UNIVERSITI TEKNOLOGI PETRONAS

PRESSURE DROP AND CUTTINGS CONCENTRATION ESTIMATION IN HORIZONTAL SECTION OF WELLBORE DURING UBD OPERATION USING ANSYS-CFX CFD

A THESIS SUBMITTED
TO
THE DEPARTMENT OF PETROLEUM ENGINEERING

BY
JOSEPH EZIBON WAIWAI BILALI

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
PETROLEUM ENGINEERING

JULY 2012

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

Certificate of approval

PRESSURE DROP AND CUTTINGS CONCENTRATION ESTIMATION
IN
HORIZONTAL SECTION OF WELLBORE DURING UBD OPERATION
USING
ANSYS-CFX CFD

Submitted by Joseph Ezibon waiwai Bilali in partial fulfillment of the requirements for the degree of Master of Science in Petroleum Engineering Department, Universiti Teknologi PETRONAS (UTP).

By,

Dr. Reza Ettehadi Osgouei ________________________
Supervisor, Petroleum Engineering Dept., UTP

Certificate of originality

I hereby declare that all the information in this document has been obtained and represented in accordance with Universiti Teknologi PETRONAS (UTP) academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

By, Joseph Ezibon Waiwai Bilali

Signature ____________________

ABSTRACT

Pressure drop and cuttings concentration are considered as sensitive issues in underbalanced drilling, especially when dealing with three phase (cuttings-gas-liquid)flow in horizontal, deep and extended reached wells. Improper estimation of the two mentioned may lead to drilling complications such as reduction in rate of penetration, pipe sticking, increase in torque and drag force and cutting bed development. In order to address this issue, there is a need of understanding the fundamental behavior of the three phase flow in the annulus and identify the most influencing parameters.

In this project, effect of rate of penetration (ROP) and fluid velocity at the annulus is analyzed by simulating the three phase flow in a horizontal section of the wellbore by using a commercial package of computational fluid dynamic (CFD) software known as ANSYS CFX 14. The length of the horizontal section is 2ft of diameter 2.91inch and the inner eccentric drillpipe diameter is 1.85inch.

The simulations were conducted at steady state flow and as a result flow patterns were identified as well as volumetric concentration of cuttings and pressure drop were inferred.

Initially, cutting bed was observed at the entry section of the annulus due to rate of penetration and low annular velocity. But as the annular velocity increases due to increase in gas superficial velocity, the bed decreases and pressure drop decreases as well. After that when cutting bed disappeared completely, the pressure drop increase again due to increase in the mixture fluid density.

However, as the ROP increases, the cuttings concentration increases, but not much change is observed in the trend of pressure drop due to the presence of the gas causing turbulence at the annulus.

The result generated by the simulation is verified with the experimental data taken from Ettehadi Osgouei et al (2010) paper and it shows a good agreement with an error difference of less than 20%. So this implies that drilling Engineers can apply

ANSYS-CFX14 to estimate pressure drop and cuttings concentration for underbalanced drilling program.

ACKNOWLEDGEMENTS

First of all, I would like to give thanks to the Lord Almighty Father for keeping me safe and healthy throughout this course program.

And sincerely, I would like to express my utmost appreciation to the department of Petroleum Engineering and Geosciences in UNIVERSITI TEKNOLOGI PETRONAS (UTP) and her counterpart HERIOT-WATT UNIVERSITY (HWU) for their support throughout the course program and it is a compliment to be thankful to all the lecturers in the department.

Not forgetting my profound gratitude to Ministry of Petroleum in South Sudan and PETRONAS for offering me this phenomenon opportunity to promote my knowledge.

I would like also to thank our Head of department A.P. Dr Ismail bin M Saaid , MSc-PE Coordinator Dr Khalik B M Sabil and IP coordinator Dr. Saleem Qadir for their patience and advice.

Special thanks go to my Supervisor Dr. Reza Ettehadi Osgouei for his unlimited support and supervision. It is really a great experience to work on such topic of underbalanced drilling under him.

To Eng. Sami.A. Musa, thank you for your encouragement and unselfish help and sharing of knowledge with me.

I would like to thank Mr. Alexander Tham for giving me his time to assist me in familiarizing myself with the ANSYS software.

Last but not least to all my colleagues, friends and family thank you for your standing behind me in achieving this important step.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Af	:	Effective particle cross section area, L
Aw	:	Wellbore area, L2
$A_{\alpha\beta}$	:	The interfacial area between the phases
Cc	:	Cuttings concentration (%)
Cd	:	Drag coefficient
Dwh	:	Wellbore diameter, L
Ddp	:	Drill pipe diameter, L
DP	:	Solid Particle Diameter, L
dUp/dt	:	Particle velocity
$d_{\alpha\beta}$	:	The interfacial length scale
e	:	Distance between the centre of inner and outer pipe, L
F_{all}	:	Sum of all forces
FD	:	Drag force
*F*D	:	Drag force acting on the particle
*F*B	:	Buoyancy force due to gravity
*F*P	:	Pressure gradient force
FR	:	Force due to domain
*F*VM	:	Virtual mass force
i	:	Each phase
*M*p	:	Mass of solid particle
$\dot{m}_{\alpha\beta}$	:	Mass flow rate per unit area from phase β to α

n	:	New
o	:	Old
QC	:	Cuttings phase flow rate, L3/t
Qw	:	water phase flow rate, L3/t
Qg	:	Gas phase flow rate, L3/t
R_o	:	Outer pipe radius (L)
R_i	:	Inner pipe radius (L)
r_α	:	Volume fraction of phase α
$\Gamma_{\alpha\beta}$	:	Mass flow rate per unit volume from β to α
Us	:	Slip Velocity
U_α	:	Velocity of phase
Vsl	:	Liquid superficial velocity, L/t
Vsg	:	Gas superficial velocity, L/t
V_p	:	particle velocity (L/t)
V_f	:	Fluid velocity(L/t)
X	:	Particle displacement (L)
τ	:	Shear stress
α, β	:	The phases
δt	:	Time step

Greek Letters

λ_g	:	Initial void fraction for gas in the three phase flow
λ_w	:	Initial void fraction for water in the three phase flow
λ_c	:	Initial void fraction for cuttings in the three phase flow
ε	:	Eccentricity ratio

CHAPTER 1

INTRODUCTION

1.1 Background

Underbalanced drilling (UBD) operation is a type of drilling carried out with hydrostatic fluid pressure inside the wellbore less than the formation pressure in the open hole section. It is mostly conducted in a reservoir with pore pressure close to fracture pressure, so fractured cap rock reservoirs, lower matrix permeability in depleted formations, etc. Therefore, the most applicable candidate is the depleted reservoirs. And the types of drilling fluids used mostly are fluids with low density such as: Gas, Air, Foam and Aerated fluid.

Field experience proved that UBD technology has more advantage in terms of reducing formation damage, minimizing loss of circulation, increase in rate of penetration and environmentally friendly. But its disadvantages are: so risky especially when dealing with reservoir with high percent of H_2S and no mud cake is form on the wall of the wellbore, so any small overbalanced may lead to deep penetration of mud filtration into the reservoir which will caused damaged to the reservoir and well instability.

Based on the literature review, few studies have been carried out to predict the estimation of pressure drop and cuttings concentrations in horizontal wellbore. (Ozbayoglu et al 2010) conducted experiment and developed mechanistic models for estimation of pressure drop and cuttings concentration. (L.Zhou et al 2006) used mathematical models to predict cuttings accumulation in the horizontal well. C.Ercan and M.E. Ozbayoglu (2009) conducted studies on reduction of pressure drop by effect of liquid polymer emulsion (PHPA).They performed experiment and found out that the optimum PHPA concentration for reduction of drag was 0.0020 (v/v).

Therefore, the main objective of this project is to estimate pressure drop and cuttings concentration in an eccentric horizontal section of wellbore during underbalanced drilling by simulating three phase flow at the annulus using ANSYS CFX14. Hence the effect of rate of penetration and fluid velocity will be analyzed for easy transport of cuttings. The obtained results will be verified with experimental data from Ettehadi Osgouei et al 2010 paper. This approach is to confirm whether the software ANSYS CFX14 can be used by drilling Engineers for designing cutting transport program in underbalanced drilling operations.

1.2 Problem Statement

During underbalanced drilling (UBD) operation, rate of penetration (ROP) can increase and if the annular velocity is low cuttings can accumulate at the lower bottom of the wellbore generating high cuttings concentration and pressure drop. And these cuttings concentration and accumulation can lead to some drilling problems such as pipe sticking, low drilling speed, increase in torque and drag force which will create fluctuation in hole cleaning performance and cuttings transport.

Therefore, there is a need of understanding the three phase flow behavior at the annulus to analyze the effect of the influencing parameters such as rate of penetration and fluid velocity on pressure drop and cuttings concentration for easy transport of cuttings to the surface.

1.3 Objectives and Scope of Study

1.3.1 **Objectives:**

The main objective of this study is to:

- Understand the fundamental behaviour of three phase flow in the horizontal annulus.
- Identify the flow patterns
- Observe and analyze the effect of ROP and fluid velocity on pressure drop and cutting concentration.

1.3.2 **Scope of Study**

The scope of this project is as follows:

- Review the Literature of all the related previous works on the topic.
- Apply ANSYS-CFX14 to simulate the effect of ROP and fluid velocity on pressure drop and cuttings concentration in the horizontal section of wellbore.
- Verifying the results of ANSYS-CFX14 with experimental results from Ettehadi Osgouei et al 2010 paper.

1.4 Thesis overview

This section outline briefly about what is discussed in each chapter.

Chapter one is talking about the general understanding of the study in terms of project background, problem statement, objectives, scope of the study and general overview of the thesis.

Chapter two is looking into what has been done in the past in relationship with the topic of this project through literature review and theory. And the most related ones will be analysis.

Chapter three describes the methodology used to achieve the objectives of this study.

Chapter four presents the outcome of the study, analyze and discuss the details of the outcome.

Chapter five shows the conclusion of what has been achieved and recommendation for future work.

CHAPTER 2

LITERATURE REVIEW AND THEORY

Many studies have been carried out in relationship with prediction of pressure drop and cutting concentration in a wellbore of horizontal well during underbalanced drilling. But the following literature review articles are the most related one to the topic. And theory behind the ANSYS CFX 14 CFD is presented as well.

