WELLBORE PRESSURE PREDICTION AFTER PIPE CONNECTION OPERATION IN UNDERBALANCED DRILLING

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

Faculty of Chemical and Energy Engineering
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NOVEMBER 2015

I would like to dedicate this thesis to my family, Iraj, and Javad who have been great inspiration in completing this thesis.

ACKNOWLEDGEMENT

I wish to appreciate first and foremost the Almighty God for his great mercies towards me and his tremendous help in helping me get to this stage of this my academic journey. Without his help I would not have achieved anything. I praise him for all the supply.

My profound many thanks go to my untiring supervisor, Professor Dr. Ariffin Bin Samsuri who has always been there to attend to my inquiries and to give me the necessary supervisory attention required. Your humility has been a huge boost in propelling me to prosecute this research successfully.

I wish to express my profound gratitude to my family. Your encouragement, support and prayers have seen me through this challenging journey. Besides, I would like to thank the authority of Universiti Teknologi Malaysia (UTM) for providing me with a good environment and facilities to complete this project.

ABSTRACT

In underbalanced drilling (UBD), bottom hole pressure (BHP) must be maintained in the defined limit. Maintaining underbalanced drilling conditions after pipe connection operation is required for the success of underbalanced drilling operations. Modeling and simulation of gas-liquid two phase flow in an UBD operation is very significant in order to accurately predict the wellbore pressure and other parameters of two phase flow. After pipe connection operation in UBD, upon restarting mud circulation system, frictional pressure influenced the BHP and the fluid slugs in the drill string are transferred into the annulus. Therefore, the hydrostatic pressure will increase and UBD pipe connection operations create a BHP vibration, which is a critical point. This particular time can reduce the benefits obtained to drill the well in an underbalanced environment. In this study, a mechanistic steady state gas-liquid two phase flow model was used to simulate the two phase flow after pipe connection operation in UBD. Simulation was carried out to predict the parameters; such as wellbore pressure, liquid holdup, and velocities of the two phases at different flow patterns, namely slug, bubble, churn, dispersed bubble, and annular flow. In order to predict wellbore pressure, a steady state model was developed to predict flow patterns, pressure gradient, and liquid holdup for gas-liquid flow in vertical annulus and drill string. The model included flow pattern transition models and hydrodynamic models for individual flow pattern. The model equations along with appropriate constitutive relations formed a system of coupled drift flux, momentum, and energy equations, which were solved using the well known iterative Newton Raphson method. All model equations were implemented in a computer program named Fortran 95. The effect of gas and liquid flow rates, and choke pressure on the wellbore pressure, particularly in the BHP was evaluated numerically. In order to validate the results of the developed model, they were compared with actual field data and the results of the WELLFLO software using different mechanistic models. The results revealed that the two phase model developed can accurately predict wellbore pressure, particularly BHP, wellbore temperature, gas/liquid velocities, and two phase flow patterns.

