Hole Cleaning Analysis for Underbalanced Drilling by Using Landmark

by

Chey Wan Sin

Dissertation submitted in partial fulfillment of

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

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Approved by,

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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.

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CHEY WAN SIN

ABSTRACT

The study on hole cleaning analysis for underbalanced drilling and the impact of inefficient hole cleaning during the drilling operation has been conducted. Inefficient hole cleaning is not pleasing for the drilling operation and hence optimization in hole cleaning has to be achieved in order to increase the overall gross production and saving drilling time The objective of this study to determine the optimum hydraulic parameters for the two-phase nitrogen gasified Newtonian fluids in the horizontal, inclined and near vertical wells for underbalanced drilling using three different methods, which are Beggs and Brill calculation, based on experimental setup and results simulation using Landmark. From the study, Landmark gives results on lowest pressure drop, optimum flow rate and small nozzle size compared to the Beggs and Brill and experimental data. In addition, criteria method A is considered as the most ideal criteria to be used for optimization calculation.

ACKNOWLEDGEMENT

I would like to acknowledge and extend my heartfelt gratitude to those who have made the completion of this final year project possible. First and utmost would be my supervisor, Dr. Reza Ettehadi Osgouei, who has been providing me with his vital encouragement; support, understanding, and most importantly constant guidance throughout my project. Also, I would like to extend my gratitude to Mr. Azzuma Razali and Mr. Mohd. Aimran Mohd Iqbar, my Landmark instructors for teaching me how to use Landmark and assisting me in solving problems regarding to Landmark. Also to Mr. Amin and Ms. Rajeswary, my final year project coordinator for assisting in the collection of reports, giving briefing and guidance. Not forgetting all Petroleum Engineering and Geoscience Department faculty members and Staff for the constant reminders and much needed motivation. I would like to extend my gratitude to department of Petroleum and Natural Gas Engineering, Middle East Technical University for providing sources for researches purposes.

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Abbreviations and Nomenclature

UBD	Underbalanced Drilling
ECD	Equivalent Circulating Density
HHP	Hydraulic Horsepower
MWD	Measurement While Drilling
GLR	Gas Liquid Ratio
TVD	True Vertical Depth
TFA	Total Flow Area
ROP	Rate of Penetration

CHAPTER 1

INTRODUCTION

1.1 Background Study

Over the years, the drilling technology has evolved and becoming more advanced due to the ever-increasing demand for energy, which is the oil and gas, and the increase in price as well. In the same time, the majority of hydrocarbons being exploited today are found in existing pressure depleted or complex and lower quality reservoirs have forced today's petroleum industry to rethink both its operating methods and technologies aiming at improving recovery and cost reduction (Hani, Zaki&Abdelaziz, 2011). Underbalanced drilling technology is introduced and is seen as the way to achieve cost reduction, enhancing recovery and adding reserves (Maqsood, 2008). Underbalanced drilling (UBD) is the mode of rotary drilling with the intentional reduction of the drilling fluid density, which means lower equivalent density (ECD) causing the hydrostatic pressure in a wellbore to be lower than the pore pressure with in a formation thereby permitting reservoirs fluids to be reduced while drilling (John, 2006). As for hole cleaning, it is the basic function of any drilling fluid. Cuttings generated by the bits plus any caving or sloughing must be carried out to the surface by the mud. Hole cleaning deficiency can cause accumulation of cuttings in the bottomhole and consequently impede the rate of penetration (Lim, 1996).

1.2 Problem Statement

Inadequate hole cleaning can contribute to several major drilling problems, which include: increase in torque and drag, that can limit the reach to target, mechanical pipe sticking and difficulties in casing/cementing and logging operations that can increase well cost significantly (Azar& Alfredo, 1997). Salar and Hani (2010) mentioned that with underbalanced drilling operation, the wells are being drilled in a kick condition, which in other words, there are presence of two phase gasified liquids flow.

The author has narrowed down the studies of hole cleaning analysis for underbalanced drilling operation by focusing more on drilling hydraulics. Lim (2010) stated that bit hydraulics is related to the effects of nozzle sizes, number of nozzles, the jet velocity of drilling fluid passing through the bit nozzle and the pressure loss across the bit. Optimized hydraulics will be able to reduce the overall drilling cost (Indra& Rudi, 2002).

Hence, optimization in hole cleaning has to be achieved in order to increase the overall gross production and saving drilling time. Since the focus has narrowed down to bit hydraulics, determination of the optimum hydraulic parameters for liquid and gas flow rate using different method will be carried out.

1.3 Objectives

- To determine optimum hydraulic parameter for liquid and gas flow rate obtain from different methods: Beggs and Brill, Experimental and Landmark™
- To determine the ideal criteria for optimum pressure loss and optimum mixture flow rate calculation. The criteria that will be studied include maximum hydraulic horsepower (HHP), maximum jet impact force, method A, method B and method C.
- To compare and analyze the results obtained from the three different methods.

1.4 Scope of Study

This project will be focusing more on the calculation of the optimum mixture flow rate since gasified liquids are present in underbalanced drilling operation in order to determine the optimum frictional pressure loss and optimum nozzle size using three different methods: Beggs and Brill, Experimental and Landmark. In calculation of the optimum frictional pressure loss, there are five criteria in which the author will take into account of, which are maximum hydraulic horsepower (HHP), maximum jet impact force, method A, method B and method C (Method A, B, C are being regarded as the modern methods). The types of wells that are being studied in this project are near vertical wells (which are 77.5 degree from horizontal), inclination wells (45 degree from horizontal) and horizontal wells (90 degree).

1.5 Relevancy of the Project

Underbalanced drilling is a new drilling technology, which the procedure to drill the well ensure that the pressure in the wellbore is kept lower than fluid pressure in the formation being drilled. As hole cleaning has always been a major problem during the drilling process be it in the conventional drilling method or drilling underbalanced, there is a need to ensure that hole cleaning be done effectively in order to prevent the adverse effects of it, which are: torque and drag, mechanical pipe sticking which could cause losses to the well.

Since the author a Petroleum Engineering student majoring in drilling and production operation, this project has helped the author to learn more about drilling is definitely relevant to her scope of study in the university.

1.6 Feasibility of Study

In accomplishing this project, the author had been doing researches on underbalanced drilling, beggs and brill method, hole cleaning, multiphase flow by reading relevant journals, published technical papers, SPE papers, books and also online readings. The author also spent time to be familiar with Landmark™ software developed by Halliburton in order to obtain the results using Landmark™. The project is accomplished within the time frame as the author had constructed a gantt chart with milestones to be achieved as a guideline in doing this project.

CHAPTER 2

LITERATURE REVIEW

2.1 Underbalanced Drilling

John (2010) claimed that underbalanced drilling (UBD) is the alternative drilling technology as opposed to the conventional method, which will be able to help the industry in its hunger for new horizons for the exploration and production of oil and gas. Underbalanced drilling is defined as a mode of rotary drilling that I carried out with a bottom hole wellbore pressure less than the formation fluid pressure (Salar& Hani, 2010). As opposed to conventional drilling method, underbalanced drilling is the intentional reduction of the drilling fluid density, which means lower equivalent circulating density (ECD) causing the hydrostatic pressure in a wellbore to be lower than the pore pressure within a formation thereby permitting reservoir fluids to be produced while drilling (Johan, Vollen&Tonnesen, 2004).Figure 1 and figure 2 below show the difference between conventional and underbalanced drilling:

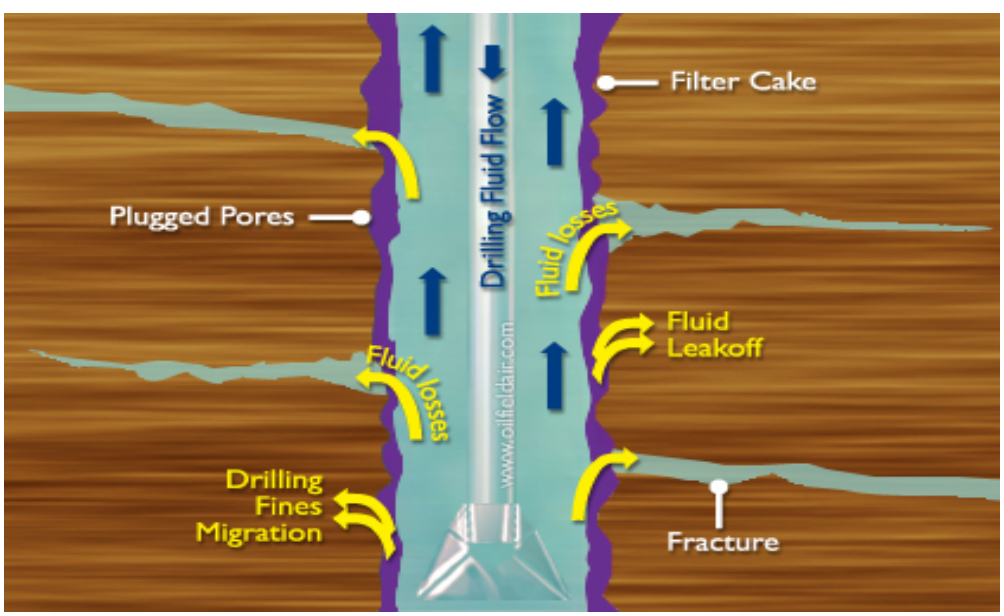


Figure 1: Conventional Drilling (Rigzone, 2011)