2.1 Pressure drop in wellbore:

Most of the investigations done on prediction of pressure drop are based on experimental and developed mechanistic models as their methodologies.

Osgouei et al. (2010) aimed their study to investigate the hole cleaning process using gasified fluid at horizontal annulus. They carried out experiments at METU Multiphase flow loop using wide range of air and water flow rates. Based on that they developed mechanistic model to estimate frictional pressure losses and total cuttings concentration inside the horizontal annular. And they observed that increase in pipe rotation doesn't change the total cuttings concentration including the stationary and moving particles in horizontal annuli as the cuttings injection rate, liquid and gas flow rate are kept constant. Hence they verified the model and found out that the model predictions are in good match with the experimental data. Therefore the outcome of the model can be used in any underbalanced drilling operating with gasified fluid.

Ozbayoglu et al (2010) conducted their study with the aim of determining some very-difficult –to- identify data for estimating total pressure drop and total cuttings concentration inside the wellbore. They performed extensive experiments along the eccentric annulus using water- cuttings flow loop at METU for various pipe rotation speeds, cuttings injection rates, fluids flow rates for horizontal and inclined wellbores. So during the experiment, all the process carried out was recorded using a high speed digital camera and as a result, moving particles concentration, slip velocity, cuttings accumulations were obtained. And they observed that as the ROP increases, cuttings concentration increase as well which leads to increase in frictional pressure losses. Also as the flow rate increases, transport velocity of cuttings increase. They tested the obtained data into a simple mechanistic model for estimating pressure drop inside a wellbore in the presence of cuttings and they found out that the mechanistic model improved significantly.

C.Ercan and M.E. Ozbayoglu (2009) emphasized their study on reduction of pressure drop by effect of liquid polymer emulsion which composed of Partially Hydrolyzed PolyAcrylate (PHPA).They performed a straight pipe flow experiment at different concentration of PHPA solutions and they found out that the optimum PHPA concentration for reduction of drag was 0.0020 (v/v). The measured and theoretical frictional pressure losses values showed that drag is reduced as PHPA concentration increase. And also they proposed a new friction factor as a function of Reynold number and PHPA concentration; and the results proved that the pressure losses can be estimated with an error less than 15% when the proposed friction factor is used.

Y.Peysson and B.Herzhaft (2008) based their case study analysis on pressure drop variation with low flow rate in a circular pipe for different foam qualities and formations in the experimental test. First they calculated the pressure drop by taking only the rheological properties of the foam into account; but the results show a huge difference between the calculated and the experimental observation. Then they used the developed lubrication model which takes liquid lubrication at the wall of the pipe into consideration plus large range of foam quality. And the result is compared; it showed a very good agreement. So they concluded that liquid lubrication plays great role in giving accurate measurements which can be used in designing the hydraulic process inside drill pipe.

Barkim Demirdal and J.C. Cunha (2007) concentrated their study on investigating pressure drop of non- Newtonian fluid during drilling in onshore and offshore operations. They looked at the effect of rheological model and equivalent diameter definition on pressure drop. They used three different rheological model

(Bingham plastic, Power law and yield power law) and four different equivalent diameter definition. When they compared the results of the two methods; they found out that pressure gradients determined in the annuli are not only dependent on the equivalent diameter definition, but also on rheological model, since the regime is laminar remain the dominant.

C. Omurlu Metin and M.E.Ozbayoglu (2007) aimed their study on estimating frictional pressure loss in the horizontal wells as gas-liquid mixture flow through fully eccentric annuli. They conducted experiment tests at METU and hence developed mechanistic model for estimating frictional pressure losses that can be used for both circular pipe and annular geometries. They observed that as the eccentricity increases, frictional pressure drop decrease. While velocity profiles at any cross-section can be deduced by using finite element method. The results of the models were compared with the experimental data, it shows that the proposed mechanistic model can estimate frictional pressure drop with an accuracy of less than 20% and it can also identify flow pattern correctly.

T.Hemphill and K.Ravi (2006) discussed in their study about the effect of pipe rotation and pressure drop in concentric and eccentric annulus during the axial flow of non Newtonian fluid. They used models and correlations to calculate the pressure drop at the annuli for a fluid whose rheological properties are calculated from Herschel-Bulkey model. So as a result, they observed that pipe rotation is so efficient in hole cleaning when the pipe is at eccentric position in the annulus. Therefore, the calculation can be applied in designing the hole cleaning during drilling and cementing.

S.T. Johansen et al (2003) are looking for generic model for calculation of frictional pressure loss in pipe and annular flow. They generated turbulent model from theoretical concepts taken from fluid dynamics. The input of the model is fluid rheology taking pressure and temperature into account while the output is mainly pressure drop and wall shear stress. The model is verified against experiment data and mostly agreed with the measured data.
But in order to improve the hydraulic model, more concentration on rheological data should be done.

C. Perez-Tellez et al (2003) proposed a new comprehensive mechanistic model that can allow more precise predictions of wellbore pressure and two phase flow parameters for underbalanced drilling (UBD). They performed a full-scale experiment as well as gathered actual (UBD) data from field. Based on that, they developed a mechanistic model incorporating all the fluid properties and pipe sizes. The model predictions are verified against the experimental data. And the result showed a good match. The model is also compared against two different commercial, empirically based UBD simulators and it shows that the mechanistic models perform better than the empirical corrections.

Sunthankar et al (2000) emphasized their study on better understanding of aerated mud flows hydraulics which could be use for calculation of bottomhole pressure and optimal flow rates more accurately. They conducted an extensive experiment in a unique field-scale low pressure flow loop in horizontal position with and without drillpipe rotation. The type of fluids used was air- aqueous polymer solution and air- water at different flow rates. As a result, higher frictional pressure drop was observed in case of flow with drillpipe rotation and using air-aqueous polymer solution which gives rise to development of pipe model. But for annuli flow, the pipe model was developed using hydraulic diameter; but it doesn't show good match with the experimental data. Then a mechanistic model developed by Xiao et al (24) was modified for flow in the annuli; and when compared with the experimental data, it underpredicts the total pressure drop in the annuli. So they concluded that, a new mechanistic model should be developed which incorporates annular geometry, non-Newtonian fluid and drillpipe rotation.

R. Subramanian and J.J. Azar (2000) based their study on experimental study on friction pressure drop for drilling fluid in pipe and annular flow. They used the experimental data achieved to generate a useful plot called "Friction factor" against "Generalized Reynolds number". From the plot friction factor is inferred and used for calculation of pressure drop in the pipe and annular. And they observed that frictional pressure losses in eccentric are lower than in concentric under the same conditions for all mud tested.

Zhou, et al. (1996) applied multi-phase flow theory to calculate and control injection pressure, flow rate, frictional pressure losses inside the pipe and annulus, and pressure loss at the bit nozzles. They also analyzed rheology of the aerated mud, casing program, gas-liquid ratio, mud density and annulus back-pressure. They concluded that the flow pattern should be bubble-flow and/or slug-flow in the annulus for better cuttings transport.

2.2 Cuttings concentration in the wellbore:

Numerous theoretical and mechanistic models were introduced for describing the mechanism of cuttings concentration and bed development in the horizontal and inclined wells.

M.E. Ozbayoglu et al (2010), their main aim of the study is to develop equation that can be use in estimating hole cleaning performance in horizontal wells during underbalanced drilling(UBD). In their paper they used empirical correlations to estimate the critical fluid velocity required to avoid development of stationery bed when the fluid velocity is lower than critical one. And also they considered rough estimation of bed thickness. They have also conducted cutting transport experiment at Middle East Technical University (METU) by using water to determine flow rates, rate of penetration and various inclinations. They subjected the inner portion of the pipe to a sagging and more realistic annular representation is achieved. So the results showed that:

- ❖ Stationery bed can be developed even when the inclination of the wellbore is 50 degree
- ❖ Proposed equation for estimating stationery cuttings bed area can be predicted with an error of +/- 15%
- ❖ Critical fluid velocity is estimated using the three correlations to avoid cuttings accumulation inform of stationery bed or moving bed inside the wellbore.
- ❖ Dimensional analysis proved that the main variable influencing the cuttings bed thickness is shear stress acting on the cutting bed surface.

So they concluded that the above obtained parameters can be use to design hole cleaning program of horizontal and inclined wells during underbalanced drilling operation.

Li and Kuru (2004) developed a 1-D two phase mechanistic cuttings transport model for foam drilling in horizontal and inclined wells. For horizontal wells, the model assumes the flow is consist of two layers; the top layer consist of foam cuttings mixture with low solid concentration and the bottom layer consist of stationery bed cuttings with foam entrained in the pores. The model predicts cutting bed height as function of rate of penetration, gas and liquid injection rates and borehole geometry. They also modified Orsoskar and Turian's correlation for critical deposition prediction in the two layers model. The results showed that increase in drilling rate or drill pipe eccentricity increases the cuttings bed height.

L.Zhou et al (2005) in their study, they use two methods: manually and Nuclear densitometers. So for them to investigate cuttings transport efficiency using aerated fluids under high pressure and temperature condition, firstly they measured in-situ cuttings concentration manually by flushing out the cuttings into a container and weighing them. And secondly they use nuclear densitometers to measure the in-situ cuttings concentration under dynamic condition. Then, the obtained results from the two methods were compared and a very good agreement is observed. Therefore, they concluded that nuclear densitometers should be set to a higher sampling rate and steady state condition should be identified using average mixture density.

Desmond. N. and S.S. Rahman (1998) presented their ideas with primary objective of developing a new mathematical model, based on improved understanding of mechanism and theory of particles transport that can describe the various modes of cuttings transport in horizontal to highly deviated wells.
The new mathematical model is demonstrated into three-layer cuttings transport model which interrelates flow rate, annular geometry, cuttings size, and mud rheology to various flow patterns including saltation, stationary bed, sliding bed, and suspended flow. As a result a computer algorithm has been developed from the model that allows the prediction of a complete range of transport modes that have been observed in laboratories. Simulations for the effects of various parameters and

operational conditions were presented in terms of bed thickness or annular cuttings concentration vs. mean annular velocity, and in terms of pressure gradient vs. mean annular velocity. This clearly demonstrates the potential of this model as a tool for effective design of cuttings removal from horizontal and highly deviated annuli.

