i, 9).Value * (Cells(10, 2).Value) / 12) / Cells(16 + i, 11).Value

'Flow Pattern
    If Cells(16 + i, 7).Value < 0.01 And Cells(16 + i, 12).Value < Cells(16 + i, 13) Then
        Cells(16 + i, 3).Value = "Segregated"

    ElseIf Cells(16 + i, 7).Value >= 0.01 And Cells(16 + i, 12).Value < Cells(16 + i, 14) Then
        Cells(16 + i, 3).Value = "Segregated"

    ElseIf Cells(16 + i, 7).Value >= 0.01 And Cells(16 + i, 14) <= Cells(16 + i, 12).Value And Cells(16 + i, 12).Value <= Cells(16 + i, 15) Then
        Cells(16 + i, 3).Value = "Transition"
```

```
    ElseIf Cells(16 + i, 7).Value >= 0.01 And Cells(16 + i, 7).Value < 0.4 And Cells(16 + i, 15) < Cells(16 + i, 12).Value And Cells(16 + i, 12).Value <= Cells(16 + i, 13) Then
        Cells(16 + i, 3).Value = "Intermittent"

    ElseIf Cells(16 + i, 7).Value >= 0.4 And Cells(16 + i, 15) < Cells(16 + i, 12).Value And Cells(16 + i, 12).Value <= Cells(16 + i, 16) Then
        Cells(16 + i, 3).Value = "Intermittent"

    ElseIf Cells(16 + i, 7).Value < 0.4 And Cells(16 + i, 12).Value >= Cells(16 + i, 13) Then
        Cells(16 + i, 3).Value = "Distributed"

    ElseIf Cells(16 + i, 7).Value >= 0.4 And Cells(16 + i, 12).Value > Cells(16 + i, 16) Then
        Cells(16 + i, 3).Value = "Distributed"

    Else
        Cells(16 + i, 3).Value = "Not Defined"

    End If

'A
    Cells(16 + i, 18) = (Cells(16 + i, 15) - Cells(16 + i, 12)) / (Cells(16 + i, 15) - Cells(16 + i, 14))

'Liquid Holdup
    If Cells(16 + i, 3).Value = "Segregated" Then
        Cells(16 + i, 4).Value = (0.98 * Cells(16 + i, 7).Value ^ 0.4846) / (Cells(16 + i, 12).Value ^ 0.0868)

    ElseIf Cells(16 + i, 3).Value = "Intermittent" Then
```

```
        Cells(16 + i, 4).Value = (0.845 * Cells(16 + i, 7).Value ^ 0.5351) / (Cells(16 + i, 12).Value ^ 0.0173)

    ElseIf Cells(16 + i, 3).Value = "Distributed" Then
        Cells(16 + i, 4).Value = (1.065 * Cells(16 + i, 7).Value ^ 0.5824) / (Cells(16 + i, 12).Value ^ 0.0609)

    ElseIf Cells(16 + i, 3).Value = "Transition" Then
        Cells(16 + i, 4).Value = (Cells(16 + i, 18).Value * ((0.98 * Cells(16 + i, 7).Value ^ 0.4846) / (Cells(16 + i, 12).Value ^ 0.0868))) + ((1 - Cells(16 + i, 18)) * ((0.845 * Cells(16 + i, 7).Value ^ 0.5351) / (Cells(16 + i, 12).Value ^ 0.0173)))

    Else
        Cells(16 + i, 4).Value = "Not Defined"

    End If

'y
    Cells(16 + i, 19).Value = Cells(16 + i, 7).Value / Cells(16 + i, 4).Value ^ 2

's
    Cells(16 + i, 20).Value = Log(Cells(16 + i, 19).Value) / (-0.0523 + (3.182 * Log(Cells(16 + i, 19).Value)) - (0.8725 * (Log(Cells(16 + i, 19).Value)) ^ 2) + (0.01853 * (Log(Cells(16 + i, 19).Value) ^ 4)))

'Fn
    Cells(16 + i, 21).Value = 1 / (2 * Application.WorksheetFunction.Log(Cells(16 + i, 17).Value / ((4.5223 * Application.WorksheetFunction.Log(Cells(16 + i, 17).Value)) - 3.8215))) ^ 2

'Friction Factor
    Cells(16 + i, 5).Value = (Exp(Cells(16 + i, 20).Value)) * Cells(16 + i, 21).Value
```

```
'Frictional Pressure Loss - Calculated
    Cells(16 + i, 6).Value = ((Cells(16 + i, 5).Value * Cells(16 + i, 8).Value * Cells(16 + i, 9).Value ^ 2) / (2 * Cells(12, 2).Value * (Cells(10, 2).Value / 12))) / 144

'Calculated ECD
    Cells(16 + i, 26).Value = ((Cells(16 + i, 6).Value * 3915.5) / (2500 * 0.052)) + Cells(16 + i, 23).Value

'Observed ECD
    Cells(16 + i, 27).Value = ((Cells(16 + i, 24).Value * 3915.5) / (2500 * 0.052)) + Cells(16 + i, 23).Value

'WELLPLAN ECD
    Cells(16 + i, 28).Value = ((Cells(16 + i, 25).Value * 3915.5) / (2500 * 0.052)) + Cells(16 + i, 23).Value



Next i

Application.ScreenUpdating = True

End Sub
```

Appendix 2 Developed Excel Macro to Calculated Frictional Pressure Loss and Equivalent Circulating Densities in Inclined Well Section.