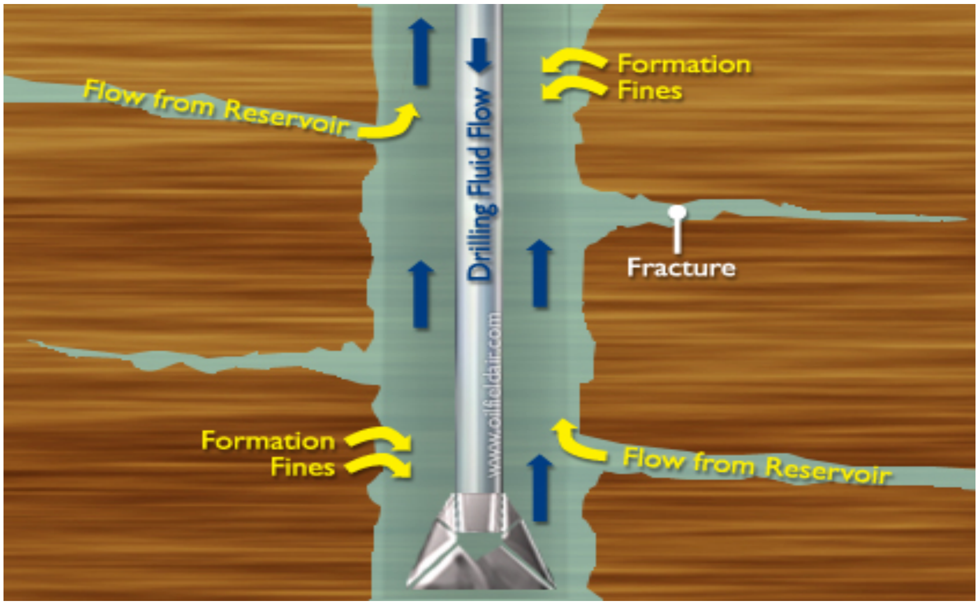


Figure 2: Underbalanced Drilling (Rigzone, 2011)

As the well is being drilled, formation fluid flows into the wellbore and up to the surface. This is the opposite of the usual situation, where the wellbore is kept at a pressure above the formation to prevent formation fluid entering the well. Johan, Vollen and Tonnesen (2004) stated that in such a conventional overbalanced well, the invasion of the fluid is considered a kick, and if the well is not shut-in, it can lead to a blowout which is a very dangerous situation and not pleasing to the oil and gas industry. In underbalanced drilling, there is a rotating head at the surface; essentially a seal that diverts produced fluids to a separator while allowing the drill string to continue rotating (Brant, 2012).

During underbalanced drilling operation, lightweight drilling fluids and/or gases including air, nitrogen and natural gas are being used to maintain the bottom hole circulating pressure below formation pressure and to permit hydrocarbons to flow while drilling (Strata, 2011). Most of the time, nitrogen is more preferred because it is lower in cost of generation, scale of control and minimal potential for downhole fires (Maqsood, 2008).

There are four main techniques to achieve underbalanced drilling, which are using lightweight drilling fluids, injecting gas down the drill pipe, gas injection via parasite string, and using nitrogen foam which is the least common compared to the other three methods. Among the four techniques, the simplest way to reduce wellbore pressure is by using lightweight drilling fluids such as fresh water, diesel and lease crude (Rigzone, 2011). As for injection of gas down the drill pipe, it involves adding air or nitrogen to the drilling fluid that is pumped directly down the drill pipe. Gas injection via parasite string is achieved by installing a second pipe outside the intermediate casing (Strata, 2011). As for nitrogen foam application, it is less damaging to reserves that exhibit water sensitivities but due to higher in cost, this technique is rather prohibitive (Eissa& Al-Harthi, 2003).

Although initially more costly, underbalanced drilling, also known as managed-pressure drilling, reduces common conventional drilling problems for example reduction in formation damage in reservoirs where overbalanced drilling would reduce production due to skin damage (Arnold, 2007). This damage is caused by a number of factors including solid invasions, phase trapping, clay swelling, and emulsification. Hence, correctly applied underbalanced drilling can provide an increment in the net present value as well as the amount of economically recoverable reserves (John, 2010).

Hani, Zaki and Abdelaziz (2011) in their paper "Enhancing Ultimate Recovery and Adding Reserves by Underbalanced Drilling Technology", also claimed that underbalanced drilling will be able to enhance the ultimate recovery of the well through discovery of the new zones, reducing formation damage and increase intra-zone contribution, lower abandonment pressure, increase well drainage area and accesses challenging reservoirs. Other than that, underbalanced drilling has many other advantages, which include (Brant, 2012):

- Minimize the potential for lost circulation
- Minimize the potential for differential sticking
- Eliminate need for costly mud systems and costly disposal of exotic muds
- Improve rate of penetration (ROP) on drilling, reducing drilling costs and increased bit life (Maqsood, 2008)
- Mitigation of extensive and expensive completion and stimulation operations
- Potential economic benefit from flush production during drilling
- Potential to flow test while drilling

Underbalanced drilling does bring disadvantages, which include:

- Safety and well control concerns in high pressure or sour environments
- Highest cost for drilling due to high technology requirements and high technical skills
- Inability to use conventional measurement while drilling (MWD) technology for through string injection techniques (Brant, 2012)
- Failure to maintain a continuously underbalanced condition resulting in significant invasion damage (Salar& Hani, 2010)

Therefore, it is important to realize that underbalanced drilling is not a miracle technique; as practiced most often today, it is a complicated process that, in general, increases the overall production risk (John, 2006). Hole instability; hole cleaning, well control issues and detection of kick need to be considered when choosing to utilize underbalanced drilling.

2.2 Hole Cleaning

Hole cleaning issue need to be considered when choosing to utilize underbalanced drilling. Hole cleaning is the basic functions of any drilling fluid. Cuttings generated by the bits, plus any caving and/or sloughing must be carried to the surface by the mud (Nazari, 2010). There are many factors that impact on hole cleaning while drilling which include (Azar& Alfredo, 1997):

- Annular drilling fluid velocity
- Hole inclination angle
- Drillstring rotation
- Annulus eccentricity
- Rate of penetration
- Drilling fluid properties
- Characteristics of drilled cuttings

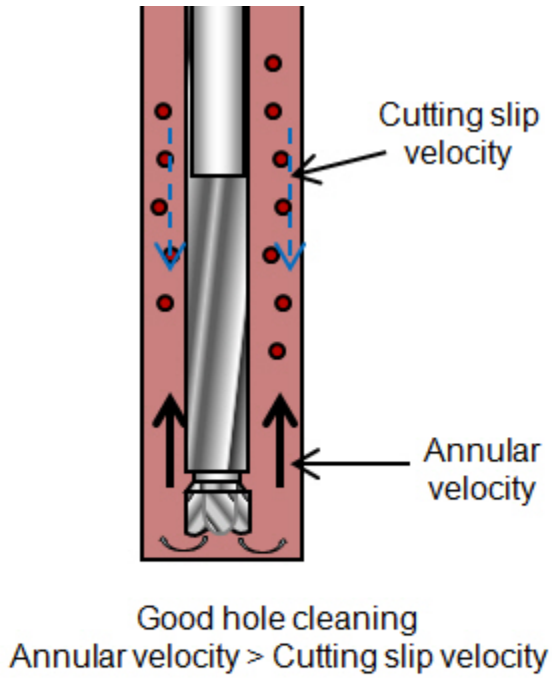


Figure 3: Hole Cleaning (Zhou, 2011)

As a matter of fact, poor hole cleaning often responsible for up to 70% of all drilling problems (Drillfloor, 2011). Inadequate hole cleaning can contribute to several major drilling problems which include:

- Increase torque and drag that can limit the reach to target
- Mechanical pipe sticking
- Difficulties in casing/cementing
- Difficulties in logging operations that can increase well cost significantly (Indra, 2002).
- Lower drilling rate
- Formation fracturing and premature bit wear (Azar& Alfredo, 1997)

There are several types of drilling fluids used for hole cleaning depending on the drilling conditions encountered, which are the water-based mud that is most frequently used, oil based mud and synthetic materials (Zhou, 2011).

A wide variety of fluid systems have been used in the underbalanced drilling operations, including straight, air, mist, foam, gasified fluids and straight liquid fluids (Lim, 1996).

During underbalanced operations, introducing gas phase into the flow system creates more dynamic hole cleaning characteristics (Maqsood, 2008).

The selection of the appropriate drilling fluid system is crucial for the application of a successful underbalanced operations as well as the selection of each of its phases, when multiphase drilling fluids sytems are required (Lim, 1996). Gasified fluids, having two phases, are commonly used in drilling operations especially for achieving underbalanced conditions. While adjusting the flow rates for each phase, common application is to adjust liquid phase for proper cuttings transport, and to adjust gas phase for controlling bottom hole pressure. Since these phases flow with relatively different local velocities, occurred various flow patterns lead to fluctuations in hole cleaning formation as well as frictional pressure (Reza, 2010).

In this project, the selected gas phase will be nitrogen gas phase whereas for liquid, the selected liquid model is Newtonian fluid.

2.3 Beggs and Brill Method

In this project, the Beggs and Brill method is being applied in the calculation of the liquid holdup, $H_L$and also frictional pressure loss.

The Beggs and Brill method was the first one to predict flow behavior at all inclination angles and was developed from an experimental data obtained in a small scale test facility consisting of 1 inch and 1.5 inch sections of acrylic pipe which is 90ft long. The pipe can be inclined at any level (James &Hemanta, 1999).

The performance of correlation is given below:

i) Tubing Size – For the range in which the experimental investigation was conducted (i.e., tubing sizes between 1 and 1.5 in.), the pressure losses are accurately estimated. Any further increase in tubing size tends to result in an over prediction in the pressure lose.

ii) Oil Gravity – A reasonably good performance is obtained over a broad spectrum of oil gravities.

iii) Gas-Liquid Ratio (GLR) – In general, an over predicted pressure drop is obtained with increasing GLR. The errors become especially large for GLR above 5000.

iv) Water-Cut – The accuracy of the pressure profile predictions is generally good up to about 10% water-cut. (Beggs, 1973)

The parameters studied and the ranges of variation were:

i) Gas flow rate from 0 – 300 Mscf/D.

ii) Liquid flow rate from 0 – 30 gal/min.

iii) Average system pressure from 35 to 95 psia.

iv) Pipe diameter from 1 – 1.5 in.

v) Liquid holdup from 0 – 0.87.

vi) Pressure gradient from 0 – 0.8 psi/ft.

vii) Inclination angle from -90º to +90º.

viii) Horizontal flow pattern.

Fluid used in the experiments was water and air.

For different pipe sizes, the liquid and gas flow rate were varied so that all flow patterns were observed for horizontal pipe. The angle of pipe was varied to get the angle on holdup and pressure gradients. The correlations were developed after 584 measured tests from angles of plus and minus 0, 5,10,15,20,35,55,75 and 90 degrees (James &Hemanta, 1999).