Doan, et al. (2003) presented the model in order to understand the mechanisms involved in the transport of cuttings in UBD. The model simulated the transport of drill cuttings in an annulus of arbitrary eccentricity and includes a wide range of transport phenomena, including cuttings deposition and re-suspension, formation, and movement of cuttings bed. The model consists of conservation equations for the fluid and cuttings components in the suspension and the cuttings deposit bed. Interaction between the suspension and the cuttings deposit bed, and between the fluid and cuttings components in the suspension, are incorporated. Solution of the model determines the distribution of fluid and cuttings concentration, velocity, fluid pressure, and velocity profile of cuttings deposit bed at different times. The model was used to determine the critical transport velocity for different hydrodynamic conditions. But, the effect of drill pipe rotation was not considered in their model. Results from the model approved quite closely, qualitatively, with experimental data obtained from a cuttings transport flow loop at the Technology Research Center of the Japan Natl. Oil Corp. (TRC/JNOC)'s Kashiwazaki Test Field in Japan.

Adari R.B (2000), managed to find the optimum combination of drilling fluid rheological properties and flow rate to ensure the best hole cleaning in horizontal and deviated wells. He used different empirical methods to relate the cuttings bed height to drilling fluid rheological flow rate.

A.L. Martins, and A.M.F. Lourenço (2001), they summarized their paper in extensive experimental program to determine effective foam drilling conditions in horizontal wells. The program included foaming-agent selection, foams rheological characterization and development of a flow loop to test. They performed 60 bed tests at a cuttings-transport flow loop; as a result, correlations were proposed to predict the cuttings-bed erosion capacity in horizontal wells as functions of the foam quality and the mixture’s Reynolds number. The methodology proposed for predicting bed heights as a function of foam quality and liquid flow rates properly reflects the phenomena involved in cuttings-bed removal process and may be of practical use.

Y. Li et al (2004) aimed their study on numerical modeling of cuttings transport in horizontal wells using conventional drilling fluids. They developed a one dimensional transient mechanistic model for cuttings transport with conventional drilling fluids in horizontal wells. The model is solved numerically to predict cuttings bed height as a function of drilling fluid flow rate and rheological characteristics, drilling rates, wellbore geometry and drillpipe eccentricity. The sensitivity analysis carried out showed that, effects of drillpipe eccentricity, cuttings diameter and drilling fluid density on the cuttings bed height are not significant. But the drilling rate and drilling fluid flow rate are the most important factors controlling the formation of stationary cuttings bed. Higher drilling rates results into higher cuttings bed height. Increasing drilling fluid flow rates, on the other hand, decreases cuttings bed height. The model developed in this study can be used to develop computer programs for practical design purposes to determine optimum drilling fluid rheology and flow rates required for drilling horizontal wells.

Zhou et al. (2004) carried out experiments in a unique full-scale flow loop in different liquid and gas flow rates as well as elevated temperatures. The in-situ cuttings concentration was determined by using a special designed multiphase measurement system. The results clearly show that in addition to liquid flow rate and gas-liquid ratio, temperature essentially affects the cuttings transport efficiency and the associated frictional pressure drop. The volume of cuttings which accumulated in the annulus was very sensitive to the liquid flow rate. Also in this study; a mechanistic model for cuttings transport with aerated fluids under EPET conditions has been developed to predict frictional pressure loss and cuttings concentration in the annulus.

Martins et al (1996) presented results of an extensive experimental program that was focused on the understanding the phenomena evolved in the erosion of a cuttings bed deposited on the lower side of a horizontal annular section. A set of correlations, based on the experimental results, was developed for prediction of bed height and critical flow rate during the circulation of a horizontal well. The results of the experiments indicated that fluid yield point (YP) was significant only in the bed erosion of eccentric annuli. However, the additional research was required to establish more accurate interpretation of fluid rheological effects. The correlations seemed to be helpful tools for optimizing of horizontal drilling and cementing operations.

J.Li and S. Walker (2001) studied the effects of gas-liquid ratio, flow rate, phase slip velocities, rate of penetration, and inclination and fluid properties on cuttings bed thickness for aerated fluids systems. They observed that liquid is the dominating parameter for cuttings transport in aerated systems. As the liquid ratio increases, for a constant in-situ flow rate, cuttings transport improves.

Iyoho and Azar (1980) presented a new model for creating analytical solutions to the problems of non-Newtonian fluid flow through eccentric annuli. During the study, they achieved some important results. First, it was observed that flow velocity was reduced in the eccentric annulus. It was a crucial observation for the directional drilling since drill pipe tended to lie against the hole. Secondly, the study had a practical application that included the calculation of velocity distribution in chemical processes that were involving fluid flow through eccentric annuli.

2.3 Application of Computational Fluid Dynamics (CFD) for Cuttings transport

There are very limited studies conducted in relationship with application of computational fluid dynamics (CFD) to estimate pressure drop and cuttings concentration.

H.I. Bilgesu et al (2002) introduced a new approach to determine the parameters affecting cutting transport in any wellbores. They used computational fluid dynamics (CFD) software program to the cutting transport efficiencies in vertical and horizontal wellbores. The affecting parameters used are cuttings size and mud properties (density). The parameters were varied in the simulation and they observed that annular velocity plays an important role in hole cleaning and also increase in cuttings transport efficiency is more pronounced at low flow rates. The results were compared with the reported data and was found out that they were in good agreement; just that the model prediction deviated a bit from the laboratory data as the annular velocity increase for all mud densities due to difference in particle size.

Dongping yao and Samuel. G. Robello (2008) aimed their study on determination of impacts of the standoff devices on pressure drop calculation and downhole circulating density. They used computational fluid dynamic (CFD) software for the standoff devices analysis and Navier-Stoke equations for calculating pressure drop. As a result they managed to develop a model which showed improvement to the prediction of pressure drop with standoff devices. So they concluded that, this equation can be used for stabilizers and other devices.

N. Singhal et al (2005) investigate the flow behavior and frictional pressure losses of Newtonian and Non-Newtonian fluids in concentric. In their study they used computational fluid dynamics (CFD) software program to simulate different annular flow for both laminar and turbulent flow regime. They observed that for Newtonian fluid in laminar flow regime the best correlation is Jones and leung while for turbulence flow regime is drew. The results have been compared with the experimental data with available correlation for Newtonian and Non-Newtonian fluids and it gives good agreement.

2.4 THEORY

2.4.1 ANSYS-CFX 14.CFD

ANSYS CFX 14 is one of the commercial software packages of computational fluid dynamic (CFD) that combines an advanced solver with powerful pre- and post-processor capabilities of integrating problem definition, analysis and results presentation.

In this project, ANSYS CFX 14 is applied to simulate the three phase flow in the horizontal section of a wellbore considering the effect of influencing parameters such as rate of penetration and fluid velocity at the annulus. As a result, flow pattern, pressure drop and cuttings concentration will be identified at the annulus.

The main equations governing for estimation of pressure drop and cuttings concentration in ANSYS CFX 14 are equation of continuity which is used for calculation of mass transfer of solid-liquid flow and equation of momentum used for observing the motion of solid particles in the liquid (According to ANSYS CFX-Solver Theory Guide) .

The momentum equation is defined as follows:

$$\nabla . \left(r_\alpha (\rho_\alpha U_\alpha \otimes U_\alpha)\right) + r_\alpha \nabla p_\alpha = \nabla . \left(r_\alpha \mu_\alpha (\nabla U_\alpha + (\nabla U_\alpha)^T)\right) + \sum_{\beta=1}^{2} \left(\Gamma_{\alpha\beta}^{+} U_\beta - \Gamma_{\beta\alpha}^{+} U_\alpha\right) \quad (2.1)$$

Where,

$$\Gamma_{\alpha\beta}^{+} U_\beta - \Gamma_{\beta\alpha}^{+} U_\alpha = \Gamma_{\alpha\beta} \quad (2.2)$$

Where,

α, β = the phases

r_α = volume fraction of phase α

U_α= velocity of phase α

$\Gamma_{\alpha\beta}$= mass flow rate per unit volume from β to α

$\dot{m}_{\alpha\beta}$= mass flow rate per unit interfacial area from phase β to α

$A_{\alpha\beta}$ = the interfacial area between the phases

$d_{\alpha\beta}$ = the interfacial length scale

The equation of continuity is defined as follows:

$$\nabla .(r_\alpha \rho_\alpha U_\alpha) = \sum_{\beta=2}^{2} \Gamma_{\alpha\beta} \quad (2.3)$$

$$\Gamma_{\alpha\beta} = \dot{m}_{\alpha\beta} A_{\alpha\beta} \quad (2.4)$$

$$A_{\alpha\beta} = \frac{r_\alpha r_\beta}{d_{\alpha\beta}}$$

2.4.2 Model used for simulating the three phase flow:

In ANSYS- CFX 14 there are two models used for simulating multiphase flow and they are: Eulerian-Eulerian and Lagrangian particle transport model. But in this project, Lagrangian particle transport model is used because Particle Transport model is capable of modelling the solid particles which are discretely distributed in a continuous phase (water). Thus, each particle interacts with the fluid and other particles discretely throughout the flow field (Based on CFX-modelling guide).
Lagrangian modelled the particles by tracking a few number of particles through the continuum fluid from the point they are injected until they are out of the domain
The particles tracking are done by forming a set of ordinary differential equations in time for each particle. These equations are then integrated using a simple integration method to calculate the behaviour of the particles as they traverse the flow domain (ANSYS CFX-Solver guide).

The following sections explain the methodology to track the particles.

The particle displacement is calculated Using forward Euler integration of particle velocity over time step as follows.

$$x_i^n = x_i^o + v_{pi}^o \delta t \tag{2.5}$$

Where,

x = particle displacement

n = new

o = old

V_p = particle velocity

δt = time step

The particle velocity is calculated using the following equation as per forward Euler integration.

$$v_p = v_f + \left(v_p^o - v_f\right) \exp\left(-\frac{\delta t}{\tau}\right) + \tau F_{all}\left(1 - \exp\left(-\frac{\delta t}{\tau}\right)\right) \tag{2.6}$$

Where,

v_f = fluid velocity

τ = shear stress

F_{all} = sum of all forces

2.4.3 **Forces acting on the particle**

As the drilling fluid flows through the annulus, various forces act upon the motion of a particle in the fluid and the main forces are: Drag force($F_{d)}$, Buoyancy force ($F_{b)}$, Lift force($F_{l)}$, Friction force (F_f), Gravitational force (F_g) and Van der Waals force (F_{van}) as shown in Figure 1. And these forces are included in the particle equation of motion in ANSYS CFX.