ABSTRAK

Dalam penggerudian imbang bawah (UBD), tekanan dasar lubang (BHP) mesti dikekalkan pada had yang ditetapkan. Pengekalan keadaan penggerudian imbang bawah selepas operasi penyambungan paip adalah diperlukan bagi menjamin kejayaan operasi penggerudian terbabit. Pemodelan dan penyelakuan aliran dua fasa gas-cecair bagi suatu operasi UBD adalah sangat penting bagi meramal secara tepat tekanan lubang telaga dan parameter lain dalam aliran dua fasa. Selepas selesainya operasi penyambungan paip dalam UBD, sebaik sahaja bermulanya semula pengedaran lumpur dalam sistem, tekanan geseran akan mempengaruhi BHP dan slug bendalir di dalam rentetan gerudi akan berubah kedudukan ke anulus. Dengan itu, tekanan hidrostatik akan meningkat dan operasi penyambungan paip dalam UBD menghasilkan getaran BHP yang merupakan suatu titik kritikal. Keadaan ini boleh mengurangkan manfaat yang diperoleh daripada penggerudian telaga dalam persekitaran imbang bawah. Dalam kajian ini, model mekanistik aliran keadaan mantap dua fasa gas-cecair telah digunakan untuk menyelaku aliran dua fasa terbabit selepas operasi penyambungan paip dalam UBD. Penyelakuan dilaksanakan untuk meramal parameter misalnya tekanan lubang telaga, tahanan cecair, dan halaju dua fasa pada pelbagai corak aliran, iaitu slug, gelembung, pusaran, gelembung tersebar, dan anulus. Dalam usaha untuk meramal tekanan lubang telaga, suatu model keadaan mantap telah dibangunkan bagi meramal corak aliran, kecerunan tekanan, dan tahanan cecair untuk aliran gas-cecair di dalam anulus tegak dan rentetan gerudi. Model terbabit merangkumi model peralihan corak aliran dan model hidrodinamik untuk corak aliran yang berlainan. Persamaan model itu berserta dengan hubungan juzuk yang sesuai telah membentuk sistem gandingan fluks sesaran, momentum dan persamaan tenaga yang boleh diselesaikan menerusi penggunaan kaedah lelaran Newton Raphson. Semua persamaan model diaplikasi menggunakan program komputer, Fortran 95. Kesan gas dan kadar aliran cecair serta tekanan pencekik terhadap tekanan lubang telaga terutama dalam BHP dinilai secara berangka. Dalam usaha untuk mengesahkan keputusan model terbabit, semua pencapaiannya dibandingkan dengan data sebenar medan dan hasil daripada perisian WELLFLO yang menggunakan pelbagai model mekanistik. Hasil kajian yang diperoleh menunjukkan bahawa model dua fasa yang dibangunkan boleh meramal secara tepat tekanan lubang telaga terutama BHP, suhu lubang telaga, halaju gas/cecair dan corak aliran dua fasa.

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LIST OF ABBREVIATIONS

Acc - Acceleration component
AN - Annular flow
B - Bubble flow
BOP - Blowout preventer
Bh - Bottom hole
BHA - Bottom hole assembly
BHCP - Bottom hole circulation pressure
BHP - Bottom hole pressure
Cal - Calculation
CFD - Computational fluid dynamic
CH - Churn flow
DB - Dispersed bubble flow
DTB - Developed Taylor bubble
DSU - Developing slug unit
DTB - Developing Taylor bubble
DF - Drilling fluid
Ep - Equi-periphery
ECD - Equivalent circulation density
FDTB - Fully developed Taylor bubble
F - Film
FT - Tubing film
Fric - Friction component
G - Gas
GC - Gas casing
GT - Gas tubing
H - Hydraulic
HUBS - Hydraulic underbalanced simulator
Hy - Gravity component
I - Axial increment thickness

IC - In situ condition or inner casing
IT - Inner tubing
L - Liquid
LS - Liquid slug
LC - Liquid holdup in gas core
LF - Liquid film
LFC - Casing liquid film holdup
LFT - Tubing liquid film holdup
LS - Slug liquid holdup
LSC - Slug liquid holdup corresponding to casing liquid film
MPD - Managed pressure drilling
N - Nozzle
N - Nitrogen
NG - Natural gas
OBD - Overbalanced drilling
OT - Outer tubing
ODE - Ordinary differential equation
P - Pipe
R - Radius, m
R - Reservoir
RBOP - Rotating blowout preventer
RCH - Rotating control head
ROP - Rate of penetration
S - Surface
S - Slug flow
Sc - Standard condition
SG - Superficial gas
SL - Superficial liquid
SU - Slug unit
T - Total or translational
TB - Taylor bubble
Up - Upstream
UBD - Underbalanced drilling
W - Water or wall
Wp - Wellbore pressure

LIST OF NOMENCLATURES

A - Area, ft^2 (m^2)

C - Constant

C_0 - Velocity profile coefficient, dimensionless

D - Diameter, in (m)

D_e - Equivalent pipe diameter, m (in)