The horizontal-flow patterns are illustrated as below:

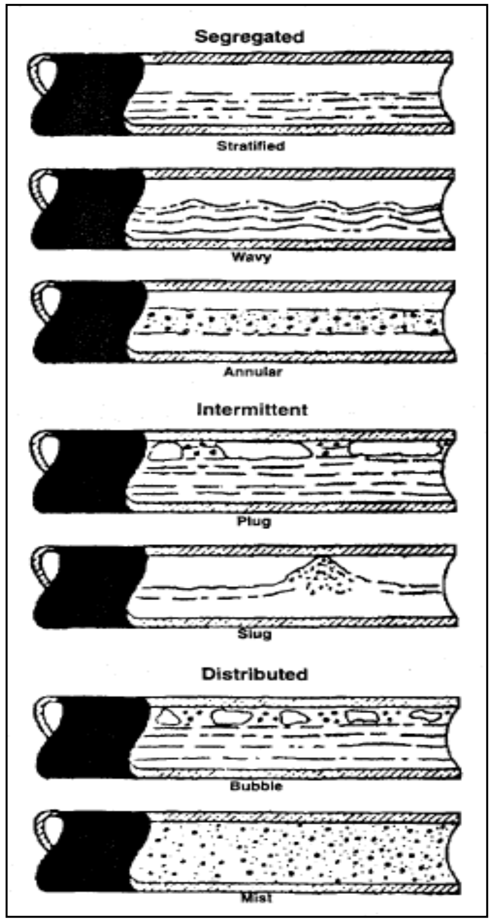


Figure 4: Horizontal Flow Patterns (James &Hemanta, 1999)

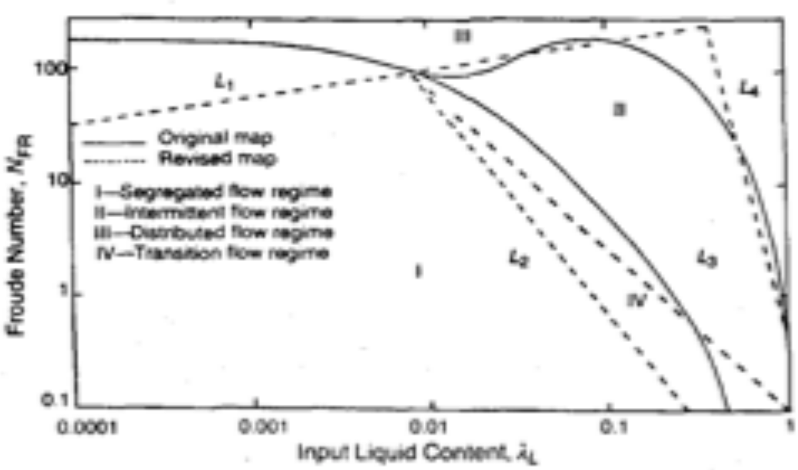


Figure 5: Beggs and Brill Horizontal Flow Pattern Map (Beggs, 1973)

The Liquid holdup is defined as the in-situ volume fraction or often the value that is estimated by multiphase correlations (Beggs, 1973). When two or more phases are present in a pipe, they tend to flow at different in-situ velocities. These in-situ velocities depend on the density and viscosity of the phase. Phase that is less dense will tend to flow faster than the other. This will cause a “slip” or holdup effect, which means that in-situ volume fractions of each phase (under flowing conditions and vary flow pattern) will differ from the input volume fractions of the pipe (James &Hemanta, 1999).

The equation below shows the calculation for liquid holdup:

$$H_{L(0)} = [(a\lambda_L)^b / (N_{Fr})^c$$

The same equations are used for calculation of liquid holdup for all patterns by differing the empirical correlations for each flow pattern.

With that, Beggs and Brill had come up with the empirical coefficients for horizontal liquid holdup in annuli (James&Hemanta, 1999).

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

Table 1: Beggs and Brill Empirical Coefficients for Horizontal Liquid Holdup

As for inclined wells, Beggs and Brill have come up with another correlations and constants to calculate the liquid holdup. To calculate the liquid holdup for inclined wells, Beggs (1973) claimed that a correction factor has to be taken into consideration as angles of the well have to be taken into account of.

The equation below shows the calculation for liquid holdup for inclination wells:

$$H_{L(\theta)} = H_{L(0)} \psi$$

$$\psi = 1.0 + C\,[\sin(1.8\theta) - 0.333\,\sin^3(1.8\theta)]$$

Where, θ = actual angle of the pipe from horizontal and C is defined as

$$C = (1.0 - \lambda_L)\ln[e(\lambda_L)^f (N_{Lv})^g (N_{Fr})^h]$$

The empirical coefficients for C are as the table below:

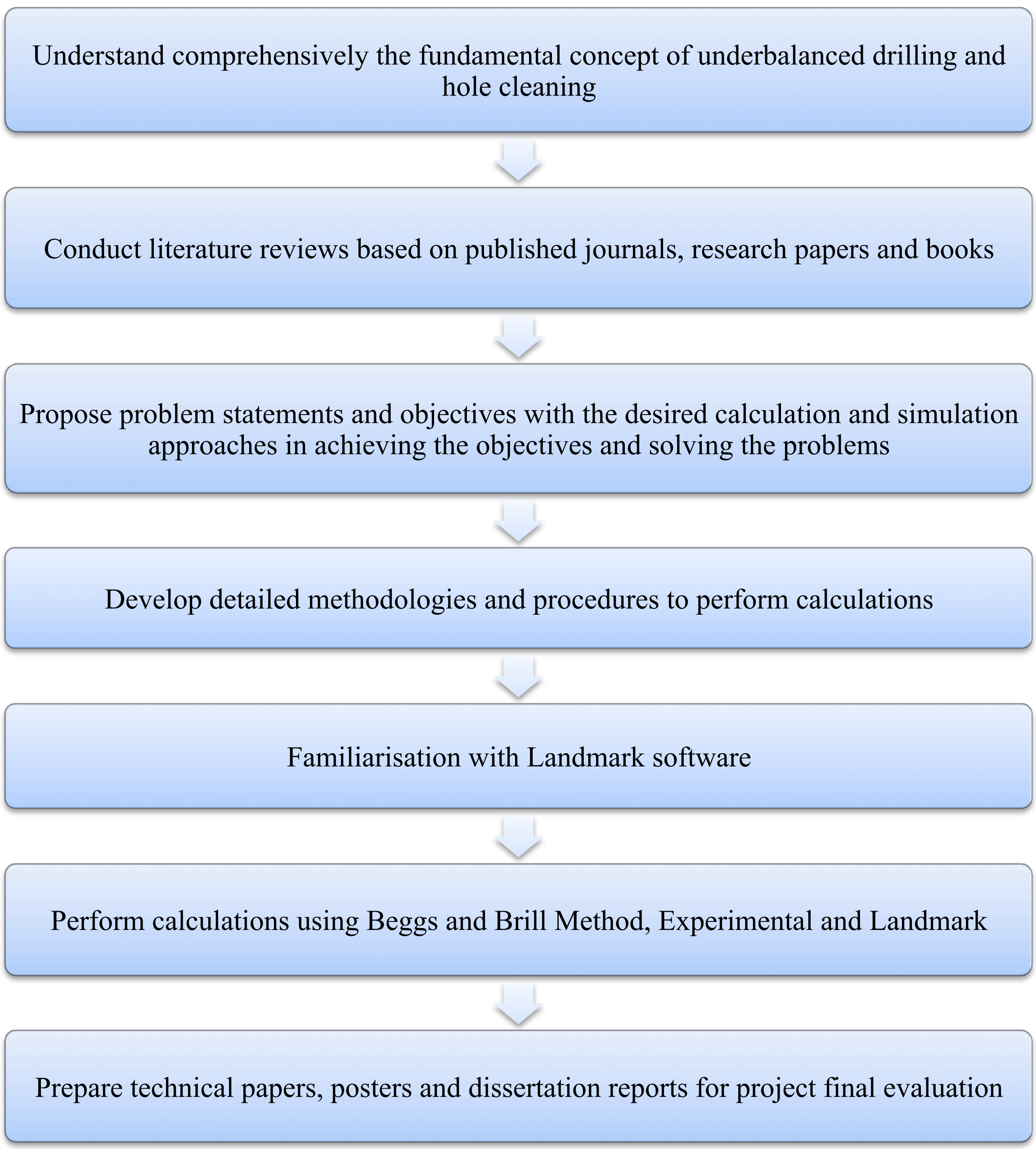
Flow Pattern	e	f	g	h
Segregated uphill	0.011	-3.7680	3.5390	-1.6140
Intermittent uphill	2.960	0.3050	-0.4473	0.0978
Distributed uphill	No correlation: C = 0; ψ = 1			
All patterns downhill	4.700	-0.3692	0.1244	-0.5056

Table 2: Beggs and Brill Empirical Coefficients for C

CHAPTER 3

METHODOLOGY

3.1 Research Methodology



3.2 Project Activities

In order to determine optimum hydraulic parameters for underbalanced drilling operations, three different methods are being considered, which are: beggs and brill, experimental and Landmark. In addition, 5 different criteria, which are maximum hydraulic horsepower, maximum jet impact force, method A, method B, method C, for calculating optimum frictional pressure loss are being taken into account to as well. The steps in calculating the Froude number, liquid holdup, friction factor, and pressure gradient will be shown and explained step by step. Throughout the project, the rheological model is assumed to be Newtonian fluid, and the gas phase that is being considered is nitrogen gas phase. Since gasified liquids are being used in underbalanced drilling, the drilling fluid is a two-phase flow (mixture of liquid and gas).

Step 1: Calculation of Mixture velocity, V_M

Mixture velocity can be determined given the liquid superficial velocity, V_{SL} and gas superficial velocity, $V_{SG.}$ With that,

$$V_M = V_{SL} + V_{SG}$$

Unit for V_M, V_{SL}, $V_{SG:}$ ft/sec

Step 2: Calculation of no-slip liquid holdup, λ_L

The no-slip liquid holdup is defined as the ration of liquid volumetric flow rate, V_{SL} to the total volumetric flow rate, $V_{M.}$

$$\lambda_L = V_{SL} / V_M$$

Step 3: Calculation of Mixture Density, ρ_m

$$\rho_m = \rho_L (\lambda_L) + \rho_g (1 - \lambda_L)$$

Unit for ρ_m ,ρ_L, ρ_g: lb/ft^3

Step 4: Calculation of Mixture Flow Rate, Q_M

$$Q_M = V_M \text{ x } 2.448\ (OD^2 - ID^2)$$

Where OD = pipe outer diameter, inch

ID = pipe inner diameter, inch

Unit for Q_M: gpm

Step 5: Calculation of Froude Number

$$N_{Fr} = (V_m)^2 / gd$$

Where V_m = mixture velocity, ft/sec

g = gravitational force, ft/sec^2

d = Pipe inner diameter, inch

When:

$N_{Fr} = 1$, critical flow

$N_{Fr} > 1$, supercritical flow (fast rapid flow)

$N_{Fr} < 1$, subcritical flow (slow/tranquil flow)

Step 6: Determination of Flow Pattern

The equations for the modified flow-pattern transition boundaries are as followed (based on the Beggs and Brill horizontal flow-pattern map:

$$L_1 = 316(\lambda_L)^{0.302}$$

$$L_2 = 0.000925(\lambda_L)^{-2.468}$$

$$L_3 = 0.10(\lambda_L)^{-1.452}$$

$$L_4 = 0.5(\lambda_L)^{-6.738}$$

To determine the flow pattern that would exist if the pipe were horizontal, the following inequalities are being used.