$m_p \, dU_p/dt = \boldsymbol{F}_D + \boldsymbol{F}_B + \boldsymbol{F}_R + \boldsymbol{F}_{VM} + \boldsymbol{F}_P$ (2.7)

Where:

M_P: mass of solid particle

dU_p/dt = Particle velocity

$\boldsymbol{F}_D$: Drag force acting on the particle

$\boldsymbol{F}_B$: Buoyancy force due to gravity

$\boldsymbol{F}_R$: Force due to domain

$\boldsymbol{F}_{VM}$: Virtual mass force

$\boldsymbol{F}_P$: Pressure gradient force

The interactions between these forces affect the cuttings transport in the hole cleaning. Thus, the drag force, buoyancy force and lift force tend to help in cuttings transport while friction force, gravitational force and Van de Waals force tend to oppose and balance the aiding forces.

$F_D = \frac{1}{2} C_D \rho_F A_F |U_s| U_s$ (2.8)

Where:

F_D: Drag force

C_D: Drag coefficient

A_F: effective particle cross section

U_s: Slip Velocity

In ANSYS CFX 14 drag force between the continuous phase and particle phase are modelled the following three methods:

- Schiller – Naumann correlation
- Particle transport drag coefficient
- Set calculated drag force using particle user routine.

The Figure below shows the forces acting on a single solid particle in drilling fluid.

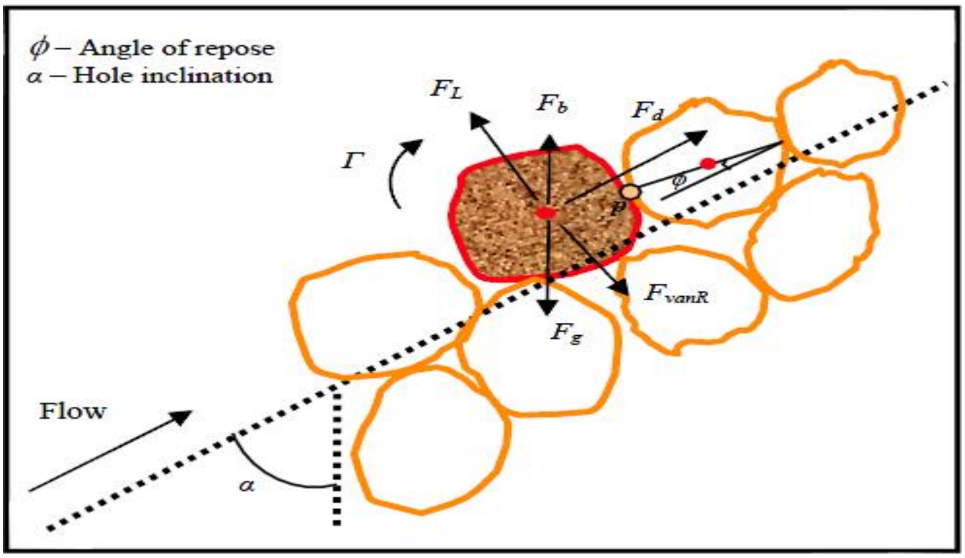


Figure 1: Forces acting on solid particle in drilling fluid (*S.T.Johansen et al 2003*)

2.4.4 Parameters influencing the Pressure Drop and Cuttings Concentration:

Table1 below shows the main parameters that influencing pressure drop and cutting concentration during drilling as cited from Ettehadi Osgouei et al 2010. Some of these parameters can be control by varying them, but others are hard to control within the context of my project. Thus, these parameters are hard to vary due to limitations and assumptions considered in this study .So they are assumed to be constant.

Table 1 : Influencing parameters on pressure drop and cutting concentration

Controllable factors	Factors Hard to control	Constant factors
• flow rate • Rate of penetration	• pipe rotation • Mixture properties • Annular geometry	• Formation properties

Flow rate and rate of penetration(ROP) play a great role in affecting the pressure drop and cutting concentration. Because the higher the flow rate, the lower the cuttings concentration and pressure drop. And the higher the rate of penetration, the higher the cuttings concentration and pressure drop. Pipe rotation, mixture properties and annular geometry are hard to vary them at the context of my project due to limitations with the computers used for applying the software ANSYS CFX14.

2.4.4 Calculation of initial void fraction for each phase in the flow:

Flow rate for each phase can be calculated from equation below:

$$Qi = Vi * Ai \qquad (2.9)$$

Initial void fraction volume for water in the three phase flow can be calculated using the equation below in (2.10):

$$\lambda w = \frac{Qw}{Qw+Qg+Qc} \qquad (2.10)$$

λw = initial void fraction volume for water in the three phase flow

Qw = water flow rate

Qg = Gas flow rate

Qc = cuttings injection rate

A = cross section area

i = each phase

The same equation in (2.10) can be used to calculated the initial void fraction for gas and cuttings.

2.4.5 **Annular Eccentricity**

The eccentricity ε is defined by:

$$\varepsilon = \frac{e}{R_o - R_i}$$

(2.0) Where,

ε = Eccentricity

e = The distance between the center of inner and outer pipe

R_o = Outer pipe radius

R_i = Inner pipe radius

Figure 2 shows concentric and eccentric annular geometries. But the one used in this study is the positive eccentricity.

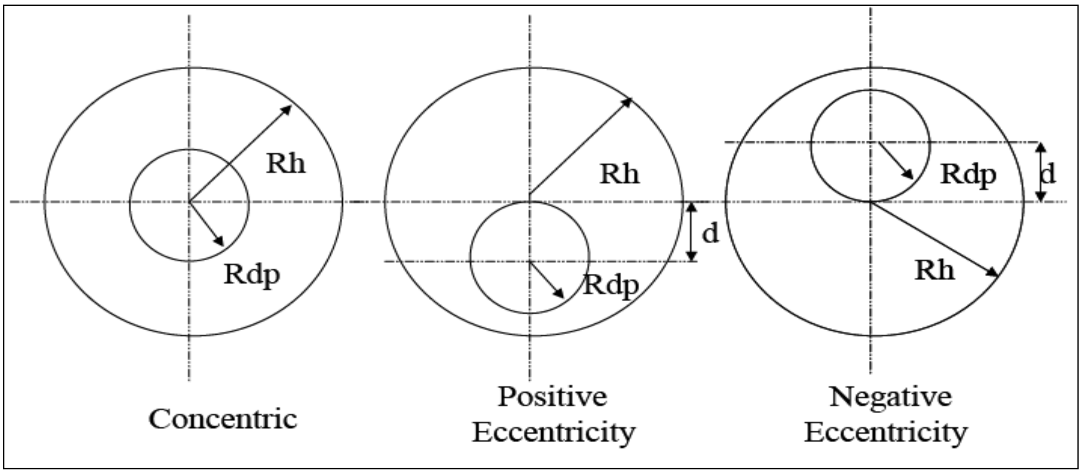


Figure 2: Shows concentric and eccentric annular geometries *(Ettehadi Osgouei et al 2010).*

The positive and negative eccentricity is defined by Iyoho and Azar (1980) as a displacement of the drill-pipe towards the lower or upper sides of the hole wall. But during drilling of horizontal well, the drill-pipe is usually not located at the center of the hole. The pipe weight forces the drill-pipe towards the lower section of the annulus due to the gravitational effect creating positive eccentricity.

CHAPTER 3

METHODOLOGY

In this chapter the methodology of achieving the objective of this project is presented by applying commercial software of Computational Fluid Dynamic (CFD) called ANSYS-CFX 14 to simulate the three phase (cuttings-gas-water) flow in the horizontal section of wellbore during underbalanced drilling.

3.1 Simulation Parameters

The simulation model is developed based on the horizontal eccentric test parameters published in Ettehadi Osgouei et al (2010).

The annular horizontal section of the wellbore is about 2ft long with an internal diameter (I.D) of 2.91 inch and inner drill pipe of outer diameter (O.D) of 1.85 inch. The eccentricity of the well is 0.623and it is a positive eccentricity due to gravity effect at the annulus. The cuttings material is gravel with diameter size of 0.079 inch and its density is 23.050 ppg.

The rate of penetrations are 50 and 100 ft/ hr with Gas superficial velocity ranges from 0.18 – 31.29 ft/s and liquid (water) superficial velocity of 2 and 4 ft/s at a temperature of $25^{o}C$ and pressure range from 17 – 19 psi .

3.2 Simulation model setup

In order to run the simulation first the model should be setup to give converging results. In the process of setting up the model, first is the design of the horizontal section of the wellbore geometry with the length of 2ft long and diameter of 2.91in. Inside the wellbore is a drill pipe of diameter of 1.85 in with eccentricity ratio of 0.623 as defined by Design Modeller in the Figure 3 below.

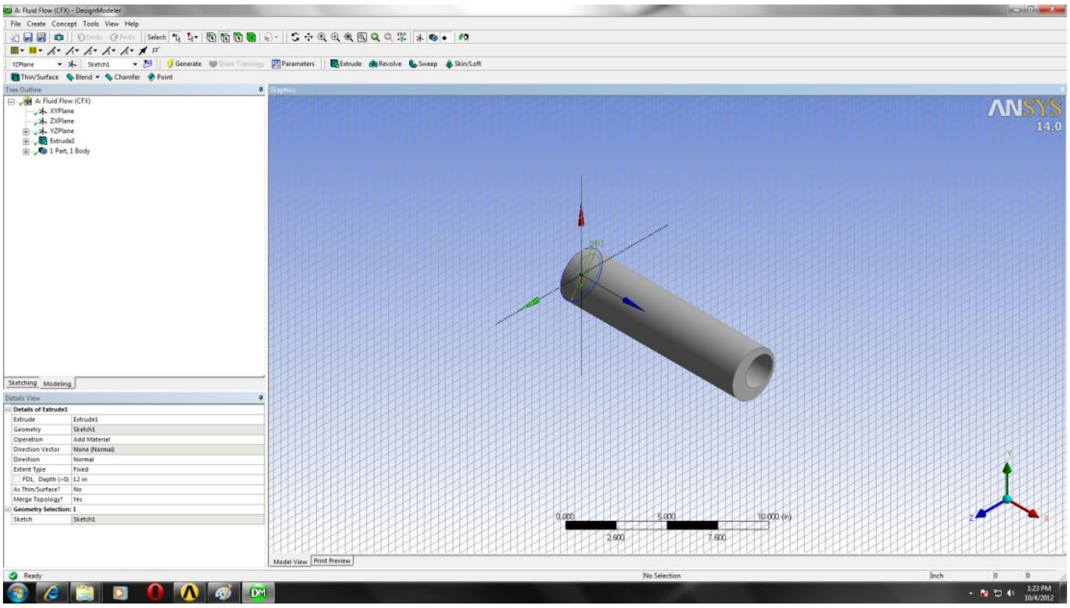


Figure 3: Design Modeller

Once the geometry is designed then elements were generated discretely on the geometry in form of mesh to define the region of the interest, creating regions of fluid flow and surface boundary and set its properties as shown in Figure 4.