D_{ep} - Equivalent periphery diameter, m

D_H - Hydraulic diameter of flow path, in

e_a - Absolute value percentage error (%)

f - Friction factor, dimensionless

f_{DF} - Drilling fluid fraction

f_{FH} - Homogeneous fanning friction factor, dimensionless

f_F - Fanning friction factor, dimensionless

f_i - Interfacial shear friction factor, dimensionless

F_E - Liquid entrainment

f_m - Moody friction factor, dimensionless

g - Acceleration of gravity, ft/s^2 (m/s^2)

g_c - Gravitational conservation constant

H - Reservoir thickness, m (ft)

H_L - Liquid holdup, dimensionless

$H_{L_{TB}}$ - Liquid holdup in the Taylor bubble

$H_{L_{LS}}$ - Liquid holdup in the liquid slug

$H_{G_{LTB}}$ - Liquid holdup in the developing Taylor bubble.

K - Diameter ratio, dimensionless

l - Length, ft (m)

L_C - Length of the bubble cap, ft (m)

L_{TB} - Length of the Taylor bubble, ft (m)

L_{LS} - Length of the liquid slug, ft (m)
L_{SU} - Length of the slug unit, ft (m)
L_{dTB} - Developing length of the Taylor bubble, ft (m)
L_{dSU} - Developing length of the slug unit, ft (m)
M - Gas molecular weight (kg/Kmol)
N_{Re} - Reynolds number
dp/dz - Pressure gradient, psi/ft
P - Pressure, psi
P_{ub} - Pressure upstream , psi
P_{bh} - Bottom hole pressure, psi
Q - Flow rate, m^3/s (gpm or scfm)
q_L - Flow rate of liquid, m^3/s (gpm or scfm)
q_G - Flow rate of gas, m^3/s (gpm or scfm)
S_g - Specific gravity of gas
t - Time, sec
T - Temperature, °F or °K
T_s - Surface temperature, °F
u - Velocity, m/s
u_G - In-situ velocity of gas, m/s
u_L - In-situ velocity of liquid, m/s
u_m - Mixture velocity, ft/sec (m/s)
u_∞ - Discrete bubble rise velocity, ft/sec (m/s)
u_{TB} - Rise velocity of the Taylor bubble, ft/sec (m/s)
$u_{L_{TB}}$ - In-situ liquid velocity in the Taylor bubble, ft/sec (m/s)
$u_{L_{TB}}$ - In-situ liquid velocity in the Taylor bubble, ft/sec (m/s)
$u_{G_{LS}}$ - In-situ gas velocity in the liquid slug, ft/sec (m/s)
$u_{L_{LS}}$ - In-situ liquid velocity in the liquid slug, ft/sec (m/s)
$u_{G_{DTB}}$ - In-situ gas velocity in the developing Taylor bubble, ft/sec (m/s)
$u_{L_{DTB}}$ - In-situ liquid velocity in the developing Taylor bubble, ft/sec (m/s)
u_n - Nozzle velocity, m/s
V - Volume, m^3
$V_{L_{TB}}$ - Liquid volume in Taylor bubble, m^3

$V_{L_{LS}}$ - Liquid volume in liquid slug, m^3

W - Weight fraction

Z - Compressibility factor, dimensionless

Z - Axial direction

Greek Letters

α - Gas volumetric fraction, dimensionless

β - Relative bubble length parameter, dimensionless

∞ - Discrete bubble

λ - No-slip holdup, dimensionless

μ - Viscosity, Pa.s (cp)

μ_L - Viscosity of liquid, Pa.s (cp)

μ_G - Viscosity of gas, Pa.s (cp)

ρ - Density, kg/m^3

σ - Interfacial tension, N/m

δ - Film thickness, m

Δ - Increment

τ - Shear stress, Pa (psi)

τ_i - Interfacial shear, Pa (psi)