For segregated flow pattern,

$\lambda_L < 0.01$ and $N_{Fr} < L1$ or $\lambda_L \geq 0.01$ and $N_{Fr} < L_2$

For transition flow pattern,

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

For intermittent flow pattern,

$0.01 \leq \lambda_L < 0.4$ and $L_3 < N_{Fr} \leq L_1$ or $\lambda_L \geq 0.4$ and $L_3 < N_{Fr} \leq L_4$

For Distributed flow pattern,

$\lambda_L < 0.4$ and $N_{Fr} \geq L_1$ or $\lambda_L \geq$ and $N_{Fr} > L_4$

Step 7: Calculation of Liquid Holdup, H_L

For horizontal pipe (90 degree), the liquid holdup calculation can be carried out with the given equation:

$$H_{L(0)} = [(a\lambda_L)^b / (N_{Fr})^c$$

Where the empirical correlations a, b and c vary for different flow pattern. Beggs and Brill have prepared and correlated the value of empirical coefficients for horizontal liquid holdup from their research:

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

The above empirical coefficients are however only applicable for horizontal wells (90 degree). For wells with inclination or near vertical well, there is another equation for liquid holdup in which it will have to be multiply with a correction factor, ψ. The equation for liquid holdup for inclination well is therefore:

$$H_{L(\theta)} = H_{L(0)}\,\psi$$

With,

$$\psi = 1.0 + C\,[\sin(1.8\theta) - 0.333\sin^3(1.8\theta)]$$

Where, θ = actual angle of the pipe from horizontal and is in radian

C is defined as

$$C = (1.0 - \lambda_L)\ln[e(\lambda_L)^f(N_{Lv})^g(N_{Fr})^h]$$

$$N_{LV} = 1.988 \times V_{SL}\,(\rho_L/\sigma_L)^{0.25}$$

And C must be ≥ 0. Based on the vary flow patterns, Beggs and Brill have came up with empirical coefficients for C.

Beggs and Brill have correlated the empirical correlations to be substituted into the above equation:

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 correlation: C = 0; ψ = 1			
All patterns downhill	4.700	-0.3692	0.1244	-0.5056

Step 8: Calculation of Liquid holdup for Transition flow pattern

When the flow pattern falls in the transition region, the liquid holdup must be interpolated between the segregated and intermittent liquid holdup values. To perform interpolation, consider the following equation:

$$H_{L(\theta)Tr} = AH_{L(\theta)Seg} + (1 - A)\, H_{L(\theta)Int}$$

Where in order to calculate A, the equation below should be used:

$$A = (L_3 - N_{Fr}) / (L_3 - L_2)$$

Step 9: Calculation of Mixture Viscosity, μ_M

$$\mu_M = \mu_L \lambda_L + \mu_g (1 - \lambda_L)$$

Where μ_L = liquid density, lb/ft^3

μ_g= gas density, lb/ft^3

Units for μ_M: lb/ft^3

Step 10: Calculation of Mixture Reynolds Number, N_{Re}

$$N_{Re} = (1488\, \rho_M V_M D) / \mu_M$$

Where V_M = mixture velocity, ft/sec

ρ_M = mixture density

μ_M = mixture viscosity

D = Pipe inner diameter, inch

Step 11: Calculation of friction factor

To calculate friction factor for two-phase flow, the equation below should be considered:

$$f = f_n (f/f_n)$$

Beggs and Brill have also correlated the ratio of the two-phase friction factor to the normalizing friction factor using experimental data, resulting with the equation:

$$f/f_n = e^s$$

Where

$$s = \ln y / [-0.0523 + 3.182 \ln y - 0.8725 (\ln y)^2 + 0.01853 (\ln y)^4]$$

$$y = \lambda_L / (H_{L(\theta)})^2$$

In the case where the calculated y is in the range of $1 < y < 1.2$, Beggs and Brill introduced the correlation for simpler way of calculating s:

$$s = \ln(2.2y - 1.2)$$

To obtain the value for normalizing friction factor, f_n, the equation below should be used:

$$f_n = 1 / [2\log(NRe / (4.5223 \log (NRe) - 3.8215))]^2$$

Substituting into:

$$f = f_n (f/f_n)$$

We can obtain the mixture friction factor

Step 12: Calculation of Frictional Pressure Loss, P_f

$$dP/dL = [f_f \rho_m V_m^2 / 2g(D/12)]/ 144$$

$$P_f = dp/dL \text{ x } TVD$$

Where V_M = mixture velocity, ft/sec

ρ_M = mixture density

g = gravitational force, ft/sec^2

D = Pipe inner diameter, inch

f_f= friction factor

TVD = true vertical depth, ft

Step 13: Calculation of Flow Exponent, m

$$m = \ln (P_{f1}/P_{f2}) / \ln (Q_{m1}/Q_{m2})$$

Where P_{f1}, P_{f2}= ration of frictional pressure loss at 2 points

Q_{m1}, Q_{m2} = ration of mixture flow rate at 2 points

Step 14: Calculation of Optimum Frictional Pressure Loss, P_{fopt}

This is the part where the 5 criteria are being taken account into for optimum frictional pressure loss calculation. The five criteria are: maximum hydraulic horsepower, maximum jet impact force (in which these two methods are also being named the conventional methods), method A, method B, and method C (in which method A, B, C are being called the modern methods).

For maximum hydraulic horsepower criteria,

$$P_{fopt} = (1 / m+1)(Pp_{max})$$

For maximum jet impact force criteria:

$$P_{fopt} = (2 / m+2)(Pp_{max})$$

There are three new method that are being considered:

For the new method, A:

$$P_{fopt} = (3 / m+3)(Pp_{max})$$

For the new method, B:

$$P_{fopt} = (4 / m+4)(Pp_{max})$$

For the new method, C:

$$P_{fopt} = (5 / m+5)(Pp_{max})$$

Where, Pp_{max} is the maximum pump pressure.

Units for P_{fopt}: psia

Step 15: Calculation of Optimum Mixture Flow Rate, Q_{Mopt}

$$Q_{opt.mix} = Q\ [\ P_{fopt} / P_{f1}\ ]^{1/m}$$

The equation for calculating the optimum mudflow rate would be:

$$Q_{opt.mud} = Q_{opt.mix} x\ H_L$$

The equation for calculating the optimum gas rate would be:

$$Q_{opt.mud} = Q_{opt.mix} x\ (1 - H_L)$$

Units for Q_{Mopt}: gpm

Step 16: Calculation of Optimum Bit Pressure, P_b

$$P_{bopt} = Pp_{max} - P_{fopt}$$

Another equation for optimum bit pressure is as such:

$$P_{bopt} = (8.3 \text{ x } 10^{-5})\rho_M Q_{Mopt}^2 \ / \ A_{nopt}^2 C_d^2$$

Step 17: Calculation of Optimum Nozzle Area, A_n

Once optimum flow rate and optimum bit pressure is determined, nozzle diameters can be calculated. In field units, total nozzle area can be determined by rearranging the equation above:

$$A_{ntotal} = [(8.3 \text{ x } 10\text{-}5)\rho_M Q_{Mopt}^2 / C_d^2 P_{bopt}]^{1/2}$$

Where Q_{Mopt} = optimum mixture flow rate, gpm

ρ_M = mixture density

C_d = discharge coefficient

Step 18: Calculation of Optimum Nozzle Diameter, d_n

If nozzle sizes are assumed to be constant, nozzle size (in) can be determined as:

$$d_{nopt} = (4A_{nopt} / \pi n)^{1/2}$$

Where,

n = number of nozzles

All the above calculations discussed are being calculated by developing a macro through Microsoft Visual Basic.

The above formulas are with consideration of Beggs and Brill Method. As for experimental data, the pressure gradients data are being collected from experiments conducted in the laboratory previously and only step 13-15 will be involved for optimum hydraulic parameters calculation.

As for Landmark, the pressure gradients are being obtained and calculated by Landmark when the raw data are being keyed in. The pressure gradients data obtained are then being used for calculation for step 13 until step 15. With sufficient and complete field data (if provided with), Landmark is capable of determining the optimum nozzle size for different drilling condition by following the steps/procedures below:

1. Designing and constructing the well using Compass, Landmark
2. Final Design check
3. Input all necessary parameters in WellPlan, Landmark in the optimum planning: hole cleaning session
4. Analysis the results obtained by plotting total force area (TFA) vs rate of penetration (ROP) graph in Landmark
5. Export the data to Microsoft Excel

Upon performing all the calculation using three different approaches: Beggs and Brill, Experimental and Landmark, the results obtained are then being compared and critical analysis are being conducted.

3.3 Gantt Chart and Milestones

FINAL YEAR 1st SEMESTER (SEPT 2011)																
No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project title selection								Mid-semester break							
2.	Preliminary research work															
3.	Extended Proposal submission															
4.	Study on fundamental concepts related to the project & familiarize the usage of Software tools															
7.	Proposal Defence															
8.	Study on mathematical model which involved in calculating bleed off annular pressure according to time.															
9.	Preparation of interim report															
10.	Submission of interim report															

Table 3: Gantt chart for the First Semester Project Implementation

	FINAL YEAR 2nd SEMESTER (January 2012)																	
No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15	16
1	Development of Computer Code and manipulate different parameters.								Mid-semester break									
2.	Submission of Progress Report																	
3.	Seeking advice and meeting with Industry Professionals.																	
4.	Conduct Sensitivity Analysis and validation between simulated data and field data.																	
6.	Create Workflow in accessing SCP.																	
7.	Preparation of Final Report																	
8.	Pre-EDX & Submission of Final Report(Softcopy)																	
9.	EDX(if selected)																	
10.	Preparation of Oral Presentation																	
11.	Final Oral Presentation																	
12.	Submission of Hardbound Copies																	

Table 4: Gantt chart for the Second Semester Project Implementation

CHAPTER 4

RESULTS AND DISCUSSIONS

Based on the methodology as discussed in Chapter 3, calculations have been performed for Beggs and Brill method, experimental and Landmark to obtain the optimum friction pressure loss, flow exponent, optimum mixture flow rate, optimum nozzle area and optimum nozzle size.

