OPTIMIZATION OF UNDERBALANCED HYDRAULICS FOR AN AERATED MUD SYSTEM

ZAYED MOHAMMED SALEM AL-TAMIMI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Petroleum)

Faculty of Petroleum and Renewable Energy Engineering
Universiti Teknologi Malaysia

JANUARY 2014

I dedicate with love and gratitude to my mother, brothers, sister, wife and lovely kids (Khalifa and Sahed).

ACKNOWLEDGEMENT

First and foremost I would like express my thanks to Almighty ALLAH on successful completion of this research work and thesis.

I hereby, express my sincere and profound gratitude to my supervisor, Associate Professor Issham Ismail for his continuing assistance, support, guidance, and understanding throughout the research work and thesis writing. His trust, patience, knowledge, great insight, modesty, and friendly personality have always been an inspiration for me and will deeply influence my career and future life. I would like also to express my utmost gratitude to my co-supervisor, Mr. Azmi Mohd Arshad for his support and related knowledge.

Finally, I am grateful to the SPT group, Schlumberger Company, for giving the opportunity to use WELLFLO 8.1.4 software.

ABSTRACT

Underbalanced drilling (UBD) has gained popularity during recent years, as it provides a procedure to prevent formation damage, minimise lost circulation risks, and improve the rate of penetration. However, one of the most crucial steps in UBD design is to optimise the drilling hydraulics for the highest performance during the drilling operation. This task is extremely difficult because of the complex nature of the multiphase flow in the UBD system. To accomplish this task, the bottomhole pressure must be calculated. However, the bottomhole pressure, the fluid influx flow rates and the fluid properties along the wellbore are interdependent parameters and can only be derived through a combination of iterative and finite differential methods. It is therefore necessary to use a computer program to carry out the work involved. To achieve the goals of this process, a commercial software package called WELLFLO 8.1.4 was used to model the underbalanced hydraulics. Field data from the Masila Field (Yemen) reservoirs were used as the input parameters for the UBD simulator. Software validation showed good agreement between the measured standpipe pressure and the simulated standpipe pressure with less than 6% average absolute error. The analysis showed that the liquid flow rate is responsible for carrying capacity of the fluid mixture, while the gas phase is responsible for accelerating the liquid phase. Sensitivity analysis proved that the liquid phase density of drilling fluid influences the bottomhole pressure significantly while other drilling parameters such as the rate of penetration, the gas injection density and the choke pressure cause a minimal impact on the bottomhole pressure which plays a significant role in the success of UBD operations. Furthermore, it has been observed that bottomhole pressure, the velocity of the liquid phase and the nozzle size have a strong influence on bit pressure drop.

ABSTRAK

Penggerudian imbang bawah (UBD) telah menarik perhatian ramai sejak beberapa tahun kebelakangan ini kerana UBD menyediakan satu prosedur untuk mengelakkan daripada berlakunya kerosakan formasi, mengurangkan risiko kehilangan edaran, dan meningkatkan kadar penembusan. Walau bagaimanapun, satu langkah penting dalam merekabentuk UBD adalah untuk mengoptimumkan hidraulik penggerudian bagi menghasilkan prestasi tertinggi ketika operasi penggerudian berjalan. Tugasan ini amat sukar kerana sifat kompleks aliran berbilang fasa dalam sistem UBD. Untuk menyempurnakan tugasan ini, tekanan lubang bawah mesti dikira. Walau bagaimanapun, tekanan lubang bawah, kadar aliran kemasukan cecair, dan sifat-sifat cecair sepanjang lubang telaga merupakan parameter yang saling bergantung dan hanya boleh diterbitkan menerusi gabungan lelaran dan kaedah pembezaan terhingga. Dengan itu, program komputer harus digunakan untuk melaksanakan tugasan tersebut. Untuk mencapai matlamat proses ini, pakej perisian komersial yang dikenal sebagai WELLFLO 8.1.4 digunakan untuk memodelkan hidraulik imbang bawah. Data lapangan dari medan Masila yang terletak di Yemen, telah digunakan sebagai input parameter untuk simulator UBD. Pengesahan perisian telah memberikan hasil yang setanding antara tekanan terukur paip tegak dengan tekanan simulasi paip tegak iaitu purata ralat mutlak kurang daripada 6 %. Hasil analisis menunjukkan bahawa kadar aliran cecair mempengaruhi kapasiti cecair campuran, manakala fasa gas berupaya memecut fasa cecair. Analisis kepekaan membuktikan bahawa ketumpatan fasa cecair dalam bendalir gerudi mempengaruhi tekanan bawah lubang secara ketara manakala parameter penggerudian yang lain misalnya kadar penembusan, ketumpatan gas suntikan, dan tekanan pencekik memberikan kesan yang minimum terhadap tekanan lubang bawah yang menentukan kejayaan operasi UBD. Selain itu, tekanan bawah lubang, halaju fasa cecair, dan saiz muncung mempunyai pengaruh yang kuat terhadap kejatuhan tekanan bit.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

Symbols:

CTR	-	Cuttings transport Ratio, %
C_C	-	Cuttings concentration, %
C_N	-	Loss coefficient, %
De	-	Effective orifice diameter, ft
d_H	-	Hole diameter, in
d_p		Pipe diameter, in
d_s	-	Diameter of the cuttings, in
E_a	-	Average absolute error, %
g	-	Acceleration due to gravity, 32.2 ft/sec^2
n	-	Number of bit nozzles
P	-	Pressure, psi.
P_{atm}	-	Atmospheric pressure (14.696 psia)
P_B	-	Bit pressure drop across the bit, psi
P_{bh}	-	Bottomhole pressure, psi
P_{choke}	-	Choke pressure or backpressure, psi
P_{up}	-	Upstream pressure, psi
Q_L	-	Liquid flow rate, gpm
Q_G	-	Gas flow rate, scf/min
Re_c	-	Cuttings Reynolds number
ROP	-	Rate of penetration, m/hr
SPP	-	Stand pipe pressure, psia
T_{bh}	-	Bottomhole temperature, °C

V_a	-	Annular slip velocity, ft/sec
V_{slip}	-	Slip velocity, ft/sec
V_t	-	Cutting transportation velocity, ft/sec
V_{mean}	-	mean velocity of the multiphase fluid, ft^3
W_G	-	The weight rate of flow of gas (Ib/sec)
W_L	-	The weight rate of flow of mud (Ib/sec)