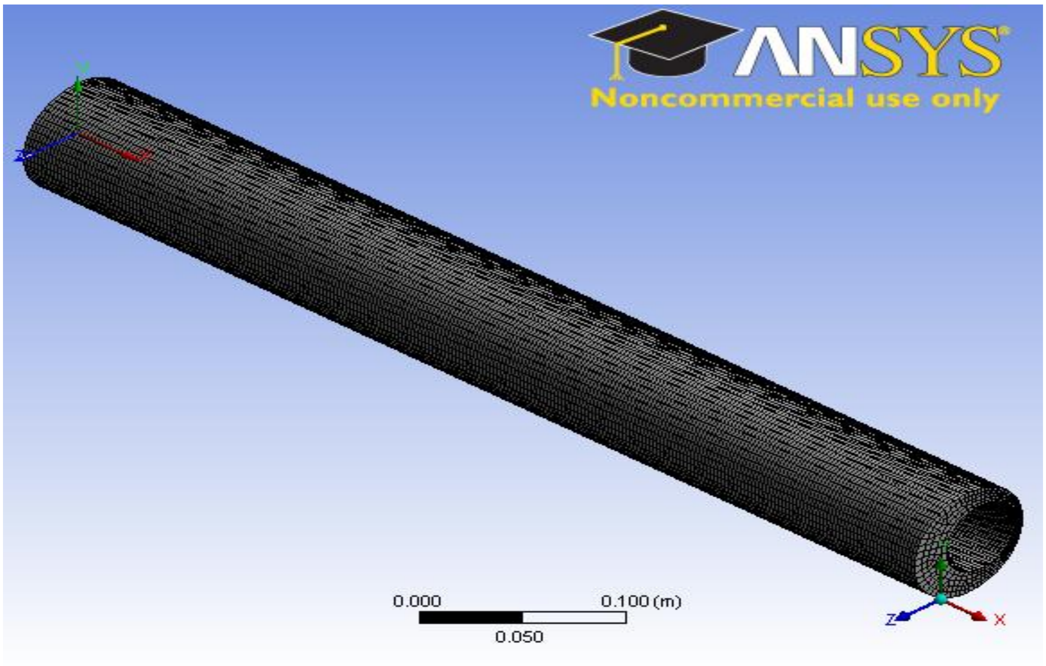


Figure 4: Isometric Meshing

In order to set up the simulation, it needs to be defined in CFX Pre by defining the following:

- Materials properties (water, Gas and cuttings)
- Domain (physical models, boundary conditions, material properties)
- Inlet and outlet (boundary conditions and fluid values)

Then the model is ready for simulation run as shown in the Figure 5.

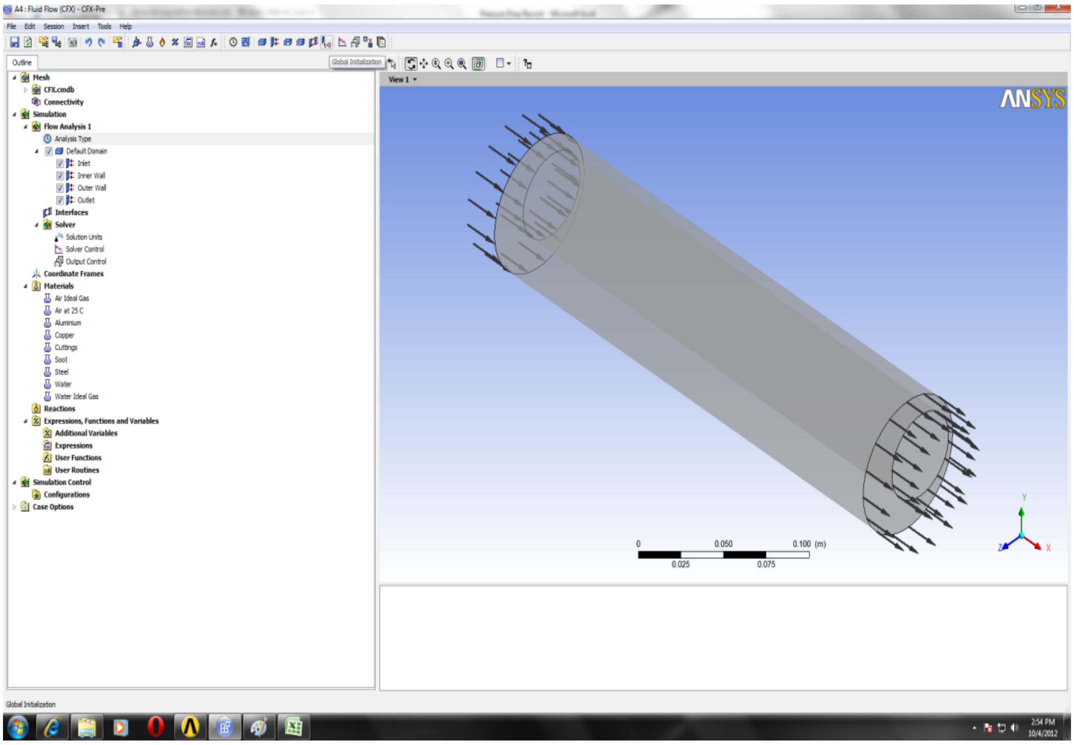


Figure 5:CFX Pre

Hence the simulation is run in CFX solver. It solves the governing equations iteratively by integrating the partial differential equations over the volumes in the region of the interest. These integral equations are converted to a system of algebraic equation and these algebraic equations are then solved iteratively.

The Figure 6 displays the working panel of CFX Solver when the simulation has completed normally.

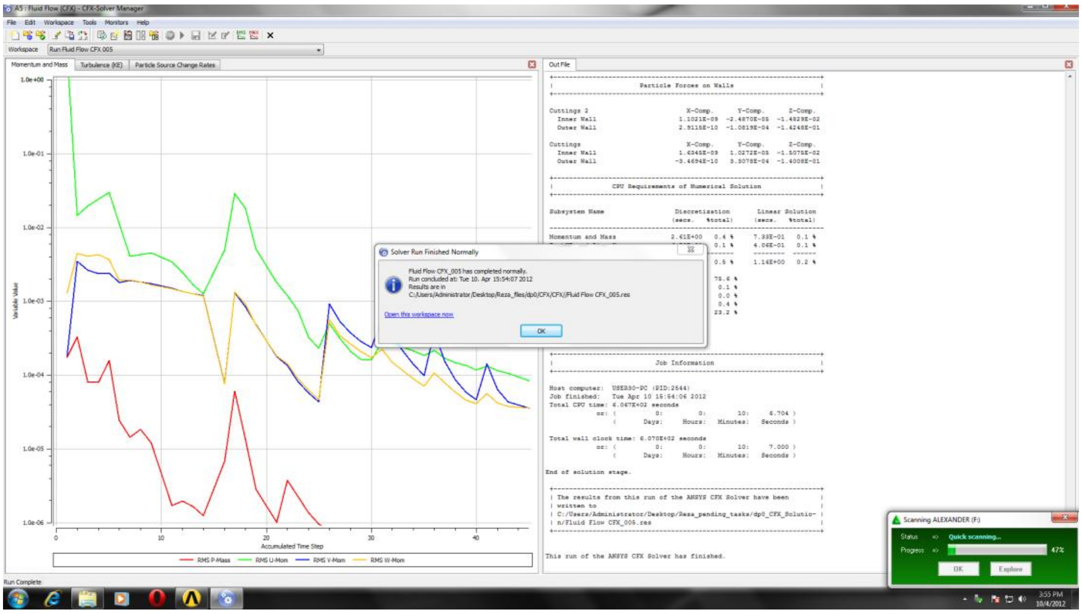


Figure 6: CFX Solver

Finally, the outcome of the simulation runs is generated by CFX Post. The pro-processor analyze, visualize and present the results interactively as shown in Figure 7.

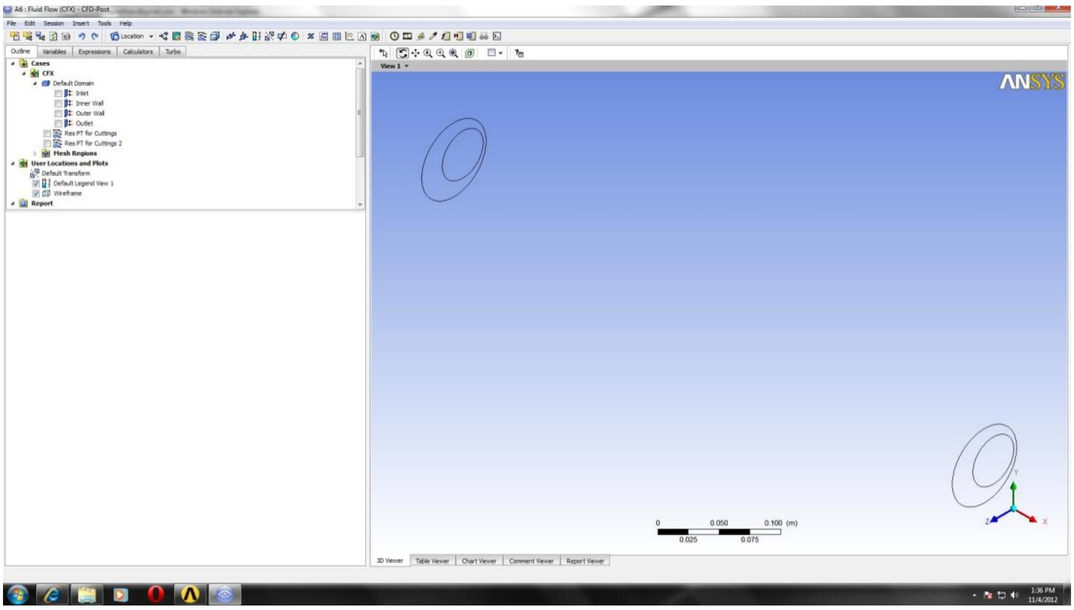


Figure 7: CFX Post

3.3 Summary work flow of ANSYS CFX 14 process

It summarizes the entire steps process for setting up the model within the ANSYS CFX 14 for simulation run.