In this project, the author is considering vertical well with 77.5 degree from horizontal, then with 45-degree inclination and eventually a horizontal well, which means 90 degree.

Since the field data was not being approved by PETRONAS to be taken out from the database, the author had no choice but to continue the project with limited data from the previous experimental and thesis (Reza, 2010). The figure below shows the design of a 77.5degree, 45 degree and 90 degree well (from horizontal).

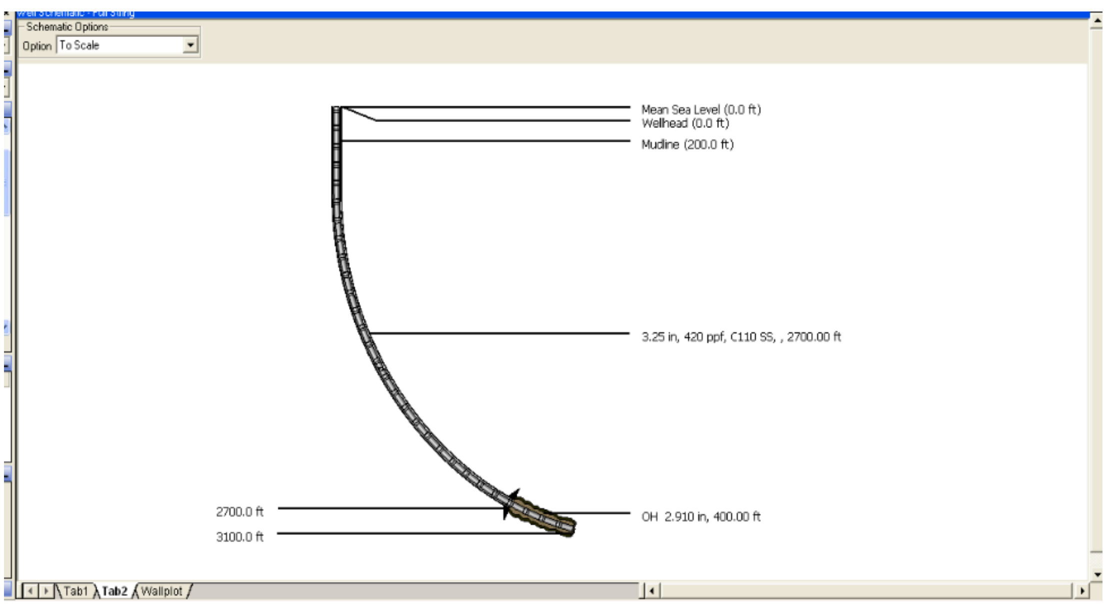


Figure 6: Design of the Studied Well by using Landmark Compass

Results obtained from Beggs and Brill:

Flow exponent, m, had been obtained from calculation and m = 1.6043333.

The flow exponent is crucial in the later calculation, as it will affect the calculation for optimum frictional pressure drop and optimum mixture flow rate. The tables are being tabulated and graphs are being plotted for better presentation and understandings of the results:

Beggs& Brill	$Q_{mopt.}$(gpm)	P_{bopt} (psia)	A_{nopt} (in^2)	D_{nopt}(in)
Max Hhp	119.0127461	14.7286	2.018333733	0.925530897
Max.Jet	149.7096578	10.642	2.986884483	1.125909919
Method A	165.4741913	8.33	3.731539154	1.258457152
Method B	175.141734	6.844	4.357274104	1.359884026
Method C	191.6228864	4.195	6.089219527	1.607589821

Table 5: Calculation Results Obtained for Beggs and Brill Method

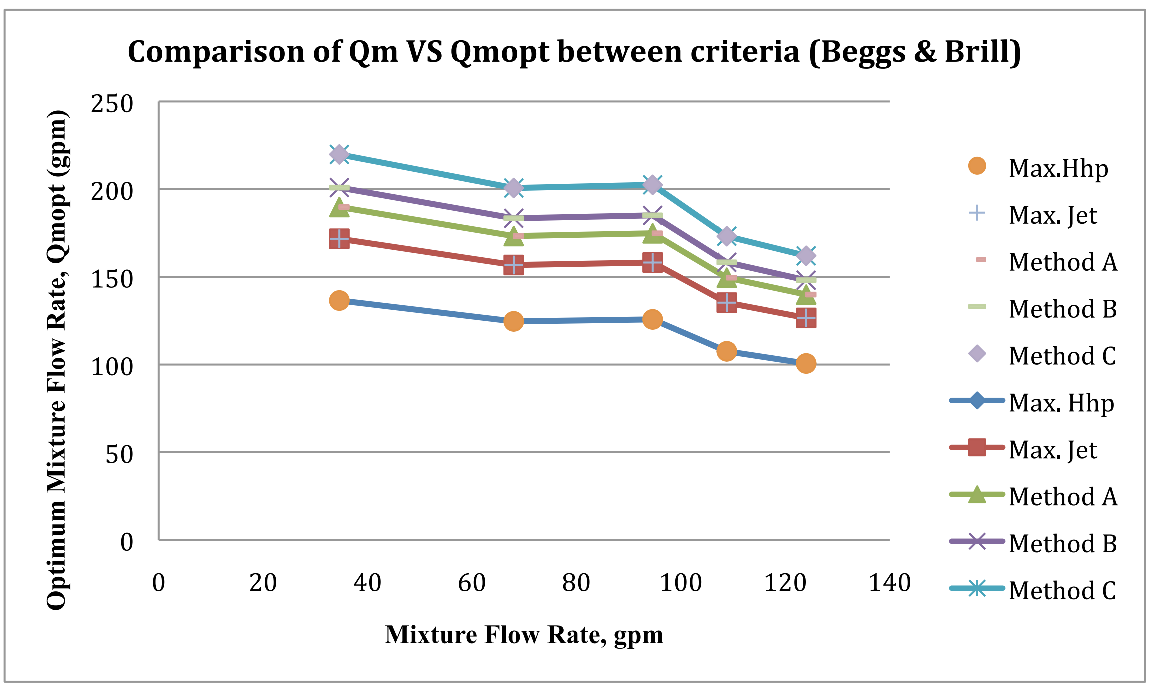


Figure 7: Comparison Graph of $Q_{m.opt}$ VS Q_{mopt} (Beggs & Brill Method)

From the graph, we can see that maximum hydraulic horsepower (HHP) criteria have the highest trend line in optimum mixture flow rate while method C has the lowest trend line. This means that the optimum mixture flow rate for maximum hydraulic horsepower criteria are increasing at a rate higher as compare to the other criteria, with method C increasing at the lowest rate and method A at the average.

Results obtained based on Pressure Obtained Experimentally:

Flow exponent, m, had been obtained from calculation and m = 1.3143333

The tables are being tabulated and graphs are being plotted for better presentation and understandings of the results:

Experimental	**$Q_{mopt.}$(gpm)**	**P_{bopt} (psia)**	**A_{nopt} (in^2)**	**D_{nopt}(in)**
Max Hhp	171.7485455	13.579	3.033467945	1.134655799
Max.Jet	220.2483972	9.482	4.655250094	1.405613568
Method A	244.792363	7.284	5.903276596	1.582854511
Method B	259.6738781	5.914	6.949728525	1.71742726
Method C	269.6873398	4.977	7.867866375	1.827354974

Table 6: Calculation Results Obtained based on Pressure Obtained Experimentally

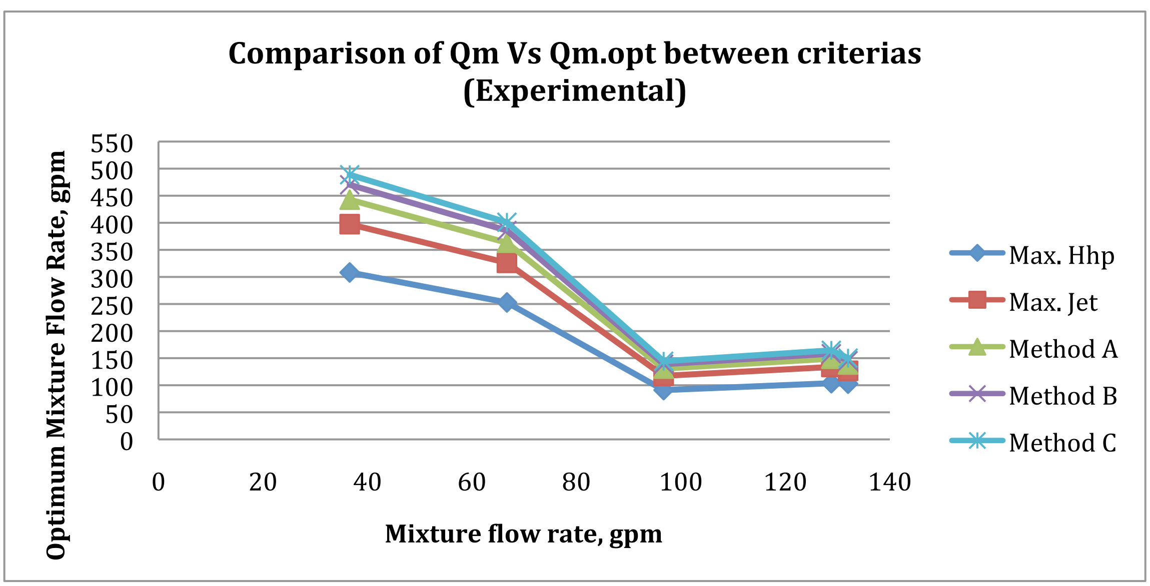


Figure 8: Comparison Graph of $Q_{m.opt}$ VS Q_{mopt} (Experimental)

Due to the difference in pressure gradient obtained for the conventional and modern method, which affect calculation for optimum mixture flow rate, we can see that there is a drastic drop in optimum mixture flow rate at the initial mixture flow rate of approximately 100gpm. However, regardless of the drastic drop in flow rate, it is obvious that maximum hydraulic horsepower criteria has the highest optimum mixture flow rate and method C has the lowest among the five criteria and with method A as the average between the maximum and minimum. In the case if the graph trend obtained for Landmark is the same, method A could be the ideal criteria for calculation of optimum frictional pressure drop and optimum mixture flow rate.