Greek Symbols:

γ_{mixbh}	-	Specific weight of the fluid mixture under Bottomhole conditions (lb/ft^3)
γ_G	-	Specific weight of the gas (lb/ft^3)
γ_L	-	Specific weight of the mud (lb/ft^3)
π	-	Constant = 3.14
ρ_G	-	Gas density, ppg
ρ_L	-	Liquid density, ppg
ρ_f	-	Mean density of the multiphase fluid, ppg
ρ_s	-	Density of the solid cuttings, ppg
Φ	-	Rock porosity, fraction
μ_f	-	Mean viscosity of the multiphase fluid, cp

UNITS:

bbl	-	barrel; (volume)
cc or cm^3	-	cubic centimeter; (volume)
m	-	meter; (length)
cm	-	centimeter = 1^{-2} m; (Length)
cm^2 or sq cm	-	square centimeter; (area)
in	-	inch = 1/12 foot; (diameter)

mm	-	millimeter = 1^{-3} m; (diameter)
ft	-	foot; (length and/or diameter)
ft^3/sec	-	cubic feet/second; (flow rate)
ft/sec	-	foot/second; (velocity)
scf/min	-	standard cubic feet/minute; (flow rate)
gpm	-	gallon per minute; (flow rate)
sec	-	second; (time)
L	-	liter; (volume)
LPM	-	liter/minute; (flow rate)
min	-	minute; (time)
cp	-	centipoises = 1^{-2} poise; (dynamic viscosity)
lb_f	-	pound force; (force)
lb_m	-	pound mass; (mass)
ppg	-	pound mass per gallon; (density)
psi	-	pound force per square inch; (pressure)
°	-	degree angle; (inclination)
°F	-	degree Fahrenheit; (temperature)
%	-	percentage
RPM	-	revolution per minute

ABBREVIATIONS:

AIME	-	American Institute of Mining, Metallurgical and Petroleum Engineers
API	-	American Petroleum Institute
ASTM	-	American Society for Testing Materials
BOP	-	Blowout Prevention
BHA	-	Bottom Hole Assembly
BHR	-	The British Hydromechanics Research
CT	-	Coiled Tubing
DC	-	Dill Collar
DEA	-	Drilling Engineering Association
DOE	-	Department of Energy

DOI	-	Digital Object Identifier
DP	-	Drill Pipe
ECD	-	Equivalent Circulation Density
EMT	-	Electromagnetic Telemetry
EMWD	-	Electromagnetic Measurement While Drilling
EPET	-	Elevated Pressures and Elevated Temperatures
HWDP	-	Heavy Weight Drill Pipe
IADC	-	International Association of Drilling Contractors
Int.J.MPF	-	International Journal of Multiphase Flow
JCPT	-	Journal of Canadian Petroleum Technology
J. PSE	-	Journal of Petroleum Science and Engineering
JPT	-	Journal of Petroleum Technology
KOP	-	Kick off Point
LIT	-	Lost Time Incident
MWD	-	Measurement While Drilling
OBO	-	Overbalanced Drilling
Oil & Gas J.	-	Oil and Gas Journal
PE J.	-	Petroleum Engineering Journal
POOH	-	Pull Out Open Hole
PVT	-	Pressure, Volume and Temperature
RIH	-	Run in Hole
ROP	-	Rate of Penetration
RPM	-	Revolution per Minute
RT	-	Rotary Table
SG	-	Specific Gravity
SPE	-	Society of Petroleum Engineers
SPE J.	-	Society of Petroleum Engineers Journal
TD	-	Total Depth
TUDRP	-	Tulsa University Drilling Research Projects
TVD	-	True Vertical Depth
UBD	-	Underbalanced Drilling
UBO	-	Underbalanced Operation
UEA	-	United Emirates Arab
USA	-	United State America

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Underbalanced drilling (UBD) is a drilling process where the drilling fluid's pressure in the wellbore is intentionally designed to be lower than the pressure of the formation being drilled. This pressure difference causes the fluid in the reservoir to flow into the wellbore while drilling thereby preventing formation damage and fluid loss. This process requires special procedures and additional equipment before commencement, during the drilling, and after a UBD operation. The UBD technique is far superior to conventional drilling techniques and has several important advantages, such as low probability of pipe sticking, improved formation damage, high penetration rate and bit life, and better formation evaluation.

This chapter introduced the underbalanced drilling technology, comparing the underbalanced and overbalanced operations, UBD's beneficial and limiting factors, gasified liquid drilling operations, and UBD challenges in the Masila oilfield. The problem statement, objectives, scopes of the study, significance of the research work, and thesis organization are also presented.

1.2 Underbalanced Drilling Technology

Comparing overbalanced drilling and underbalanced drilling allows us to establish the main differences between the two drilling techniques.

Overbalanced operation (OBO), when drilling fluid invasion and the hydrostatic pressure in a wellbore can mask potentially productive zones. Formation damage, especially in horizontal wells, is often difficult to clean up once the wells are released to production. Tight zones may have never been cleaned up, resulting in large sections of a well (especially the horizontal segment) being unproductive. Lost circulation and differential sticking can often result in severe drilling problems and many wells in depleted reservoirs never get to their planned total depth (TD) (Figure 1.1).

Underbalanced operation (UBO) can improve the detection of productive hydrocarbon zones even identifying zones that have been bypassed if the well was drilled conventionally. The use of UBO minimizes or completely eradicates damage to the reservoir rocks, including the tighter sections of a well, resulting in better production. There are no fluid losses and no differential sticking may be experienced as the drilling fluid pressure is below the reservoir pressure (Figure 1.1).