```
Sub BeggsBrill()

Application.ScreenUpdating = False
Sheets("Beggs & Brill - 45").Select

For i = 1 To 21

'Landa
    Cells(16 + i, 7).Value = Cells(16 + i, 1).Value / (Cells(16 + i, 1).Value + Cells(16
+ i, 2).Value)

'Mixture Density
    Cells(16 + i, 8).Value = (Cells(4, 2).Value * Cells(16 + i, 7).Value) + (Cells(5,
2).Value * (1 - Cells(16 + i, 7).Value))

'Mixture Velocity
    Cells(16 + i, 9).Value = Cells(16 + i, 1).Value + Cells(16 + i, 2).Value

'Mixture Flow Rate
    Cells(16 + i, 10).Value = Cells(16 + i, 9).Value * (2.448 * ((Cells(9, 2).Value ^ 2)
- (Cells(8, 2).Value ^ 2)))

'Mixture Viscosity
    Cells(16 + i, 11).Value = (Cells(6, 2).Value * Cells(16 + i, 7).Value) + (Cells(7,
2).Value * (1 - Cells(16 + i, 7).Value))

'Froude Number
    Cells(16 + i, 12).Value = (Cells(16 + i, 9).Value ^ 2) / ((Cells(10, 2).Value / 12) *
Cells(12, 2).Value)
```

```
'L1
    Cells(16 + i, 13).Value = 316 * Cells(16 + i, 7).Value ^ 0.302

'L2
    Cells(16 + i, 14).Value = 0.000925 * Cells(16 + i, 7).Value ^ -2.469

'L3
    Cells(16 + i, 15).Value = 0.1 * Cells(16 + i, 7).Value ^ -1.452

'L4
    Cells(16 + i, 16).Value = 0.5 * Cells(16 + i, 7).Value ^ -6.738

'Reynold's Number
    Cells(16 + i, 17).Value = (1488 * Cells(16 + i, 8).Value * Cells(16 + i, 9).Value *
(Cells(10, 2).Value) / 12) / Cells(16 + i, 11).Value

'Flow Pattern
    If Cells(16 + i, 7).Value < 0.01 And Cells(16 + i, 12).Value < Cells(16 + i, 13)
Then
        Cells(16 + i, 3).Value = "Segregated"

    ElseIf Cells(16 + i, 7).Value >= 0.01 And Cells(16 + i, 12).Value < Cells(16 + i,
14) Then
        Cells(16 + i, 3).Value = "Segregated"

    ElseIf Cells(16 + i, 7).Value >= 0.01 And Cells(16 + i, 14) <= Cells(16 + i,
12).Value And Cells(16 + i, 12).Value <= Cells(16 + i, 15) Then
        Cells(16 + i, 3).Value = "Transition"

    ElseIf Cells(16 + i, 7).Value >= 0.01 And Cells(16 + i, 7).Value < 0.4 And
Cells(16 + i, 15) < Cells(16 + i, 12).Value And Cells(16 + i, 12).Value <= Cells(16 +
i, 13) Then
        Cells(16 + i, 3).Value = "Intermittent"
```

```
    ElseIf Cells(16 + i, 7).Value >= 0.4 And Cells(16 + i, 15) < Cells(16 + i, 12).Value And Cells(16 + i, 12).Value <= Cells(16 + i, 16) Then
        Cells(16 + i, 3).Value = "Intermittent"

    ElseIf Cells(16 + i, 7).Value < 0.4 And Cells(16 + i, 12).Value >= Cells(16 + i, 13) Then
        Cells(16 + i, 3).Value = "Distributed"

    ElseIf Cells(16 + i, 7).Value >= 0.4 And Cells(16 + i, 12).Value > Cells(16 + i, 16) Then
        Cells(16 + i, 3).Value = "Distributed"

    Else
        Cells(16 + i, 3).Value = "Not Defined"

    End If

'A
    Cells(16 + i, 18) = (Cells(16 + i, 15) - Cells(16 + i, 12)) / (Cells(16 + i, 15) - Cells(16 + i, 14))

'Liquid Holdup (0)
    If Cells(16 + i, 3).Value = "Segregated" Then
        Cells(16 + i, 22).Value = (0.98 * Cells(16 + i, 7).Value ^ 0.4846) / (Cells(16 + i, 12).Value ^ 0.0868)

    ElseIf Cells(16 + i, 3).Value = "Intermittent" Then
        Cells(16 + i, 22).Value = (0.845 * Cells(16 + i, 7).Value ^ 0.5351) / (Cells(16 + i, 12).Value ^ 0.0173)