Results obtained based on Pressure Obtained from Landmark

Flow exponent, m, had been obtained from calculation and m = 1.095

The tables are being tabulated and graphs are being plotted for better presentation and understandings of the results:

Landmark	$Q_{mopt.}$(gpm)	P_{bopt} (psia)	A_{nopt} (in^2)	D_{nopt}(in)
Max Hhp	91.01142151	12.498	1.675544142	0.843281104
Max.Jet	120.0159788	8.46	2.685555465	1.067607203
Method A	134.5902582	6.394	3.464236607	1.21254595
Method B	143.369726	5.139	4.116218145	1.321732665
Method C	149.238169	4.296	4.686277609	1.410290037

Table 7: Calculation Results Obtained based on Pressure Obtained from Landmark

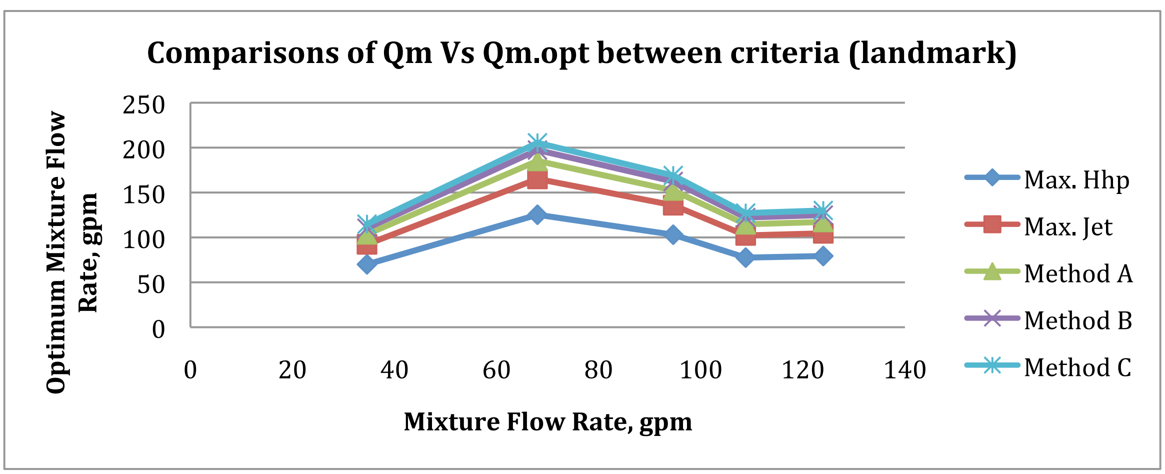


Figure 9: Comparison Graph of $Q_{m.opt}$ VS Q_{mopt} (Landmark)

Based on the graph which the calculation is conducted based on the pressure gradient obtained from Landmark, we can see that the trend is more or less the same as Beggs and Brill as well as experimental method with maximum hydraulic horsepower criteria having the highest optimum mixture flow rate and method C having the lowest among the five criteria and with method A as the average between the maximum and minimum.

Based on the initial comparisons above, it can be concluded that method A is the ideal criteria that should be used for optimum frictional pressure loss calculation because the results provided by method A is always at an average between the maximum and minimum. In drilling operations, it is not realistic to achieve the maximum mixture flow rate and not pleasing to obtain minimum mixture flow rate at all time, hence the best would be to ensure the flow rate is between the maximum and minimum range. With that, method A is currently the ideal criteria for optimum hydraulic parameters calculation.

Comparisons of Results between Three Methods

The results of the three methods: Beggs and Brill, Experimental and Landmark are then being put together for comparison purpose and also to determine which criteria that should be chosen for optimum frictional pressure loss calculation.

The tables below shows the results obtained from three different methods considering five criteria:

For comparisons between optimum mixture flow rate, Q_{mopt}

	Optimum Mixture Flow Rate, Q_{mopt} (gpm)				
	Max.Hhp	**Max.Jet**	**Method A**	**Method B**	**Method C**
Beggs & Brill	119.0127461	149.7096578	165.4741913	175.141734	191.6228864
Experimental	171.7485455	220.2483972	244.792363	259.6738781	269.6873398
Landmark	91.01142151	120.0159788	134.5902582	143.369726	149.238169

Table 8: Comparisons of Optimum Mixture Flow Rate between Different Methods

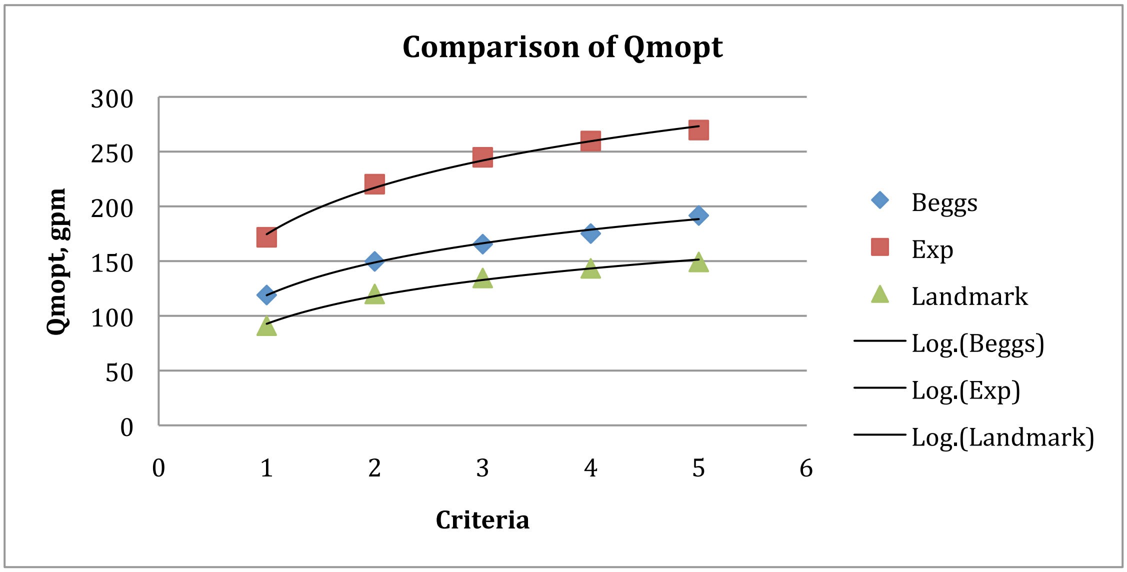


Figure 10: Comparison Graph of $Q_{m.opt}$ between Criteria of 3 Methods

For comparisons between optimum nozzle area, A_{nopt}

	Optimum Nozzle Area, A_{nopt} (in^2)				
	Max.Hhp	**Max.Jet**	**Method A**	**Method B**	**Method C**
Beggs & Brill	2.018333733	2.986884483	3.731539154	4.357274104	6.089219527
Experimental	3.033467945	4.655250094	5.903276596	6.949728525	7.867866375
Landmark	1.675544142	2.685555465	3.464236607	4.116218145	4.686277609

Table 9: Comparisons of Optimum Nozzle Area between Different Methods

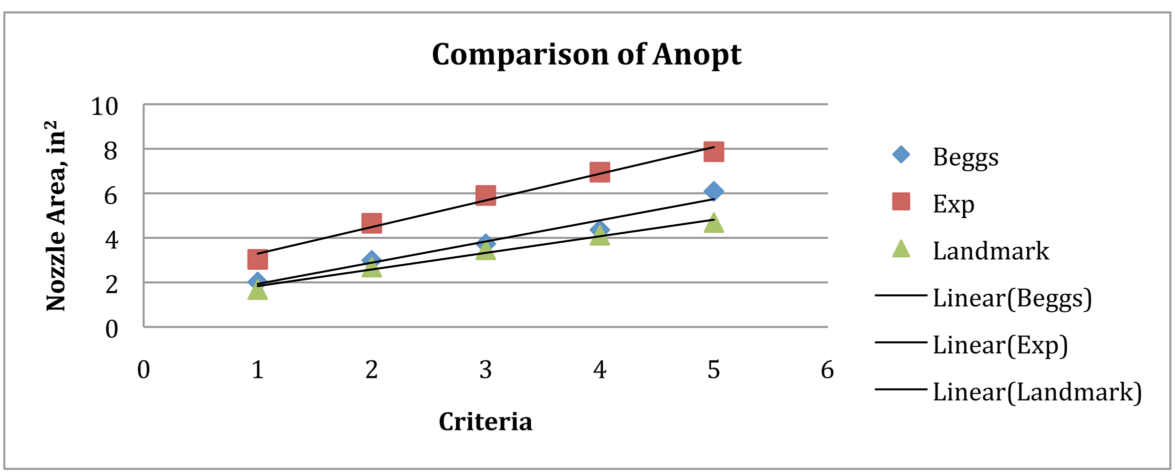


Figure 11: Comparison Graph of A_{nopt} between Criteria of 3 Methods

For comparisons between optimum nozzle diameter,

	Optimum Nozzle Diameter, D_{nopt} (in)				
	Max.Hhp	**Max.Jet**	**Method A**	**Method B**	**Method C**
Beggs & Brill	0.925530897	1.125909919	1.258457152	1.359884026	1.607589821
Experimental	1.134655799	1.405613568	1.582854511	1.71742726	1.827354974
Landmark	0.843281104	1.067607203	1.21254595	1.321732665	1.410290037