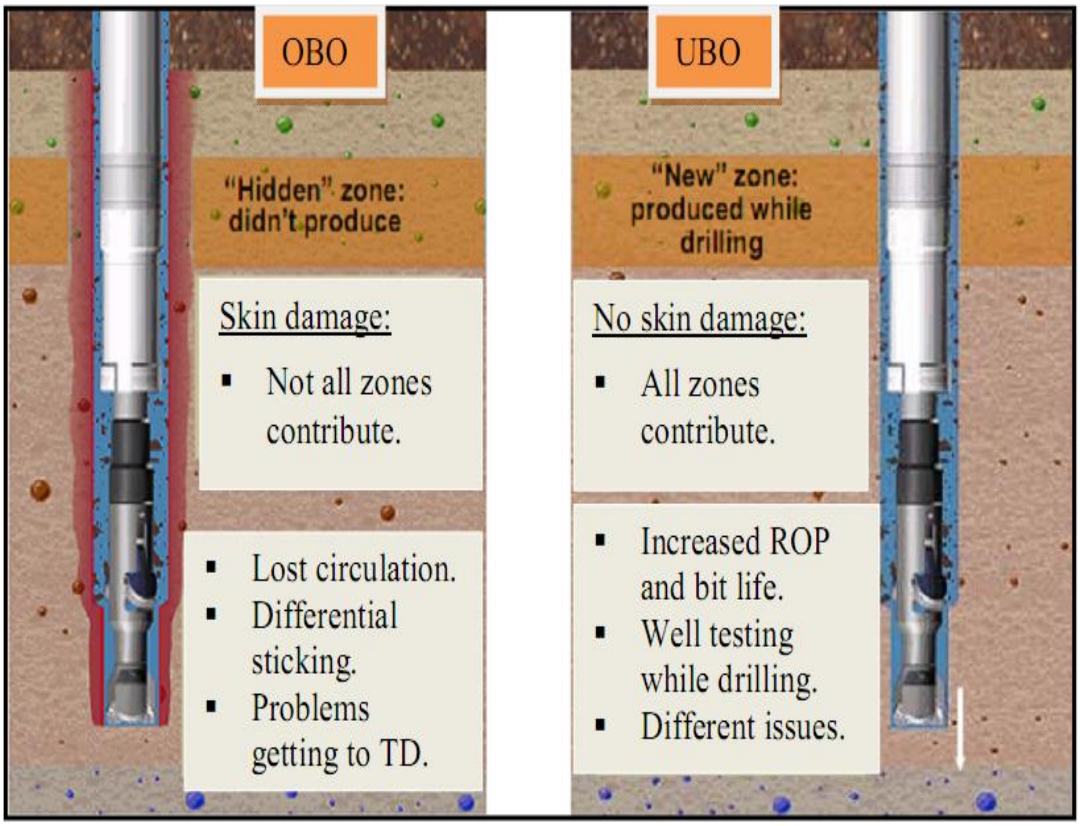

Figure 1.1 Overbalanced operations versus underbalanced operations (Nas, 2006a)

1.2.1 UBD – Beneficial and Limiting Factors

Underbalanced drilling has numerous important advantages over conventional drilling techniques. Table 1.1 shows the beneficial and limiting factors of UBD.

Table 1.1 UBD – beneficial and limiting factors (Bennion *et al.,* 1996; Baker Hughes, 1999; Mathes *et al.,* 1999)

Beneficial factors	**Limiting factors**
(1) Reduced formation damage/increased productivity/reduced stimulation requirements. (2) Improved formation evaluation/identification of fractures. (3) Minimised loss of circulation. (4) Elimination of differential sticking. (5) Increased penetration rate. (6) Increased bit life. (7) Reduction/elimination of expensive drilling fluid programmes. (8) Improved safety and reduced environmental impact. (9) Early production.	(1) Additional engineering and operational complexity. (2) Increased operational risks such as higher surface pressures and continually flowing well during drilling. (3) New methods of cutting transportation and disposal. (4) Utilization of specialized equipment. (5) Potentially higher daily operational costs.

1.3 UBD Techniques

Various UBD drilling techniques applied in the oil and gas industry employ air, gas, foam, mist, and gasified liquid (aerated liquid). Figure 1.2 shows the UBD compressible fluid classifications. However, for the purpose of this research, only the gasified liquid drilling techniques were considered. Some of the benefits of drilling with aerated fluids include the avoidance of lost circulation, reduced formation damage, prevention of differential sticking, and increased rate of penetration. The objectives are to achieve a planned total depth when drilling wells and to minimize and/or eliminate circulation losses in these wells, thereby preventing a reoccurrence of past experience recorded from drilling similar wells in the Masila field. Other objectives are to improve the penetration rate, bit life, and reduce the possibilities of encountering drilling problems such as differential sticking and inefficient hole cleaning by utilizing an aerated drilling system.

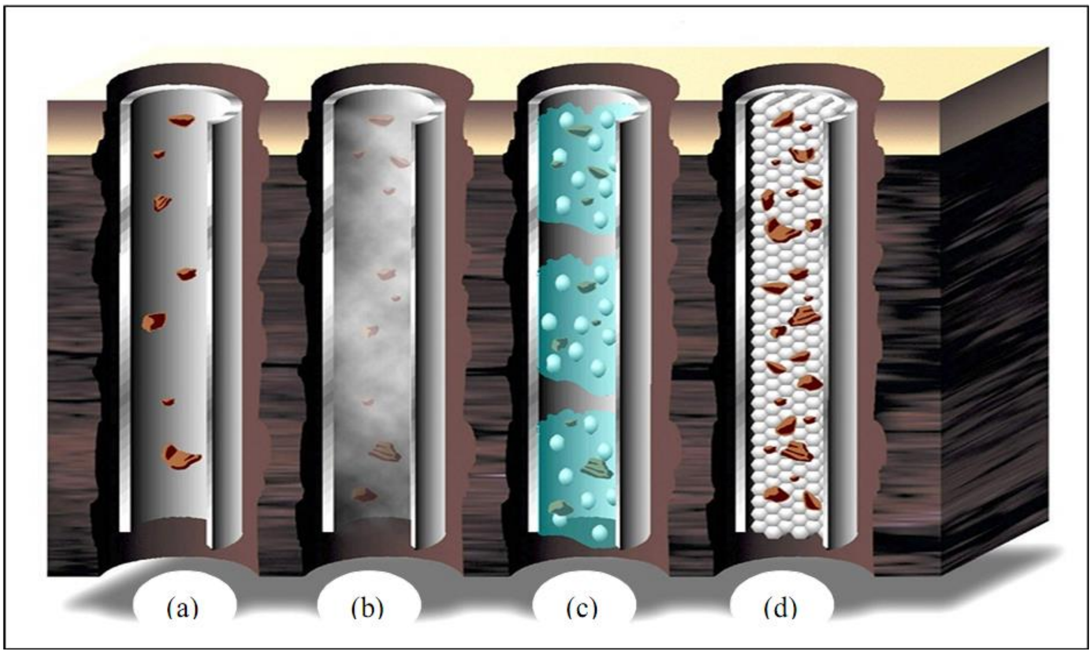

Figure 1.2 Compressible fluid classifications: (a) air or gas, (b) mist, (c) aerated liquid, (d) foam. (Weatherford, 2007)

1.4 Gasified Liquid Drilling Operations

When the liquid and gas phases are mixed on purpose in order to reduce the fluid density, we have what is called gasified or aerated fluid. Usually, the mixture occurs at the surface where the gas is injected into the fluid before pumping through the drill pipe.