ε - Roughness, m

ν - Specific gravity, m^3/kg

ρ_m - Mixture density, lb/ft^3

ρ_G - Gas density, lb/ft^3

ρ_L - Liquid density, lb/ft^3

ΔP - Pressure drop, psi

Δt_{TB} - Passing time of Taylor bubble, sec

Δt_{LS} - Passing time of liquid slug, sec

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Underbalanced drilling method is determined as drilling process in which the pressure of wellbore is lower than the formation pressure in the open hole section. The UBD system is designed to operate with pressure of wellbore below the pressure of formation. The pressure underbalanced connote that if porous and permeable formations are exposed, the reservoir fluids will enter the wellbore while drilling. In overbalanced drilling operation well control is influenced by using a hydrostatic pressure higher than the formation pressure. In UBD, this differential is eliminated and wellbore pressure is kept less the formation pressure. Thus, there is a concept of well control condition during the UBD technology. The benefits of UBD technique encompass the followings: less differential sticking, improve penetration rate, reduce formation damage, and early production.

When there are equipment failures, mismanaging of drilling fluids, poor reservoir selection, and human mistake then underbalanced drilling method failed. The underbalanced drilling technology is gaining in amicability as drilling method to dominate some of the problems faced in overbalanced drilling. Underbalanced drilling method is adopted for solving drilling problems and it also can minimize formation damage. UBD technology has improvement of oil and gas formations that otherwise would not be exploited due to the technical and economic limitations. It is also a tool both for formation performance development and formation characterization as well as for remarking drilling problems. Underbalanced drilling operation is considered to be more expensive than conventional drilling. Even though UBD technique is more expensive than conventional drilling, it has some advantages over the conventional drilling technology. Some of these advantages include early production of hydrocarbons and quick recovery of cost expended on it (UBD technique).

Generally, decrease of the hydrostatic pressure in the annular decreases the fluid losses into a reservoir formation. In underbalanced drilling operation, the bottom hole pressure must be deliberately below the pressure of formation, therefore, the fluid losses do not appear there during drilling underbalanced. Due to the lack of overburden on the reservoir formation and the absence of any filter cake, the drill string will be prevented from differential sticking while drilling underbalanced. The reduction of the overpressure over the pressure of formation has a considerable effect on the rate of penetration. It also has an affirmative impact on the bit life due to the less weight on the drilling bit.

The applications of UBD technique comprise the followings: aerated liquid, stable foam, and gas or air drilling. When liquid is combined with air/gas drilling, the drilling fluid becomes mist or unstable foam. The limitations of UBD technology comprise the followings: liquid influx problems, wellbore stability, safety and economic problems, and directional drilling problems. In some formations, when the wellbore is not stable, the underbalanced drilling cannot be used because it is not economically feasible. The surface equipment requirements of underbalanced drilling technology encompass the following: downstream choke-manifold system, wellhead rotating control device, upstream gas generation systems, geologic sampler, and open/close fluid handling systems. When the formation is exceedingly depleted, an upstream gas generation would be required.

During UBD operation in which the formation pressure is greater than hydrostatic pressure of fluids in wellbore may make a condition such as a kick. So, controlling and predicting the pressures and maintain assured environment need specific surface pressure control equipment and a group of crew who are satisfactorily educated. The kind of necessary items relies on mainly the lithology, permeabilities, and formation pressures. In under balanced drilling technique, a complex fluid system appears in the drill-string and the annulus. In underbalanced drilling operation, the well bore pressure control is obtained by conducting the well returns through surface choke pressure.

Production of formation fluids during UBD are separated by separation tanks at the well head. Therefore, the regular rotary rig must be adjusted for under balanced drilling operation with some significant adjustment. Controlling the flow pressure at the bottom-hole is the key parameter in the success of the UBD operation. If the BHP becomes greater than the formation pressure, the UBD changes to over-balanced drilling (OBD) and if the BHP becomes too lower than the formation pressure this may lead to kicking of the well or may cause the wall well collapse. Therefore, the bottom-hole pressure should be kept in a specific pressure limits known as pressure window. Keeping BHP in the window limits is more difficult than the over-balanced drilling because a specific ratio of two fluids (gas and liquid) should be continuously injected in the well to reach the desired BHP which depends mainly on the formation pressure and the choke pressure.