Table 10: Comparisons of Optimum Nozzle Diameter between Different Methods

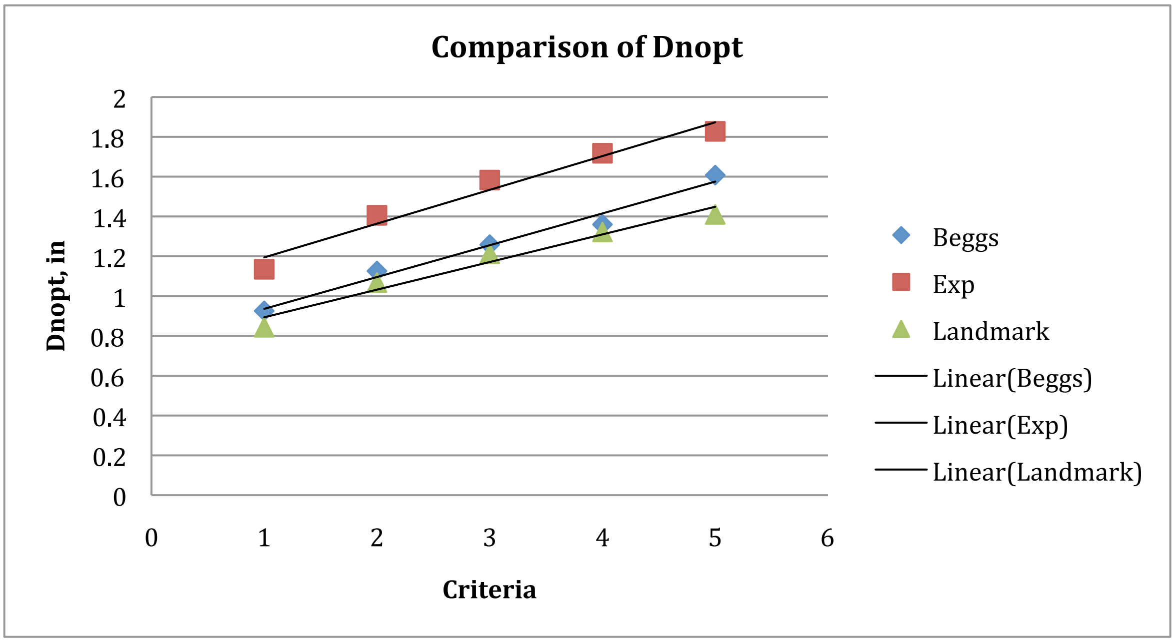


Figure 11: Comparison Graph of D_{nopt} between Criteria of 3 Methods

From the graphs above and with critical analyze, it is observed that Beggs and Brill method results are always between Experimental data and Landmark. This is due to the difference in pressure gradients obtained for each of the three methods. Based on calculations, data obtained from experiment and also results obtained from Landmark, Landmark gives the lowest in pressure gradients among the three methods and experimental data giving the highest.

Another reason for the difference between the three methods is the unavailability of field data. Without any field data on wells drilled underbalanced, it means that the well that the author is studying in this project can be only designed in Landmark Compass using the available experimental data and from the given thesis. During calculations, many assumptions have been made, which cause inaccuracy to the data especially results obtained from Landmark. In order to obtain optimum hydraulic results with limited parameters in WellPlan, Landmark, field data are very important so that data such as bit type, bit hydraulic horsepower, pump type, pump rate, given maximum pump pressure, fluid annular velocity can be retrieved and be keyed in into the Landmark interface.

Landmark was supposed to be able to determine the optimum nozzle diameter given the hydraulics parameters. Due to unavailability of the data, the author can only manage to obtain pressure gradients from Landmark by calculating the equivalent circulating density (ECD) as generated in Landmark. This has limited the author ability to obtain results of high accuracy.

In addition, Landmark is unable to give correlation for two phase flow rate as, as far as it is concerned, Landmark is designed for single phase flow and more prone towards conventional drilling as compared to underbalanced drilling. Hence, there are many limitations in Landmark in which accuracy of the results will be affected.

Based on the graphs above, the selected ideal method for determination of optimum hydraulic parameters would be the Beggs and Brill method. As for the ideal criteria that should be used in part of the calculation, modern method A should be taken into account of.

From the results, it can be concluded that in order to determine the optimum hydraulic parameters for the two-phase gasified liquids, Beggs and Brill method, with criteria method A is the ideal for performing calculation as it will give the best results as compared to other combination.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study aims to determine the optimum hydraulic parameters for the two-phase nitrogen gasified Newtonian fluids in the horizontal, inclined and near vertical wells for underbalanced drilling using three different methods, which are Beggs and Brill method, based on data from experimental setup and results simulation using Landmark. Throughout the calculation and results simulation, five criteria which can be categorized into the modern method and the conventional method have been considered that include: maximum hydraulic horsepower, maximum jet impact force, method A, method B and method C. Lengthy calculations have been performed along the way to obtain the desire results with many assumptions made for the calculation as soon as data gathering milestone had been achieved.

Upon obtaining the calculation results from the three different methods, tables are being tabulated and graphs are being plotted for better understanding and presentation of the results. Based on the results, the followings are majorly concluded:

- Results obtained from Landmark has the lowest optimum mixture flow rate, lowest frictional pressure loss and smallest optimum nozzle size as compared to results obtained from Beggs and Brill method and based on data from experimental setup.
- Based on analyze of the five different criteria, Method A is the ideal criteria that should be used for optimization calculation as it gives the results in between the maximum and minimum range, which is more realistic
- Due to unavailability of the field data and shortcomings in Landmark that include not designed for underbalanced drilling analyze and unable to simulate

results for two phases or multiphase flow, Beggs and Brill method is considered as the best method among the three for determination of the optimum hydraulic parameters as it gives the readings in between and has the smallest variation among data comparisons.

- Unavailability of field data greatly affect the accuracy of the simulated results because there are too many assumptions that have been made in the study
- As optimum frictional pressure loss increase, optimum mixture flow rate increase as well, which then lead to increment in the optimum nozzle size
- Landmark for now, is not suitable for analyze of underbalanced drilling as the design is more prone for the usage of conventional drilling.
- Landmark is only able to simulate results for single phase flow but not multiphase flow for now.

5.2 Recommendations

- Landmark should be designed for analyzing underbalanced drilling data and not restricted for conventional drilling only.
- Landmark should be adapt to multiphase flow analyze but not single phase flow analyze only.
- Field data availability should be ensured throughout the study in order to obtain results of high accuracy.
- More accurate and successful results can be achieved for determination of optimum hydraulic parameters if given more data