The benefits that can be reached from a gasified UBD are the avoidance of lost circulation, reduction of formation damage, avoidance of differential sticking, and increased rates of penetration. However, the biggest challenge faced by a gasified system is the intermittent nature of the operation as the gasified fluid starts to separate, especially in the annulus, once there is an interruption in the operation either as a result of technical issues or otherwise. This causes a hydrostatic pressure to be exerted downhole in the formation and may lead to an overstepping of the pore pressures of the reservoir anytime circulation is re-established as a result of the slug of pure liquid formed during the interruption period (Alajmi, 2003).

Gasified design often requires computer programs because of the complex nature of the fluid mixture in drilling systems where water, gas, drilled cuttings and fluid influxes from the penetrated formations are present. It can be seen from a computer simulation how an air injection rate causes the lowest flow annulus pressure for a given well geometry and mud flow rate. Investigations enhanced by computer simulation reveal the effect of different mud flow rates on their carrying capacity. It reveals that a low mud flow rate has poor carrying capacity of the gasified mud. Past research findings reveal that an optimum mix of air rates and drilling mud can be achieved for gasified liquid drilling if the annulus pressure flow and carrying capacity are taken into consideration (Guo and Rajtar, 1995; Gou *et al.*, 1996).

1.5 UBD Challenges in the Masila Oilfield

Masila oilfield, which is located in the south eastern part of Yemen, provides a good opportunity for the implementation of the UBD technology so as to address some of the challenges encountered in field operations. The Masila oilfield has a drilling history characterised by pressure loss and a highly fractured basement formation. Their low pressured reservoir has posed a serious challenge for the traditional overbalanced drilling techniques. Recently, there have been no publications discussing the potential of UBD for the Masila oilfield. Despite its several advantages and its increasing role in drilling technology, UBD has not been given the attention it deserves as very little research has been conducted in this field. This research work investigates the main UBD challenges in the Masila oilfield and summarises the solutions for dealing with them. UBD hydraulics has been identified as a problem in this study.

Considering UBD as a solution for overcoming all drilling and production problems or looking only on the bright side of this technology seems to be dogmatic. Despite playing an important role globally, even this method of drilling includes some challenges during its implementation. The main goal in most of the UBD operations that have been implemented in Yemen since 2006 was to deal with severe losses to get to Total Depth (TD). Some of the advantages of UBD have gained while others need to be more thoroughly investigated in future research in the Masila oilfields.

1.6 Problem Statement

The use of gasified drilling fluids for drilling highly fractured formations and depleted reservoirs have been on the increase. Gasification of the fluid is achieved by injecting gas and liquid through the drill string resulting in a compressible two-phase flow in the drill string. Due to the technical complexity of UBD operations, the success of such operations depends on the accuracy of a detailed engineering study that is typically carried out both before and during the actual drilling. Accurate computer modelling of the hydraulics of bottomhole pressure, hole cleaning, and pressure drop through bit nozzles is a critical component of this design and performance evaluation process.

Cuttings transport is a key factor militating against the time, cost, and quality of UBD. When holes are not adequately cleaned, drilling becomes expensive due to resultant effects like premature bit wear, pipe sticking, high torque and drag, formation fracture, and slow drilling. Cuttings transport is influenced by many variables which include the penetration rate, the rotational speed of the drill pipe, the diameter of the hole and drill pipe, the cutting size, the fluid velocity, and the flow rate of gas and liquid fluid.

It is worth mentioning that bit efficiency can be enhanced if hydraulic power is increased. This increases penetration rate and causes the cuttings to be quickly removed as soon as they are generated. Thus, the major focus of this research is on the pressure drop at the bit since the hydraulic power is dependent on the pressure drop across the bit.

1.7 Objectives

The objectives of this study are:

(1) To investigate the effect of different drilling parameters such as choke pressure, rate of penetration, mud density and gas density on bottomhole pressure.

(2) To investigate the effect of bottomhole temperature and pressure, liquid flow rate, gas injection rate, nozzle size, and bit size on bit pressure drop.

(3) To investigate the effective variables in cutting transport performance of aerated drilling fluid, which include drilling fluid rate, gas injection rate and rate of penetration.

1.8 Scopes of the Study

To accomplish the objectives of this study, the scopes of this study are divided into three sections as follows:

(1) Simulation work to determine the best combination of drilling hydraulics parameters, such as prediction of bottomhole pressure, hole cleaning and pressure drop on the bit. Works were accomplished to determine optimum selection of hydraulics parameters during UBD operations.

(2) The modelling software known as WELLFLO 8.1.4 was used for the simulation of all the UBD hydraulics parameters in this research work. The UBD simulator was validated using field case study.

(3) The simulation results were validated by comparing the predicted injection pressures against field data obtained from the Masila oilfield. Three sets of measured field data which were obtained from three wells in the Masila oilfield: X #1, X #2, and X #3. All of these wells were drilled vertically using aerated mud and air through drill string injection.

1.9 Significance of the Research Work

This research work is very significant to the oil and gas industry, especially to Masila oilfield in the south east of Yemen, for a number of reasons as shown below:

(1) The study would produce an accurate computer modelling of the hydraulics of bottomhole pressure, hole cleaning, and pressure drop through bit nozzles which could serve as a critical component for the design and performance evaluation process of UBD.

(2) The findings of the study would reveal the effective variables to be used in cuttings transport which could reduce the cost and time used on UBD.

(3) The theoretical and practical contributions of this research would provide areas for researchers who may wish to further the advancement of UBD since there are very few academic publications in this field at the moment. Practically, it could offer a solution to the challenges faced at the Masila oilfield, which is characterized by low pressured reservoirs that has until now proved difficult for traditional overbalanced approaches. The simulation results obtained from this research were expected to make positive contributions in understanding the behavior and performance of UBD hydraulics that is very much needed in designing the UBD program.