1.2 Problem Statement

The emergence of UBD technology can be used to avoid complicated drilling problems, such as reservoir damage and circulation loss. The success of a UBD operation is subdominant of the ability to keep up underbalanced situations during the whole drilling operation and this underbalanced pressure condition is needed to be maintained by bottom-hole pressure control according to specific operating conditions and actual status of fluid in wellbore. In underbalanced drilling operations with regular rigs, drilling fluids are pumped down through the drill-string, getting through the bit nozzle, and then going up in the annular space. In the annular, drilling fluids are mixed with drilling cuttings and formation fluids. Therefore, underbalanced hydraulic circulating system is typically determined by two or more phases. When a pipe moves up and down along the axis of a wellbore filled with a nonmoving fluid, friction pressure losses are induced. The main concern in friction pressure losses due to pipe movement is related to the annulus section. During pipe connection operation in UBD, the mud circulation system has to be stopped. Therefore, bottom hole pressure decreases at the beginning due to the losses frictional pressure. The stop of mud circulation causes the disruption of steady state conditions. Due to buoyancy and inertial forces the gas phases moves upward and the liquid phases flow downward.

In underbalanced drilling pipe connection operation, the process involved to stop circulation and pull out of hole the entire drill-string, making connection at the surface after which running in hole with new connection. After bottom hole assembly (BHA) touch bottom, start circulation, and continue drilling. At this stage, an annulus pressure will increase as surge pressure. Figure 1.1 indicates a schematic of the pipe connection operation. Therefore, after pipe connection is defined as a time gap between BHA touch bottom and recirculating start.