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APPENDIX I

Developed Excel Macro for Optimum Hydraulic Calculations

```
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 Gradient
   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

'Frictional Pressure Drop
   Cells(16 + i, 23).Value = Cells(16 + i, 6).Value * 3100

'Optimum Bit Pressure Drop
   Cells(31, 28).Value = 27.025 - Cells(17, 28).Value
   Cells(32, 28).Value = 27.025 - Cells(18, 28).Value
   Cells(33, 28).Value = 27.025 - Cells(19, 28).Value
   Cells(34, 28).Value = 27.025 - Cells(20, 28).Value
```

```
    Cells(35, 28).Value = 27.025 - Cells(21, 28).Value


Next i

Application.ScreenUpdating = True

End Sub


Sub beggs()

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

Cells(14, 7).Value = ((9.1824 / 1.01531) ^ (1 / 1.6043333)) * Cells(14, 6).Value
Cells(15, 7).Value = ((9.1824 / 3.4743233) ^ (1 / 1.6043333)) * Cells(15, 6).Value
Cells(16, 7).Value = ((9.1824 / 5.81645) ^ (1 / 1.6043333)) * Cells(16, 6).Value
Cells(17, 7).Value = ((9.1824 / 9.35404333) ^ (1 / 1.6043333)) * Cells(17, 6).Value
Cells(18, 7).Value = ((9.1824 / 12.83754) ^ (1 / 1.6043333)) * Cells(18, 6).Value

Cells(14, 8).Value = ((13.269 / 1.01531) ^ (1 / 1.6043333)) * Cells(14, 6).Value
Cells(15, 8).Value = ((13.269 / 3.4743233) ^ (1 / 1.6043333)) * Cells(15, 6).Value
Cells(16, 8).Value = ((13.269 / 5.81645) ^ (1 / 1.6043333)) * Cells(16, 6).Value
Cells(17, 8).Value = ((13.269 / 9.35404333) ^ (1 / 1.6043333)) * Cells(17, 6).Value
Cells(18, 8).Value = ((13.269 / 12.83754) ^ (1 / 1.6043333)) * Cells(18, 6).Value

Cells(14, 9).Value = ((15.581 / 1.01531) ^ (1 / 1.6043333)) * Cells(14, 6).Value
Cells(15, 9).Value = ((15.581 / 3.4743233) ^ (1 / 1.6043333)) * Cells(15, 6).Value
Cells(16, 9).Value = ((15.581 / 5.81645) ^ (1 / 1.6043333)) * Cells(16, 6).Value
Cells(17, 9).Value = ((15.581 / 9.35404333) ^ (1 / 1.6043333)) * Cells(17, 6).Value
Cells(18, 9).Value = ((15.581 / 12.83754) ^ (1 / 1.6043333)) * Cells(18, 6).Value

Cells(14, 10).Value = ((17.067 / 1.01531) ^ (1 / 1.6043333)) * Cells(14, 6).Value
Cells(15, 10).Value = ((17.067 / 3.4743233) ^ (1 / 1.6043333)) * Cells(15, 6).Value
Cells(16, 10).Value = ((17.067 / 5.81645) ^ (1 / 1.6043333)) * Cells(16, 6).Value
Cells(17, 10).Value = ((17.067 / 9.35404333) ^ (1 / 1.6043333)) * Cells(17, 6).Value
Cells(18, 10).Value = ((17.067 / 12.83754) ^ (1 / 1.6043333)) * Cells(18, 6).Value

Cells(14, 11).Value = ((19.716 / 1.01531) ^ (1 / 1.6043333)) * Cells(14, 6).Value
Cells(15, 11).Value = ((19.716 / 3.4743233) ^ (1 / 1.6043333)) * Cells(15, 6).Value
Cells(16, 11).Value = ((19.716 / 5.81645) ^ (1 / 1.6043333)) * Cells(16, 6).Value
Cells(17, 11).Value = ((19.716 / 9.35404333) ^ (1 / 1.6043333)) * Cells(17, 6).Value
Cells(18, 11).Value = ((19.716 / 12.83754) ^ (1 / 1.6043333)) * Cells(18, 6).Value

Cells(23, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(23, 6).Value ^ 2) / (0.9025 *
Cells(23, 7).Value)) ^ 0.5
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Cells(24, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(24, 6).Value ^ 2) / (0.9025 *
Cells(24, 7).Value)) ^ 0.5
Cells(25, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(25, 6).Value ^ 2) / (0.9025 *
Cells(25, 7).Value)) ^ 0.5
Cells(26, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(26, 6).Value ^ 2) / (0.9025 *
Cells(26, 7).Value)) ^ 0.5
Cells(27, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(27, 6).Value ^ 2) / (0.9025 *
Cells(27, 7).Value)) ^ 0.5

Cells(23, 9).Value = (4 * Cells(23, 8).Value / (3 * 3.141592654)) ^ 0.5
Cells(24, 9).Value = (4 * Cells(24, 8).Value / (3 * 3.141592654)) ^ 0.5
Cells(25, 9).Value = (4 * Cells(25, 8).Value / (3 * 3.141592654)) ^ 0.5
Cells(26, 9).Value = (4 * Cells(26, 8).Value / (3 * 3.141592654)) ^ 0.5
Cells(27, 9).Value = (4 * Cells(27, 8).Value / (3 * 3.141592654)) ^ 0.5



Application.ScreenUpdating = True

End Sub


Sub exp()

Application.ScreenUpdating = False
Sheets("Exp").Select

Cells(14, 7).Value = ((10.332 / 0.62787) ^ (1 / 1.3143333)) * Cells(14, 6).Value
Cells(15, 7).Value = ((10.332 / 1.79265) ^ (1 / 1.3143333)) * Cells(15, 6).Value
Cells(16, 7).Value = ((10.332 / 11.18739667) ^ (1 / 1.3143333)) * Cells(16, 6).Value
Cells(17, 7).Value = ((10.332 / 13.73063667) ^ (1 / 1.3143333)) * Cells(17, 6).Value
Cells(18, 7).Value = ((10.332 / 15.41512533) ^ (1 / 1.6043333)) * Cells(18, 6).Value

Cells(14, 8).Value = ((14.429 / 0.62787) ^ (1 / 1.3143333)) * Cells(14, 6).Value
Cells(15, 8).Value = ((14.429 / 1.79265) ^ (1 / 1.3143333)) * Cells(15, 6).Value
Cells(16, 8).Value = ((14.429 / 11.18739667) ^ (1 / 1.3143333)) * Cells(16, 6).Value
Cells(17, 8).Value = ((14.429 / 13.73063667) ^ (1 / 1.3143333)) * Cells(17, 6).Value
Cells(18, 8).Value = ((14.429 / 15.41512533) ^ (1 / 1.6043333)) * Cells(18, 6).Value

Cells(14, 9).Value = ((16.627 / 0.62787) ^ (1 / 1.3143333)) * Cells(14, 6).Value
Cells(15, 9).Value = ((16.627 / 1.79265) ^ (1 / 1.3143333)) * Cells(15, 6).Value
Cells(16, 9).Value = ((16.627 / 11.18739667) ^ (1 / 1.3143333)) * Cells(16, 6).Value
Cells(17, 9).Value = ((16.627 / 13.73063667) ^ (1 / 1.3143333)) * Cells(17, 6).Value
Cells(18, 9).Value = ((16.627 / 15.41512533) ^ (1 / 1.6043333)) * Cells(18, 6).Value

Cells(14, 10).Value = ((17.997 / 0.62787) ^ (1 / 1.3143333)) * Cells(14, 6).Value
Cells(15, 10).Value = ((17.997 / 1.79265) ^ (1 / 1.3143333)) * Cells(15, 6).Value
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Cells(16, 10).Value = ((17.997 / 11.18739667) ^ (1 / 1.3143333)) * Cells(16, 6).Value
Cells(17, 10).Value = ((17.997 / 13.73063667) ^ (1 / 1.3143333)) * Cells(17, 6).Value
Cells(18, 10).Value = ((17.997 / 15.41512533) ^ (1 / 1.6043333)) * Cells(18, 6).Value

Cells(14, 11).Value = ((18.934 / 0.62787) ^ (1 / 1.3143333)) * Cells(14, 6).Value
Cells(15, 11).Value = ((18.934 / 1.79265) ^ (1 / 1.3143333)) * Cells(15, 6).Value
Cells(16, 11).Value = ((18.934 / 11.18739667) ^ (1 / 1.3143333)) * Cells(16, 6).Value
Cells(17, 11).Value = ((18.934 / 13.73063667) ^ (1 / 1.3143333)) * Cells(17, 6).Value
Cells(18, 11).Value = ((18.934 / 15.41512533) ^ (1 / 1.6043333)) * Cells(18, 6).Value

Cells(23, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(23, 6).Value ^ 2) / (0.9025 * Cells(23, 7).Value)) ^ 0.5
Cells(24, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(24, 6).Value ^ 2) / (0.9025 * Cells(24, 7).Value)) ^ 0.5
Cells(25, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(25, 6).Value ^ 2) / (0.9025 * Cells(25, 7).Value)) ^ 0.5
Cells(26, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(26, 6).Value ^ 2) / (0.9025 * Cells(26, 7).Value)) ^ 0.5
Cells(27, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(27, 6).Value ^ 2) / (0.9025 * Cells(27, 7).Value)) ^ 0.5

Cells(23, 9).Value = (4 * Cells(23, 8).Value / (3 * 3.141592654)) ^ 0.5
Cells(24, 9).Value = (4 * Cells(24, 8).Value / (3 * 3.141592654)) ^ 0.5
Cells(25, 9).Value = (4 * Cells(25, 8).Value / (3 * 3.141592654)) ^ 0.5
Cells(26, 9).Value = (4 * Cells(26, 8).Value / (3 * 3.141592654)) ^ 0.5
Cells(27, 9).Value = (4 * Cells(27, 8).Value / (3 * 3.141592654)) ^ 0.5


Application.ScreenUpdating = True

End Sub

Sub landmark()

Application.ScreenUpdating = False
Sheets("Landmark").Select

Cells(14, 7).Value = ((11.413 / 5.2773333) ^ (1 / 1.095)) * Cells(14, 6).Value
Cells(15, 7).Value = ((11.413 / 5.8473333) ^ (1 / 1.095)) * Cells(15, 6).Value
Cells(16, 7).Value = ((11.413 / 10.3946667) ^ (1 / 1.095)) * Cells(16, 6).Value
Cells(17, 7).Value = ((11.413 / 16.543667) ^ (1 / 1.095)) * Cells(17, 6).Value
Cells(18, 7).Value = ((11.413 / 18.624) ^ (1 / 1.095)) * Cells(18, 6).Value

Cells(14, 8).Value = ((15.451 / 5.2773333) ^ (1 / 1.095)) * Cells(14, 6).Value
Cells(15, 8).Value = ((15.451 / 5.8473333) ^ (1 / 1.095)) * Cells(15, 6).Value
Cells(16, 8).Value = ((15.451 / 10.3946667) ^ (1 / 1.095)) * Cells(16, 6).Value
Cells(17, 8).Value = ((15.451 / 16.543667) ^ (1 / 1.095)) * Cells(17, 6).Value
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Cells(18, 8).Value = ((15.451 / 18.624) ^ (1 / 1.095)) * Cells(18, 6).Value

Cells(14, 9).Value = ((17.517 / 5.2773333) ^ (1 / 1.095)) * Cells(14, 6).Value
Cells(15, 9).Value = ((17.517 / 5.8473333) ^ (1 / 1.095)) * Cells(15, 6).Value
Cells(16, 9).Value = ((17.517 / 10.3946667) ^ (1 / 1.095)) * Cells(16, 6).Value
Cells(17, 9).Value = ((17.517 / 16.543667) ^ (1 / 1.095)) * Cells(17, 6).Value
Cells(18, 9).Value = ((17.517 / 18.624) ^ (1 / 1.095)) * Cells(18, 6).Value

Cells(14, 10).Value = ((18.772 / 5.2773333) ^ (1 / 1.095)) * Cells(14, 6).Value
Cells(15, 10).Value = ((18.772 / 5.8473333) ^ (1 / 1.095)) * Cells(15, 6).Value
Cells(16, 10).Value = ((18.772 / 10.3946667) ^ (1 / 1.095)) * Cells(16, 6).Value
Cells(17, 10).Value = ((18.772 / 16.543667) ^ (1 / 1.095)) * Cells(17, 6).Value
Cells(18, 10).Value = ((18.772 / 18.624) ^ (1 / 1.095)) * Cells(18, 6).Value

Cells(14, 11).Value = ((19.615 / 5.2773333) ^ (1 / 1.095)) * Cells(14, 6).Value
Cells(15, 11).Value = ((19.615 / 5.8473333) ^ (1 / 1.095)) * Cells(15, 6).Value
Cells(16, 11).Value = ((19.615 / 10.3946667) ^ (1 / 1.095)) * Cells(16, 6).Value
Cells(17, 11).Value = ((19.615 / 16.543667) ^ (1 / 1.095)) * Cells(17, 6).Value
Cells(18, 11).Value = ((19.615 / 18.624) ^ (1 / 1.095)) * Cells(18, 6).Value

Cells(23, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(23, 6).Value ^ 2) / (0.9025 *
Cells(23, 7).Value)) ^ 0.5
Cells(24, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(24, 6).Value ^ 2) / (0.9025 *
Cells(24, 7).Value)) ^ 0.5
Cells(25, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(25, 6).Value ^ 2) / (0.9025 *
Cells(25, 7).Value)) ^ 0.5
Cells(26, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(26, 6).Value ^ 2) / (0.9025 *
Cells(26, 7).Value)) ^ 0.5
Cells(27, 8).Value = ((8.3 * 10 ^ -5 * 46.0606 * Cells(27, 6).Value ^ 2) / (0.9025 *
Cells(27, 7).Value)) ^ 0.5

Cells(23, 9).Value = (4 * Cells(23, 8).Value / (3 * 3.141592654)) ^ 0.5
Cells(24, 9).Value = (4 * Cells(24, 8).Value / (3 * 3.141592654)) ^ 0.5
Cells(25, 9).Value = (4 * Cells(25, 8).Value / (3 * 3.141592654)) ^ 0.5
Cells(26, 9).Value = (4 * Cells(26, 8).Value / (3 * 3.141592654)) ^ 0.5
Cells(27, 9).Value = (4 * Cells(27, 8).Value / (3 * 3.141592654)) ^ 0.5


Application.ScreenUpdating = True

End Sub
```