1.10 Thesis Organization

This thesis is structured into five chapters, the references, and appendices.

Chapter 1 presents an overview of the thesis, made up of: a brief induction and background on underbalanced drilling technology, comparing the underbalanced and overbalanced operations, UBD benefits and limiting factors. The problem statement, objectives and scopes of the study are also presented.

Chapter 2 reviews literature related to the present study. Topics reviewed include modelling multiphase flow in UBD which explains how several techniques are used in order to achieve the optimum result while performing UBD operations. Next, the optimisation hydraulics of underbalanced drilling were presented in detail, including bottomhole pressure prediction, pressure drop across bit nozzles and hole cleaning in underbalanced drilling. Finally, the UBD Simulator used in this study was reviewed.

Chapter 3 explains the method employed in conducting the research. The techniques used to obtain and analyse field data for the study was reported. This segment also highlighted the actions taken to achieve the objectives of this study.

Chapter 4 discuses and summarizes the simulation results obtained.

Chapter 5 presents the conclusions and recommendations for further research.

REFERENCES

Aladwani, F. A. (2003). *Application of Mechanistic Models in Predicting Flow Behavior in Deviated Wells Under UBD Conditions*. Master Thesis. Louisiana State University and Agricultural & Mechanical College, Louisiana, United States.

Aladwani, F. A. (2007). *Mechanistic Modeling of an Underbalanced Drilling Operation utilizing Supercritical Carbon Dioxide*. Ph.D. Dissertation. Louisiana State University and Agricultural & Mechanical College, Louisiana, United States.

Alajmi, S. E. (2003). *Optimum Selection of Underbalanced Techniques*. Master Thesis. Texas A & M University, Texas, United States.

Alajmi, S. E. and Schubert, J. J. (2003). Optimum Selection of Underbalanced Techniques. SPE number 85322, *SPE/IADC Middle East Drilling Technology Conference & Exhibition*, Abu Dhabi, UAE.

Andersen, H., Vigrestad, A. and Kuru, E. (2009). Hydraulic Optimization of Aerated Mud Drilling for Maximum Drilling Rate. *IADC/SPE Managed Pressure Drilling and Underbalanced Operations Conference & Exhibition*, 12-13 February, San Antonio, Texas.

Ansari, A. M., Sylvester, N. D., Sarica, C., Shoham O. and Brill J. P. (1994). A Comprehensive Mechanistic Model for Upward Two-Phase Flow in Wellbores. *SPE Production & Operations* 9.

Asheim, H. (1986). MONA, An Accurate Two-Phase Well Flow Model based on Phase Slippage. *SPE Production Engineering*, p. 221, May.

Avila, R., Pereira, E., Miska, S., Takach, N. and Saasen, A. (2008). Correlations and Analysis of Cuttings Transport With Aerated Fluids in Deviated Wells. *Journal SPE Drilling & Completion* Volume 23, Number 2, Pages: 132-141.

Azar, J. J. and Sanchez, R. A. (1997). Important Issues in Cuttings Transport for Drilling Directional Wells. Paper SPE 39020 presented at *the 5th Latin American and Caribbean Petroleum Engineering Conference*, Brazil.

Aziz, K., Govier, G. W. and Fogarasi, M. (1972). Pressure Drop in Wells Producing Oil and Gas. *The Journal of Canadian Petroleum Technology*, Vol.11, p. 38.

Baker Hughes INTEQ. (1999). *Underbalanced Driling Manual*. Version 1.0: Baker Hughes Inc.

Baxendell, P. B. and Thomas R. (1961). The Calculation of Pressure Gradients in High-Rate Flowing Wells. *SPE Journal of Petroleum Technology 13*.

Beggs, H. D. and Brill, J. P. (1973). A Study of Two-Phase Flow in Inclined Pipes. *Journal of Petroleum Technology*, Vol. 5, pp. 607-617. doi: 10.2118/4007-pa.

Bendiksen, K. H., Maines, D., Moe, R. and Nuland, S. (1991). The Dynamic Two-Fluid Model OLGA: Theory and Application. *SPE Production Engineering*, Vol. 6, p. 171, May.

Bennion, D. B., Thomas, F. B., Bietz, R. F. and Bennion, D. W. (1996). Underbalanced Drilling Praises and Perils. SPE paper 35242 presented at *the SPE Permian Basin Oil & Gas Recovery Conference*, March 27-29, Midland, Texas.

Bennion, D. B., Thomas, F. B., Bietz, R. F. and Bennion, D. W. (1998). Underbalanced Drilling Praises and Perils. SPE paper 52889. *SPE Drilling & Completion*, Vol. 13, pp. 214-222, December.

Beyer, A. H., Millhone, R. S. and Foote, R. W. (1972). Flow Behaviour of Foams as a Well Circulating Fluid. SPE paper 3986, presented at *the SPE Annual Technical Conference and Exhibition*, San Antonio, Texas, October.

Bharath, R. (1999). *Coiled Tubing Hydraulics Modeling*. Technical Note, CTES, L.C. Texas, USA. Retrieved from: http://ctes.nov.com/documentation/technotes/Tech%20Note%20Basic%20Hydraulics.pdf.

Bijleveld, A. F., Koper, M. and Saponja, J. (1996). Development and Application of an Underbalanced Drilling Simulator. Paper IADC/SPE 39303 *presented at the IADC/SPE Drilling Conferences held in Dallas*, Texas.

Bourgoyne Jr., A. T. and Casariego, V. (1988). Generation Migration and Transportation of Gas Contaminated Regions of Drilling Fluids. SPE 18020, 63*rd* *Annual Technical Conference and Exhibition of the SPE held in H, Houston, TX,* October 2-5.

Bourgoyne, Jr., A. T., Chenevert, M. E., Millheim, K. K. and Young, F. S. (1991). *Applied Drilling Engineering*. SPE Textbook Series Volume 2. Richardson, TX: The Society of Petroleum Engineers.

Brown, K. E. (1977). *The Technology of Artificial Lift Methods*. Volume 1. Tulsa, OK : Petroleum Publishing Co.

Caetano, E. F. (1986). *Upward Two-Phase Flow through an Annulus*. Ph.D. Dissertation, the University of Tulsa.