    ElseIf Cells(16 + i, 3).Value = "Distributed" Then
```

```
        Cells(16 + i, 22).Value = (1.065 * Cells(16 + i, 7).Value ^ 0.5824) / (Cells(16 + i, 12).Value ^ 0.0609)

    ElseIf Cells(16 + i, 3).Value = "Transition" Then
        Cells(16 + i, 22).Value = (Cells(16 + i, 18).Value * ((0.98 * Cells(16 + i, 7).Value ^ 0.4846) / (Cells(16 + i, 12).Value ^ 0.0868))) + ((1 - Cells(16 + i, 18)) * ((0.845 * Cells(16 + i, 7).Value ^ 0.5351) / (Cells(16 + i, 12).Value ^ 0.0173)))

    Else
        Cells(16 + i, 22).Value = "Not Defined"

    End If

'NLV
    Cells(16 + i, 23).Value = 1.938 * Cells(16 + i, 1).Value * (Cells(4, 2).Value / Cells(11, 2).Value) ^ 0.25

'C
    If Cells(16 + i, 3).Value = "Segregated" Then
        Cells(16 + i, 24).Value = (1 - Cells(16 + i, 7).Value) * Log(0.011 * (Cells(16 + i, 7).Value ^ -3.768) * (Cells(16 + i, 23).Value ^ 3.539) * (Cells(16 + i, 12).Value ^ -1.614))

    ElseIf Cells(16 + i, 3).Value = "Intermittent" Then
        Cells(16 + i, 24).Value = (1 - Cells(16 + i, 7).Value) * Log(2.96 * (Cells(16 + i, 7).Value ^ 0.305) * (Cells(16 + i, 23).Value ^ -0.4473) * (Cells(16 + i, 12).Value ^ 0.0978))

    ElseIf Cells(16 + i, 3).Value = "Distributed" Then
        Cells(16 + i, 24).Value = 0

    ElseIf Cells(16 + i, 3).Value = "Transition" Then
```

```
        Cells(16 + i, 24).Value = (1 - Cells(16 + i, 7).Value) * Log(2.96 * (Cells(16 + i,
7).Value ^ 0.305) * (Cells(16 + i, 23).Value ^ -0.4473) * (Cells(16 + i, 12).Value ^
0.0978))

    Else
        Cells(16 + i, 24).Value = "Not Defined"

    End If

'Psi
    Cells(16 + i, 25).Value = 1 + (Cells(16 + i, 24).Value * ((Sin(1.8 * Cells(13,
2).Value)) - (0.333 * (Sin(1.8 * Cells(13, 2).Value)) ^ 3)))

'Liquid Holdup(Inclined)
    Cells(16 + i, 4).Value = Cells(16 + i, 25).Value * Cells(16 + i, 22).Value

'y
    Cells(16 + i, 19).Value = Cells(16 + i, 7).Value / Cells(16 + i, 22).Value ^ 2

's
    Cells(16 + i, 20).Value = Log(Cells(16 + i, 19).Value) / (-0.0523 + (3.182 *
Log(Cells(16 + i, 19).Value)) - (0.8725 * (Log(Cells(16 + i, 19).Value)) ^ 2) +
(0.01853 * (Log(Cells(16 + i, 19).Value) ^ 4)))

'Fn
    Cells(16 + i, 21).Value = 1 / (2 * Application.WorksheetFunction.Log(Cells(16 + i,
17).Value / ((4.5223 * Application.WorksheetFunction.Log(Cells(16 + i, 17).Value))
- 3.8215))) ^ 2

'Friction Factor
    Cells(16 + i, 5).Value = (Exp(Cells(16 + i, 20).Value)) * Cells(16 + i, 21).Value

'Mixture Density (Ps)
```

```
    Cells(16 + i, 26).Value = (Cells(4, 2).Value * Cells(16 + i, 4).Value) + (Cells(5, 2).Value * (1 - Cells(16 + i, 4).Value))

'Frictional Pressure Loss
    Cells(16 + i, 6).Value = ((Cells(16 + i, 5).Value * Cells(16 + i, 8).Value * Cells(16 + i, 9).Value ^ 2) / (2 * Cells(12, 2).Value * (Cells(10, 2).Value / 12))) / 144

'GravPressureLoss
    Cells(16 + i, 28).Value = (Cells(16 + i, 26).Value * Sin(Cells(13, 2).Value)) / 144

'Observed FricLoss
    Cells(16 + i, 30).Value = Cells(16 + i, 29).Value - Cells(16 + i, 28).Value

'Calculated ECD
    Cells(16 + i, 32).Value = ((Cells(16 + i, 6).Value * 2820.8) / (2500 * 0.052)) + Cells(16 + i, 27).Value

'Observed ECD
    Cells(16 + i, 33).Value = ((Cells(16 + i, 30).Value * 2820.8) / (2500 * 0.052)) + Cells(16 + i, 27).Value

'WELLPLAN ECD
    Cells(16 + i, 34).Value = ((Cells(16 + i, 31).Value * 2820.8) / (2500 * 0.052)) + Cells(16 + i, 27).Value

Next i

Application.ScreenUpdating = True

End Sub
```