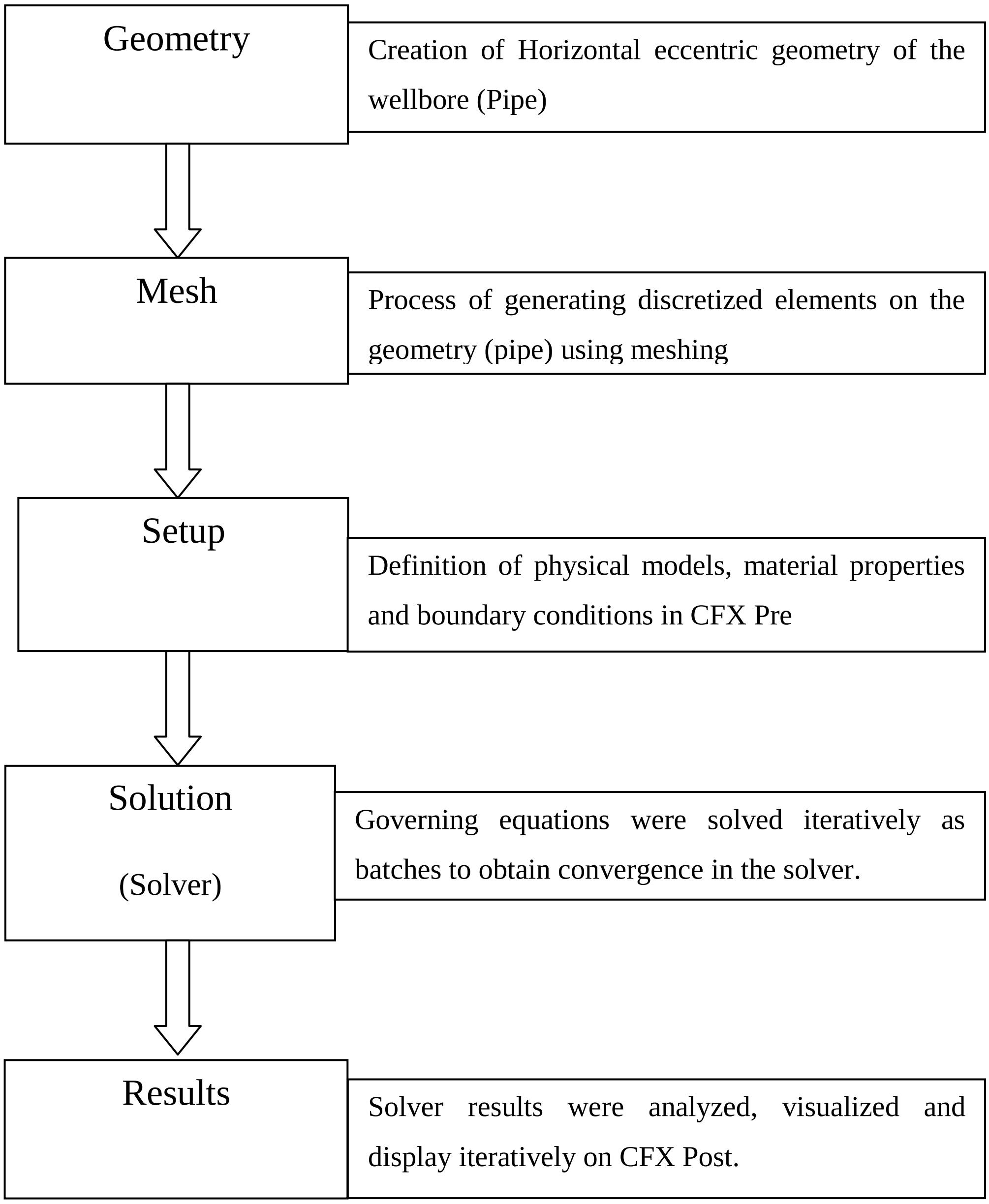


Figure 8: Work flow summary of ANSYS CFX 14 process

3.4 Assumptions of the model:

During the simulation of the model of three phase flow in ANSYS-CFX 14, the following assumptions are considered:

- Steady state flow
- Inner Pipe is stationary
- Particles shape are spherical
- Gas and water mixture is homogeneous.

3.5 Limitations during ANSYS CFX 14.application

The computers having the ANSYS CFX 14 in the laboratory have limitations which let the results generated during simulation runs not accurate. The limitations are:

- Computer memory space is very small can’t run huge models
- So fine mesh takes more computer power which make it hard to reach convergence
- Adjustment of meshing is required if convergence is not reached

CHAPTER 4

RESULTS AND DISCUSSIONS

In this chapter, the observations and analysis of the simulation runs are presented. The simulation results are verified with the experimental data from Ettehadi Osgouei et al 2010. The observations are mainly focusing on the effect of rate of penetration (ROP), gas superficial velocity and liquid superficial velocity on flow pattern, pressure drop and cuttings concentration.

4.1 Flow Patterns Identification

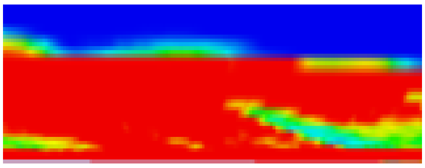
The flow patterns are generated as a result of simulating the three phase flow in the horizontal annulus by using liquid superficial velocity of 2 ft/s and 4 ft/s and gas superficial velocity varying from 0.18 – 31.29 ft/s and the rate of penetration taken was 50ft/s and 100 ft/hr. The blue color area indicates homogeneous mixture of gas-water fluid while the red color area indicates the cuttings concentration. So as the red color reduces means the cuttings concentration decreases.

4.1.1 **Flow Patterns for ROP of 50 ft/hr**

In this section, the flow patterns are identified based on local observation and interpretation. As generated by the software, there are three main flow pattern identified: Stationary bed, Moving bed and dispersed bed.

4.1.1.1 Stationary bed

Due to rate of penetration (ROP) cuttings are generated at the bottom of horizontal section of the wellbore forming a cuttings concentration and a bed due to gavity as a result of low annular velocity at the entry. The upper area is occupied by gas-liquid fluid as shown in Figure 9

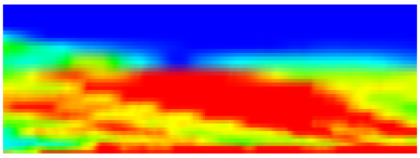


Vsg = (0.18 – 5.54ft/s)

Figure 9: Stationary Beds

4.1.1.2 Moving bed

As the annular velocity increases due to increase in gas superficial velocity, the flow at the annulus starts forcing the cutting bed to move creating motion to the stationary bed as shown in Figure 10 below.

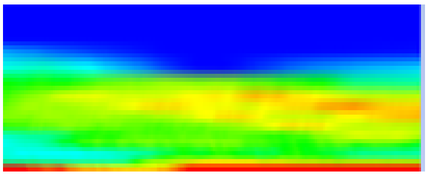


Vsg = (9.45-13.34ft/s)

Figure 10: Moving Bed

4.1.1.3 Dispersed bed

When the gas superficial velocity is increased to 15.2ft/s onwards, the flow area increases due to reduction in cuttings bed in the annulus, as a result cuttings are dispersed coarsely in the liquid- gas phase as shown in Figure 11



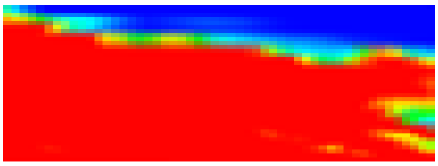
Vsg = (15.20 - 26.20ft/s)

Figure 11: Disperse Beds

As the annular velocity increases due to increase in gas superficial velocity, the flow patterns change from stationary bed to dispersed flow. Based on local observation, the stationary bed is observed at gas velocity from 0.18 ft/s to 5.54 ft/s. And from 9.45 ft/s to 13.34 ft/s is moving bed while from 15.20 ft/s to 31.29ft/s dispersed flow is observed.

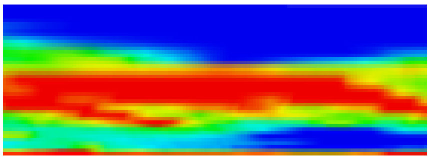
4.1.2 Flow Patterns for ROP of 100 ft/hr

Similarly when the ROP is increased to 100 ft/hr using the same liquid superficial velocities 2ft/s and 4ft/s while varying the gas superficial velocity from 0.18ft/s - 31.29ft/s, three flow pattern is also observed as follows: Stationary bed (a), moving bed (b) and dispersed bed (c) as shown in figure 12 below.



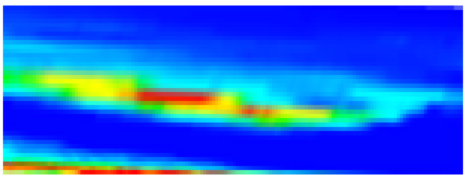
Vsg = (0.18 – 9.45ft/s)

(a) Stationary bed



Vsg = (13.34 – 15.29ft/s)

(b) Moving bed



Vsg = (21.22 – 31.29ft/s)

(c) Dispersed bed

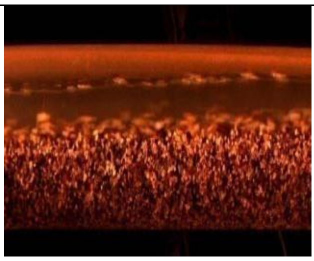
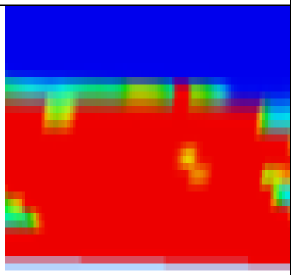
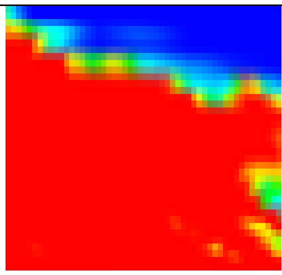
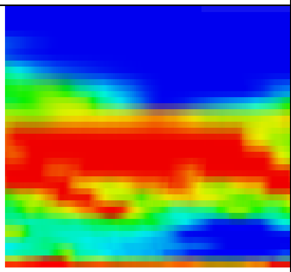
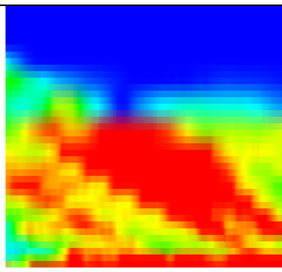
Figure 12: Flow Patterns for ROP of 100 ft/hr