Cho, H., Shah, S. N. and Osisanya, S. O. (2002). A Three-Layer Modeling for Cuttings Transport with Coiled Tubing Horizontal Drilling. SPE 63269, Presented at *the 2000 SPE Annual Technical Conference and Exhibition, Dallas-Texas* (October 1-4) and *Journal of Canadian Petroleum Technology*, Volume 41, Number 6, June.

Duda, J. R., Medley, G. H. and Deskins, W. G. (1996). Strong Growth Projected for Underbalanced Drilling. *Oil & Gas Journal*, September 23.

Duns, H. and Ros, N. C. J. (1963). Vertical Flow of Gas and Liquid Mixtures in Wells. Proceedings of *the 6th World Petroleum Congress*, pp. 451- 465.

Falcone, G., Teodoriu, C., Reinicke, K. M. and Bello, O. O. (2008). Multiphase Flow Modeling Based on Experimental Testing: An Overview of Research Facilities Worldwide and the Need for Future Developments. *SPE Projects, Facilities & Construction,* Volume 3, Number 3, pp. 1-10.

Fancher, G. H. and Brown, K. E. (1963). Prediction of Pressure Gradients for Multiphase Flow in Tubing. *Society of Petroleum Engineers Journal*, pp. 59-69.

Gillies, R. G., McKibben, M. J. and Shook, C. A. (1997). Pipeline Flow of Gas, Liquid and Sand Mixture at Low Velocities. *Journal of Canadian Petroleum Technology*, Vol. 39, No. 9, pp. 36-42, October.

Gomez, L. E., Shoham, O., Schmidt, Z., Chokshi, R. N., Brown, A. and Northug, T. (1999). A Unified Mechanistic Model for Steady-State Two-Phase Flow in Wellbores and Pipelines. *SPE Annual Technical Conference and Exhibition*, Society of Petroleum Engineers, Houston, Texas.

Govier, G. W. and Fogarasi, M. (1975). Pressure Drop in Well Producing Gas and Condensate. *Journal of Canadian Petroleum Technology*, Vol. 14, No. 4, pp. 28-411, October.

Gregory, G. A. (2000). Wellbore Temperature Profile Calculations for Underbalanced Drilling Applications. *Proc. of 2nd North American Conf on Multiphase Flow, sponsored by BHR Group*, Banff, AB, June.

Gregory, G. A. (2003). Foam Flow Modelling for UBD Applications. *Journal of Canadian Petroleum Technology*, Vol. 42, No. 3, pp. 8-13, March.

Gucuyener, I. H. (2003). Design of Aerated Mud for Low Pressure Drilling. *SPE Asia Pacific Oil and Gas Conference and Exhibition.* Jakarta, Indonesia: *Society of Petroleum Engineers Inc*.

Guo, B. and Liu, G. (2011). *Applied Drilling Circulation Systems*: *Hydraulics, Calculations and Models*. 1st Edition. USA: Gulf Professional Publishing is an imprint of Elsevier.

Guo, B. and Rajtar, J. M. (1995). Volume Requirements for Aerated Mud Drilling. SPE paper 26956 *Drilling & Completion Journal*, June, pp. 165-169.

Guo, B., Hareland, G. and Rajtar, J. M. (1996). Computer Simulation Predicts Unfavorable Mud Rate and Optimum Air Injection Rate for Aerated Mud Drilling. *SPE Drilling & Completion 11*.

Guo, B., Ghalambor, A. and Al-Bemani, A. S. (2002). Prediction of Sonic Flow Conditions at Drill Bit Nozzles to Minimize Complications in UBD. Presented at *the Petroleum Society's Canadian International Petroleum Conference*, Calgary, Alberta.

Guoqiu, F. (1992). An Experimental Study of Free Settling of Cuttings in Newtonian and Non Newtonian Drilling Fluids: Drag Coefficient and Settling Velocity. Paper of *Society of Petroleum Engineers*, No. 26125.

Gupto, A. (2006). *Feasibility of Supercritical Carbon Dioxide as A Drilling Fluid for Deep Underbalanced Drilling Operations*. Master Thesis. Louisiana State University and Agricultural & Mechanical College, Louisiana, United States.

Kaya, A. S., Sarica, C. and Brill, J. P. (1999). Comprehensive Mechanistic Modeling of Two-Phase Flow in Deviated Wells. *SPE Annual Technical Conference and Exhibition, Society of Petroleum Engineers*, Houston, Texas.

Kuru, E., Okunsebor, O. M. and Li, Y. (2005). Hydraulic Optimization of Foam Drilling For Maximum Drilling Rate in Vertical Wells. *SPE Drilling & Completion 20*.

Kuru, E., Miska, S., Pickell, M., Takach, N. and Volk, M. (1999). New Directions in Foam and Aerated Mud Research and Development. SPE 53963. *Presented at the 1999 Latin American and Caribbean Petroleum Engineering Conference*, Caracas-Venezuela (April 21-23).

Hagedorn, A. R. and Brown, K. E. (1965). Experimental Study of Pressure Gradient Occurring during Continuous Two-Phase Flow in Small Diameter Vertical Conduits. *Journal of Petroleum Technology*, pp. 475-484.

Hasan, A. R. and Kabir, C. S. (1992). Tow-Phase Flow in Vertical and Inclined Annuli. *International Journal of Multiphase Flow*, Vol. 18, No. 2, pp. 279-293.

Isabel, C. G. and Sara, S. (2003). Comparison of Wellbore Hydraulics Models to Maximize Control of BHP and Minimize Risk of Formation Damage. *IADC/SPE Underbalanced Technology Conference and Exhibition*. Houston, Texas.

Lage, A. C. V. M. and Time, R. W. (2000). An Experimental and Theoretical Investigation of Upward Two-Phase Flow in Annuli. S*PE Asia Pacific Oil and Gas Conference and Exhibition*, Society of Petroleum Engineers Inc., Brisbane, Australia.

Lage, A. C. V. M., Rommetveit, R. and Time, R. W. (2000). An Experimental and Theoretical Study of Two-Phase Flow in Horizontal or Slightly Deviated Fully Eccentric Annuli. I*ADC/SPE Asia Pacific Drilling Technology*, Kuala Lumpur, Malaysia.

Liu, G. and Medley, G. H. (1996). Foam Computer Model Helps in Analysis of Underbalanced drilling. *Oil and Gas Journal*, July, p. 116.