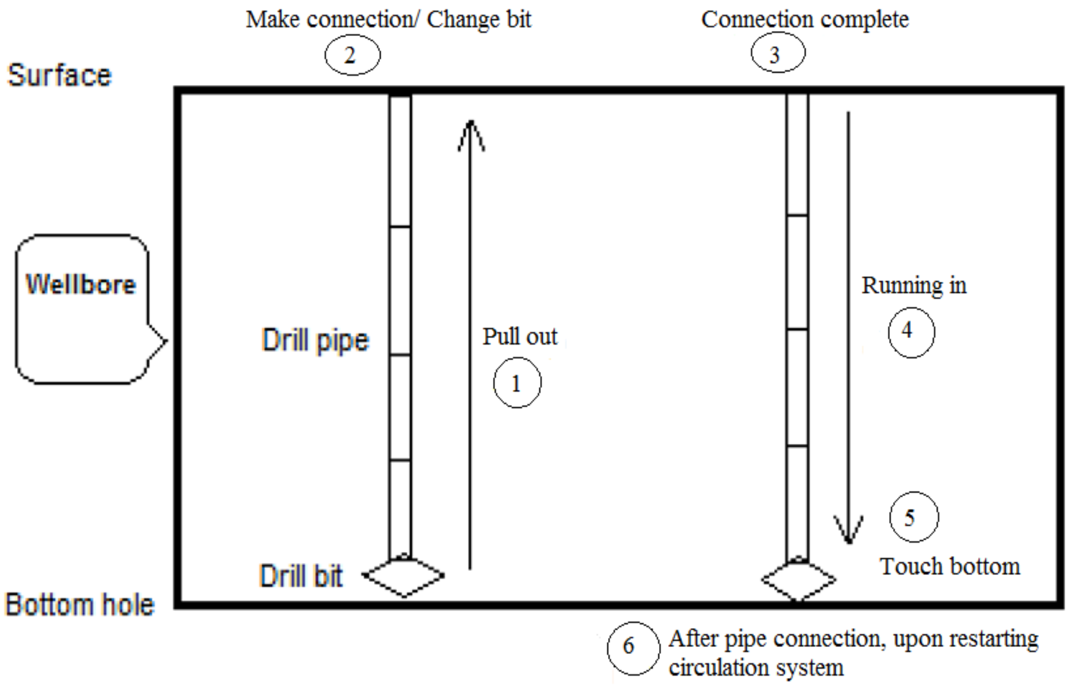

Figure 1.1 Schematic of pipe connection operation during drilling

After pipe connection operation in UBD, upon restarting mud circulation system, frictional pressure influenced the BHP and the fluid slugs in the drill-string are transferred into the annular space. Therefore, the hydrostatic pressure will be increasing. Since this event occurs after pipe connection operation, and the period between drilling and pipe connection is inadequate to obtain steady situations again, underbalanced drilling pipe connection operations create a bottom hole pressure vibration. If the bottom hole pressure vibration is not properly maintained below the pressure of formation, the reservoir formation will lead to an OBD condition after pipe connection operation. Consequently, after pipe connection in UBD a pressure spike is observed with a short period of sustaining higher BHP that usually exposes the formation to overbalanced conditions. This particular time can reduce the benefits obtained to drill the well underbalanced. Therefore, the foundation of UBD analysis and study is to establish mechanistic steady state two phase flow model to predict wellbore pressure. As shown in Figure 1.2 the BHP vibrations recorded after pipe connection operation upon restarting circulation system in underbalanced drilling operation. It's also shown that changing a choke pressure setting may also cause severe vibrations in the BHP.

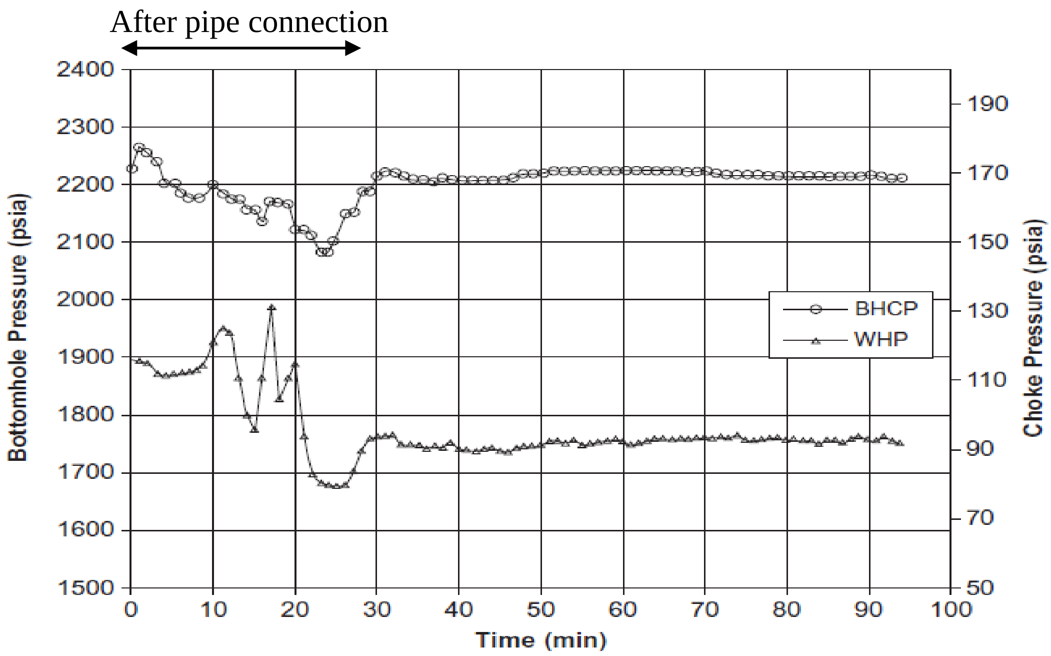

Figure 1.2 Typical BHP vibration after pipe connection in UBD (Guo and Liu, 2011).

The key factor for a successful UBD operation is to achieve the objectives through maintaining underbalanced drilling condition. In order to achieve such success, the bottom hole pressure should be maintained within a pressure window that is bounded below by the formation pore pressure and above the wellbore stability pressure or surface facilities restrictions. Hence, the prediction of wellbore pressure should be as accurate as possible in order to assist in designing equipment needed to UBD operations. Recently, development of mechanistic models has allowed accurate prediction of wellbore pressure. Mechanistic models are based on the physical phenomena of the complex fluid system and flow rather than the use of empirical correlations, which are based mainly on experimental data.