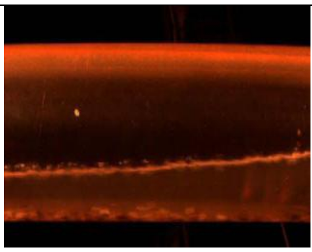
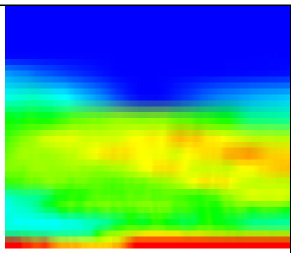
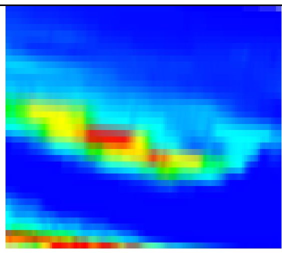
So, increase in ROP to 100ft/hr increases the cuttings concentration and accumulation at the horizontal section of the wellbore due to low velocity of the gas-liquid fluid mixture at the beginning. But when the fluid velocity at the annulus increases due to increase in gas and liquid superficial velocity, transitional flow is observed from stationary bed to dispersed bed. So moving bed is form as gas velocity varies from 5.54ft – 9.45ft/s and dispersed flow is deduced as the gas velocity varies from 13.34ft/s – 31.29ft/s.

4.1.3 **Flow pattern comparison**

Table 2: shows the comparison between the flow patterns obtained from ANSYS CFX 14 simulations with experimental flow patterns from Ettehadi Osgouei et al 2010.

Table 2: Flow pattern comparison

Experiment flow pattern	**ROP 50 ft/hr**	**ROP 100ft/hr**	**Flow pattern**
			Stationary bed
			Moving bed

			Dispersed bed

4.2 Effects on Pressure Drop

4.2.1 Effects on pressure drop due to ROP 50ft/hr at liquid superficial Velocity of 2ft/s.

The pressure drop estimated from the simulation runs are verified against the experimental data (Ettehadi Osgouei et al 2010) as shown in Figures 13 for water velocity of 2ft/s as gas velocity varies from 0.18ft/s – 31.29ft/s with ROP of 50 ft/hr.

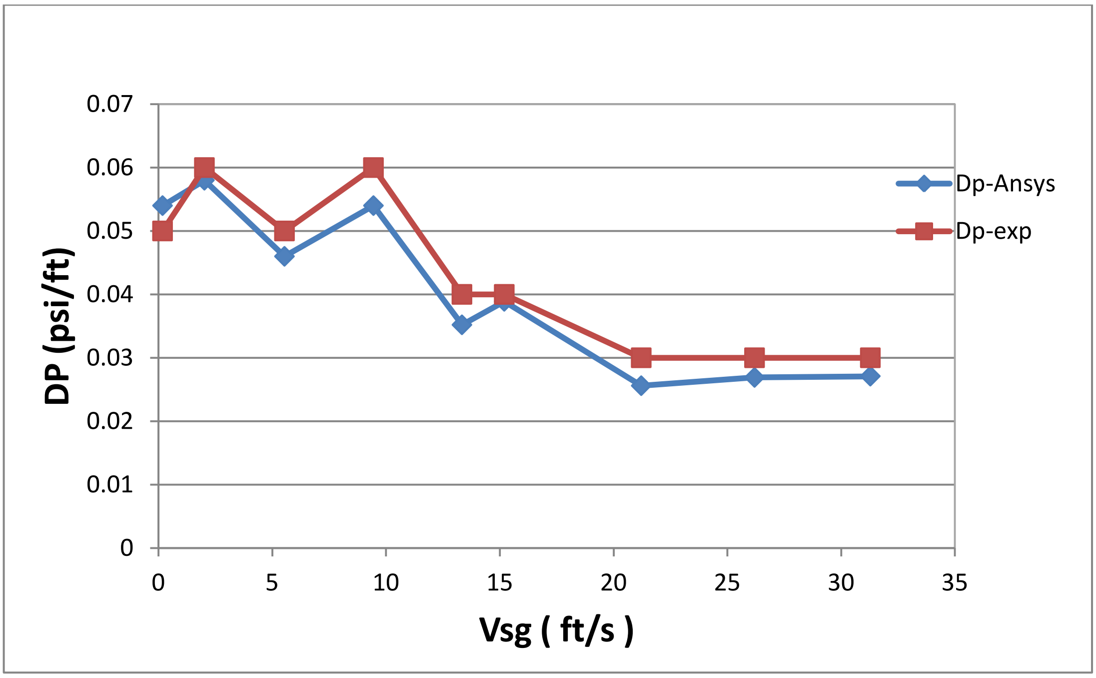


Figure 13: Compares ANSYS pressure drop results with Experimental data Vs. gas superficial velocity for Vsl = 2ft/s and ROP = 50ft/hr

From the figure above it is clearly shown that the simulation results are in good agreement with the experimental results and the error difference is less that 15%.

Initially the pressure drop is high due to high concentration and accumulation of cuttings at the entry of the wellbore. But as the fluid velocity at the annulus increases due to increase in gas superficial velocity, the pressure drop decreases. But once the cutting bed disappeared completely, pressure drop increase again due to density of the mixture fluid.

The pressure drop fluctuation occurred as the stationary bed tends to move and change to dispersed flow as the gas superficial velocity varies from 0.186ft/s to15.20 ft/s.

4.2.2 Effects on pressure drop due to ROP 100ft/hr at liquid superficial velocity of 2ft/s.

Then, the ROP is increase to 100 ft/hr and compared with ROP 50 ft/hr to observe the effect of the increase as shown in Figure 14.

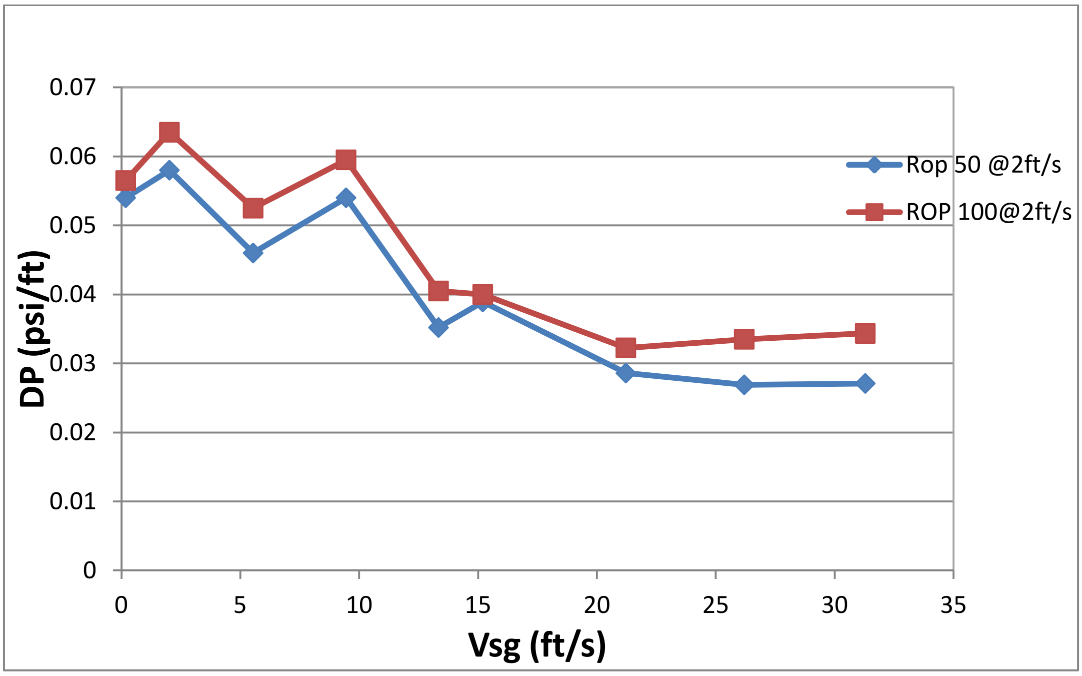


Figure 14: Compares ANSYS pressure drop Vs. gas superficial velocity for Vsl = 2ft/s and ROP = 50ft/hr and 100ft/hr

It is so clearly shown that the pressure drop estimated from ROP 100ft/hr shows similar trend results as the ROP 50ft/hr with error difference of less than 20 %.

Due to high concentration and accumulation of cuttings generated by 100 ft/hr leads to increase in pressure drop compared to ROP 50 ft/hr.

4.2.3 Effects on pressure drop due to ROP 50ft/hr and 100ft/hr at liquid superficial velocity of 4ft/s.

So when the liquid velocity is increased to 4ft/s and the gas velocity range is kept constant with the same ROP 50ft/hr and 100ft/hr, not much changes are observed in the pressure drop trend due to the presence of the gas causing high turbulence effect at the annulus in all cases as shown in Figures 15, 16 respectively.