Li, J. and Walker, S. (1999). Sensitivity Analysis of Hole Cleaning Parameters in Directional Wells. SPE paper number 54498 presented at *SPE/ICoTA Coiled Tubing Roundtable,* Houston, Texas.

Li, J. and Walker, S. (2001). Sensitivity Analysis of Hole Cleaning Parameters in Directional Wells. *SPE Journal*, Vol 6, Number 4, December.

Li, Y. and Kuru, E. (2006). Numerical Modeling of Cutting Transport with Foam in Inclined Wells. *Canadian International Petroleum Conference*. Paper 2003-66.

Lopes, C. A. (1997). *Feasibility Study on the Reduction of Hydrostatic Pressure in a Deep Water Riser Using a Gas-Lift Method.* Ph.D. Dissertation, Louisiana State University. USA.

Lourenco, A. M. F., Martins, A. L., Andrade Jr, P. H. and Nakagawa, E. Y. (2006). Investigating Solids-Carrying Capacity for an Optimized Hydraulics Program in Aerated Polymer-Based-Fluid Drilling. *SPE Drilling Conference*, 21-23 February, Miami, Florida, USA.

Lyons, W. C. (2010). *Working Guide to Drilling Equipment and Operations.* 1st Edition. Amsterdam: Elsevier Publishing Company.

Lyons, W. C., Guo, B., Graham, R. L. and Hawley, G. D. (2009). *Air and Gas Drilling Manual*. 3rd Edition. Amsterdam: Elsevier Publishing Company.

Mathes, R. A. and Jack, L. J. (1999). Successful Drilling of an Underbalanced Dual-lateral Well in the Sajaa Field, Sharjah, UAE. Paper SPE/IADC 57569 presented at *the SPE/IADC Middle East Drilling Technology Conference,* 8-10 November, Abu Dhabi, UAE.

Martins, A. L. C., Sa, H. M., Lourenco, A. M. F., and Compose, W. (1996). Optimizing Cuttings Transport in Horizontal Well Drilling. Paper SPE 35341 presented at *the Petroleum Conference & Exhibition of Mexico*, 5-7 March.

Maurer Engineering Inc. (1998a). *Underbalanced Drilling and Completion Manual.* Copyrighted 1998, DEA-101, Houston, Texas, USA.

Maurer Engineering Inc. (1998b). Air/Mist/Foam/ Hydraulics Model, Version 2 User's Manual, copyrighted 1998, DEA-101, Houston, Texas, USA.

Nakagawa, E. Y., Sliver Jr, V., Boas, M. B. V., Silva, P. R. C. and Shayegi, S. (1999). Comparison of Aerated Fluids/Foam Drilling Hydraulics Simulators Against Field Data. *SPE Asia Pacific Oil and Gas Conference and Exhibition, Society of Petroleum Engineers*, Jakarta, Indonesia.

Nas, S. (2006a). *Indroduction to Underbalanced Drilling*. Technical Report Revision 001. Wethreford Underbalnced System, Singapore. Retrieved from: http://dc131.4shared.com/doc/yYJVm7PS/preview.html

Nas, S. (2006b). Underbalanced Drilling. In Lake, L.W. and Mitchell, R. F. (Eds.), Petroleum Engineering Hand Book: Vol. 2. Drilling Engineering (pp. 519–569). Richardson, Texas, USA: Society of Petroleum Engineers.

Nossen, J., Shea, R. H. and Rasmussen, J. (2000). New Developments in Flow Modeling and Field Data Verification. Multiphase Technology. BHR Group Conference Series, No. 40, pp. 209-222, presented at *the Second North American Conference on Multiphase Technology*, Banff, Canada, June 21-23.

Omana, R., Houssiere, Jr. C., Brown, K. E., Brill, J. P. and Thompson, R. E. (1969). Multiphase Flow Through Chokes. *Fall Meeting of the Society of Petroleum Engineers of AIME, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc.*, Denver, Colorado.

Orkiszewski, J. (1967). Predicting Two-Phase Pressure Drops in Vertical Pipe. S*PE Journal of Petroleum Technology 19.* doi: 10.2118/1546-pa.

Osman, M. E., and Dokla, M. E. (1990). Gas Condensate Flow through Chokes. *European Petroleum Conference, Society of Petroleum Engineers,* The Hague, Netherlands.

Osman, M. E., and Dokla, M. E. (1992). Correlation Predict Gas-Condensate Flow Through Chokes. *Oil and Gas J.*, March 16, 1992, pp. 43-46.

Osunde, O., and Kuru, E. (2006). Numerical Modeling of Cutting Transport with Foam in Inclined Wells. *Canadian International Petroleum Conference*. Paper 2006-07.

Ozbayoglu, M. E., Kuru, E., Miska, S. and Takach, N. (2000). A Comparative Study of Hydraulic Models for Foam Drilling. *SPE/CIM International Conference on Horizontal Well Technology*, Calgary, Alberta, Canada.

Peden, J. M., Ford, J. T. and Oyeneyin, M. B. (1990). Comprehensive Experimental Investigation of Drilled Cuttings Transport In Inclined Wells Including The effects of Rotation and Eccentricity. Paper SPE 20925 presented at *the Europec 90*, The Hague, Netherlands, 22-24 October.

Perez-Tellez, C. (2002). *Improved Bottomhole Pressure Control For Underbalanced Drilling Operations.* Ph.D. Dissertation, Louisiana State University and Agricultural & Mechanical College, Louisiana, USA. p. 141.

Perez-Tellez, C., Smith, J. R. and Edwards, J. K. (2002). A New Comprehensive, Mechanistic Model for Underbalanced Drilling Improves Wellbore Pressure Predictions. *SPE International Petroleum Conference and Exhibition* in Mexico, Copyright 2002, Society of Petroleum Engineers Inc., Villahermosa, Mexico.

Perez-Tellez, C., Smith, J. R. and Edwards, J. K. (2003). A New Comprehensive, Mechanistic Model for Underbalanced Drilling Improves Wellbore Pressure Prediction. *SPE Drilling & Completion 18*. doi: 10.2118/85110-pa.

Pilehvari, A. A. and Azar, J. J. (1996). State-of-Art Cutting Transport in Horizontal Wellbores. Paper SPE 37079 presented at the *Conference on Horizontal Well Technology held in Calgary.*

Rehm, B. (2002). *Practical Underbalanced Drilling and Workover*. 1st Edition Petroleum Extension Services. The University of Texas at Austin, USA.