Therefore, it seems that one should use better mechanistic steady state model for two phase flow in which a set of partial differential equations are used to describe the physics of the flow. This research is the study in which the mechanistic steady state two-phase flow through the annulus, bit nozzles, and drill-string is used to simulate flow behavior in the UBD operation. Two phase flow patterns in the annulus and drill-string, wellbore pressure predictions, gas/liquid superficial velocities in the wellbore, liquid and gas holdup, two phase flow pattern maps, wellbore temperatures, and minimum gas volume requirement in the wellbore are presented accordingly. The performance of the development model is validating with field data and previous works. In this steady state two phase flow model development, two phases are considered as the two interpenetrating continua. Steady state two phase flow model development has a high potential for the analysis of two-phase flows and has extensively been used in modeling different two-phase flow.

1.3 Research Objective

In this study, the main objective is to predict BHP after pipe connection operation in UBD in which mud circulation system restarts. The details of objective encompass the followings:

i. To develop mechanistic steady state model for two phase flow through the annulus and drill-string.
ii. To predict BHP after pipe connection operation in UBD.
iii. To review two phase flow patterns in UBD operation.
iv. To analyze the effect of the choke pressure and gas/liquid flow rate on the BHP.

1.4 Scope of Study

In this study, the bottom hole pressure prediction is based on the outcomes of a mechanistic steady state model development by developing analytical equations using fundamental laws of physics and mathematics to predict the wellbore pressure and BHP, the flow behavior, flow patterns and their transitional boundaries for two phase flow (gas-liquid) through drill-sting, bit nozzle and in the annular space. In flowing, effects of gas/liquid flow rate recharges and also choke pressures change on pressure and flow patterns are defined. Then this model equation, based on drift flux model is defined and computer program by means of Fortran 95 will be developed. The following simplifications have been adopted in order to establish flow model in UBD: (i)·It is a steady state model and can only simulate an established situation; (ii) The drilled cuttings are transported at the same velocity in the annulus as the liquid phase; (iii) The cross section of the wellbore is circular and concentric with drill-string; (iv) The gas resolution in drilling fluid is negligible and there is no chemical reaction; (v) The ·gas and liquid medium is in thermodynamics balanced status, and pressure and density is single valued function; (vi) No fluid production from reservoirs are considered.

1.5 Significance of Study

Previous steady state gas-liquid two-phase models in UBD operations fall into three categories. The first is the steady state computer programs that neglect slip between phases by assuming that aerated mud can be treated as a homogeneous mixture. The second is the steady state computer programs that used empirical correlations to take into account slip between phases and predict different flow patterns. The third is the steady state computer programs based on mechanistic models rather than empirical correlations to take into account slip between phases and predict different flow patterns. Most studies on UBD models focused on the first and the second types of models in the recent years. Validations show that lowers prediction accuracy than the accuracy needed in practical operations. The mechanistic approach postulates the existence of different flow configurations and formulates separate models for each one of these flow patterns to predict the main parameters, such as gas fraction, two phase flow patterns, and wellbore pressure. Consequently, mechanistic steady state two phase flow models, rather than empirical correlations, have been used with increasing frequency for the design of multiphase wellbore pressure system. But, the previous studies did not use mechanistic models to reach good accuracy of wellbore pressure and two phase flow parameters in the annulus and drill-string during underbalanced drilling operation. Therefore, there is a need to predict wellbore pressure in the annulus and drill-string during underbalanced drilling operation using mechanistic steady state two phase flow model. This research is the study in which the mechanistic steady state two phase flow model is used to predict wellbore pressure in the annulus and drill-string in the underbalanced drilling operation. Furthermore, two phase flow patterns, flow pattern maps, void fraction, wellbore temperature, and minimum gas volume requirement in the annulus and drill-string are presented. In addition, the effects on bottom-hole pressure of different back pressures at the wellhead, gas and liquid injection flow rate are simulated and analysed. The flow patterns used in the research include five types: bubble flow, dispersed bubble flow, churn flow, annular flow, and slug flow according to the configurations of two phase flow in the wellbore. Computational methods for gas void fraction and pressure drop are presented in each flow pattern respectively.

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