Rommetveit, R., Vefring, E. H., Wang, Z., Research, R. R., Bieseman, T. and Faure, A. M. (1995). A Dynamic Model for Underbalanced Drilling With Coiled Tubing, SPE/IADC Drilling Conference, 1995, Copyright 1995, SPE/IADC *Drilling Conference*, Amsterdam, Netherlands.

Samble, K. J. and Bourgoyne, A. T. (1977). An Experimental Evaluation of Correlations Used for Predicting Cutting Slip Velocity. SPE 6645 *presented at the 52nd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME* held in Denver, Colorado. Oct 9 - 12.

Sample, K. J. and Bourgoyne, A. T. (1978). Development of Improved Laboratory and Field Procedures for Determining the Carrying Capacity of Drilling

Fluids. Paper SPE 7497 *presented at the SPE Annual Technical Conference and Exhibition*, Houston, Oct. 1-4.

Sanchez, R. A., Azar, J. J., Bassal, A. A. and Martins, A. L. (1997). The Effect of Drill pipe Rotation on Hole Cleaning During Directional Well Drilling. SPE paper 37626 presented at *the Drilling Conference*, Amsterdam (Mar. 4-6).

Saponja, J. (1998). Challages with Jointed-Pipe Underbalanced Operations. Paper SPE 37066. *SPE Drilling and Completion*, June, Vol. 13, pp. 121-128. Presented originally at the *SPE International Conference on Horizontal Well Technology,* Calgary.

Shirkavand, F. and Hareland, G. (2009). The Design and Development of a Drilling Simulator for Planning and Optimizing Underbalanced Drilling Operations. *Canadian International Petroleum Conference.* Calgary, Alberta.

Sifferman, T. R., Myers, G. M., Haden, E. L. and Wahl, H. A. (1974). Drill Cutting Transport in Full-Scale Vertical Annuli. *Journal of Petroleum Technology.* Nov. 1295-1302.

Skalle, P., Podio, A. L. and Tronvoll, J. (1991). Experimental Study of Gas Rise Velocity and Its Effect on Bottomhole Pressure in a Vertical Well. SPE 23160, *presented at the Offshore Europe Conference,* Aberdeen, Sept. 3-6, 1991.

Smith, S. P., Gregory, G. A., Munro, N. and Mugeem, M. (1998). Application of Multiphase Flow Methods to Horizontal Underbalanced Drilling. *Proceeding of 1st North American Conf. on Multiphase Flow, sponsored by BHR Group,* Banff, AB, June.

Smith, S. P., Gregory, G. A. and Brand, P. R. (2000a). Application of Multiphase Flow Methods to Underbalanced Drilling Pilot Test Data. *Proceeding of 2nd North American Conf. on Multiphase Flow*, sponsored by *BHR Group,* Banff, AB, June.

Smith, S. P., Gregory, G. A. and Brand, P. R. (2000b). Application of Multiphase Flow Methods to Underbalanced Drilling Pilot Test Data. *Presented at the IADC Underbalanced Drilling Conference and Exhibitions,* Houston, Texas, August 28-29.

Smith, S. P. and Gregory, G. A. (2002). Foam Flow Modelling in Underbalanced Drilling-Current Reliability and Future Directions. *Proceedings of the BHR Group 3rd North American Conference on Multiphase Technology,* p. 81, Banff, AB, June.

SPT Group, A Schlumberger Company. (2013). UBD/MPD Flow Modeling. Retrieved from: http://www.sptgroup.com/en/Products/WELLFLO/UBDMPD-Flow-Modelling/

Trick, M. D. (2003). Comparison of Correlations for Predicting Wellbore Pressure Losses in Gas-Condensate and Gas-Water Wells. Conference paper presented at the *Petroleum Society's Canadian International Petroleum Conference*, Calgary, Alberta.

Sunthankar, A. A., Miska, S., Kuru, E. U. and Kamp, A. P. (2003). New Development in Aerated Mud Hydraulics for Drilling Inclined Wells. SPE paper 83638, *SPE Drilling and Completion,* March.

Sunthankar, A. A., Miska, S., Kuru, E. and Kamp, A. P. (2004). New Developments in Aerated Mud Hydraulics for Horizontal Well Drilling. SPE paper 87675, *SPE Journal*, March.

Suryanarayana, P. V., Smith, B., Hasan, A.B.M., Leslie, C. and Pruitt, R. (2004). Basis of Design for Coiled Tubing Underbalanced Through-Tubing Drilling in Sajaa Field. Paper IADC/SPE 87146 *presented at IADC/SPE Drilling Conference*, Dallas, March.

Tian, S. and Medley, G.H. (2000). Re-evaluating Hole Cleaning in Underbalanced Drillings Applications. Paper *presented at the IADC Underbalanced Drilling Conference and Exhibitions*, Houston, Texas.

Tian, S., Medley, G. H. and Stone, C. R. (2000). Optimizing Circulation While Drilling Underbalanced. *World Oil*, June, pp. 48-55.

WELLFLO 8.1.4 (2006). *Technical and User Documentation.* Neotechnology Consultants Ltd. Calgary, Canada.

Weatherford Underbalanced Services (2007). *General Underbalanced Presentations*. Weatherford International, Inc. USA.

Yu, M., Takach, E., Nakamura, D. R. and Shariff, M. M. (2007). An Experimental Study of Hole Cleaning Under Simulated Downhole Conditions. *SPE Annual Technical Conference and Exhibition*, 11-14 November, Anaheim, California, USA. doi: 10.2118/99201-pa.

Zhou, L., Ahmed, R. M., Miska, S. Z., Takach, N. E., Yu, M. and Pickell, M. B. (2004). Experimental Study and Modeling of Cuttings Transport with Aerated Mud in Horizontal Wellbore at Simulated Down hole Conditions. *SPE Annual Technical Conference and Exhibition*, 26-29 September, Houston, Texas. doi: 10.2118/90038-ms.

Zhou, L. (2008). Hole Cleaning During Underbalanced Drilling in Horizontal and Inclined Wellbore. *SPE Drilling & Completion*, Volume 23, Number 3, pp. 267-273. doi: 10.2118/98926-pa.