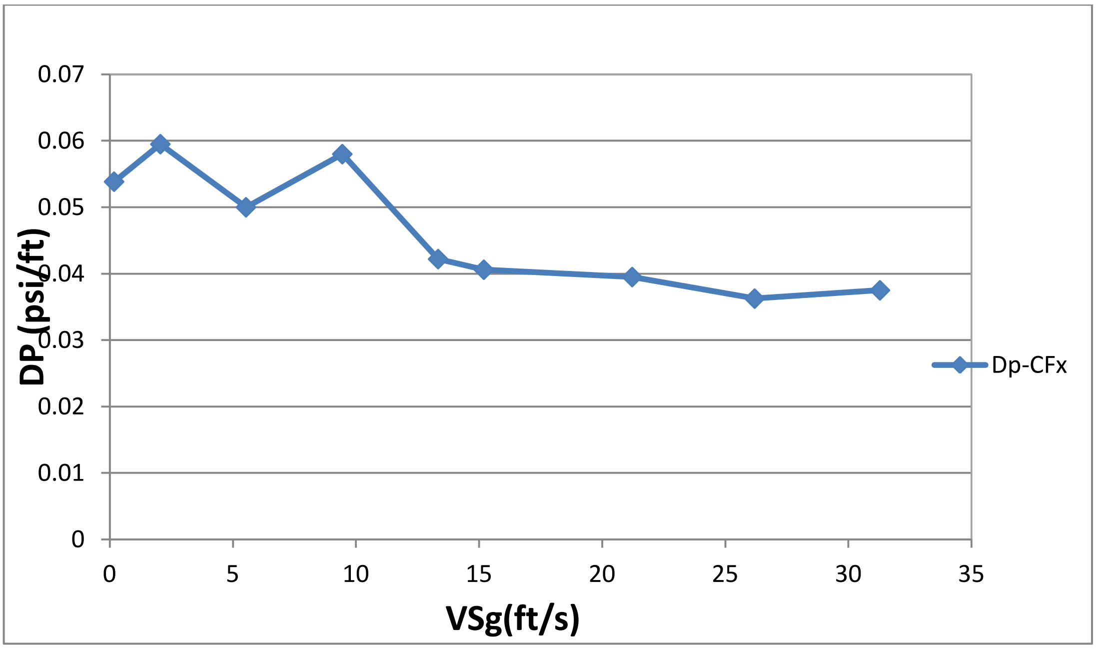


Figure 15: ANSYS Pressure drop Vs. gas superficial velocity for Vsl = 4ft/s and ROP 50ft/hr

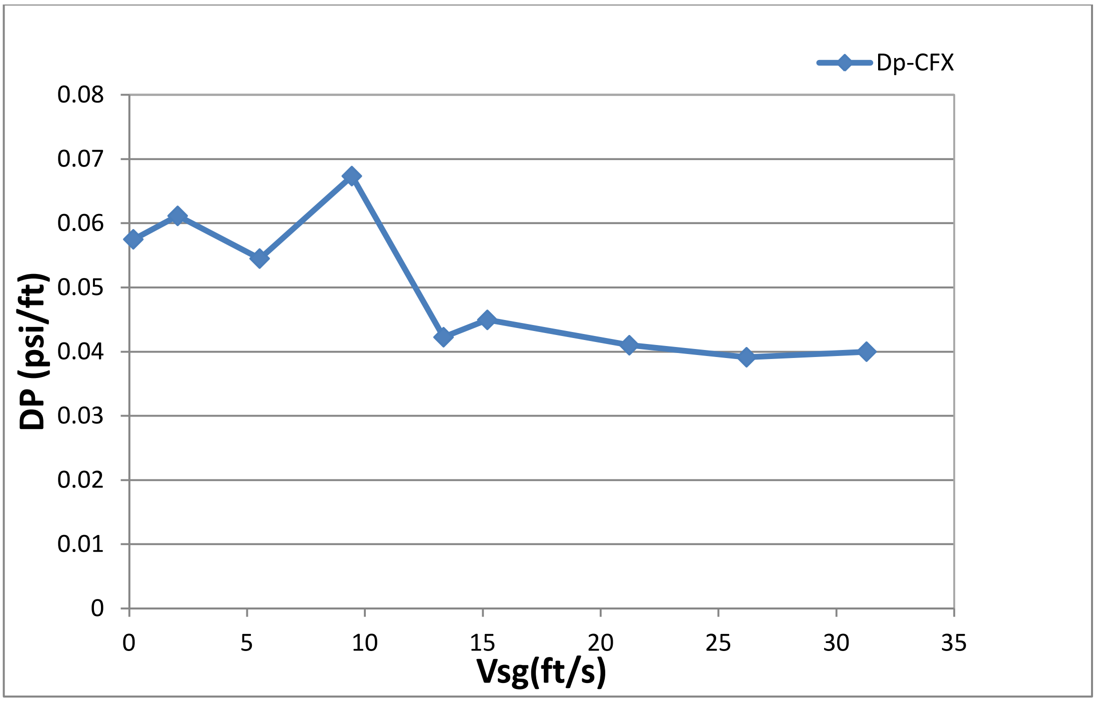


Figure 16: ANSYS Pressure drop Vs. gas superficial velocity for Vsl = 4ft/s and ROP 100ft/hr

4.2.4 Comparison between pressure drop-Ansys of ROP 50ft/hr and 100ft/hr at 4ft/s.

Figure 17 shows the comparison between the results of increase in ROP from 50ft/hr to 100ft/hr and liquid superficial velocity from 2ft/s to 4ft/s.

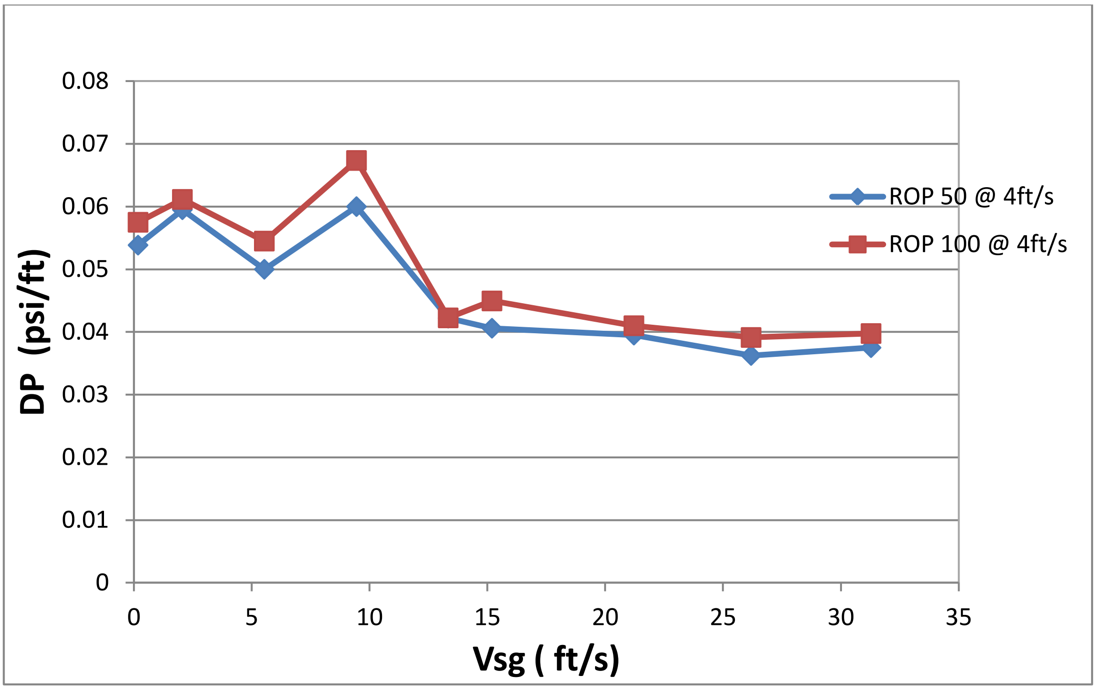


Figure 17: Compares ANSYS pressure drops Vs. gas superficial velocity for Vsl = 4ft/s and ROP = 50ft/hr and 100ft/hr

From the figure is clearly indicating that the two curves are so close to each other, just that the ROP 100ft/hr shows an increase in pressure drop due to high cuttings concentration and accumulation.

4.2.5 General Comparison between pressure drop-Ansys and Experiment results for ROP 50ft/hr and 100ft/s at liquid velocity of 2ft/s and 4ft/hr.

The figure below shows the comparison of ROP 50ft/hr and 100ft/hr at liquid superficial velocity of 2ft/s and 4ft/s with the experimental data for ROP 50ft/hr at liquid velocity of 2ft/s.

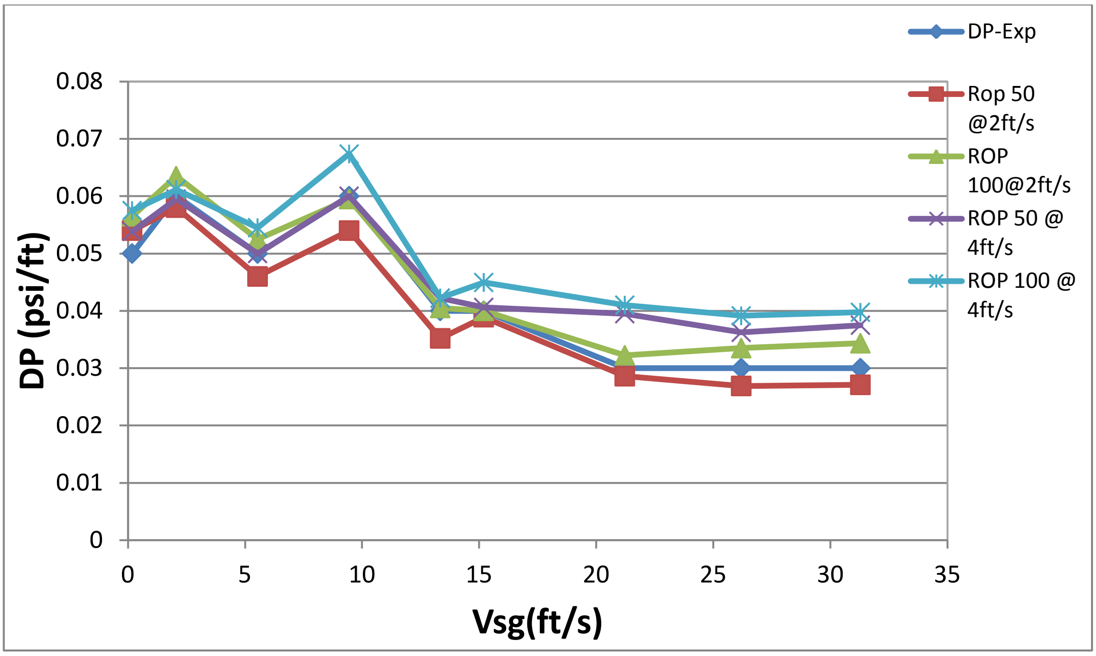


Figure 18: Compares ANSYS pressure drops with Experimental data Vs. gas superficial velocity for Vsl = 2 & 4 ft/s and ROP = 50 & 100 ft/hr

From the figure above, it is clearly indicating that the pressure drop generated due to increase in ROPs, gas and liquid superficial velocity are in same trend with the experimental curve of ROP 50ft/hr. Just that the pressure drop is a bit higher for ROP 100ft/hr compared to 50ft/hr. This is due to higher concentration and accumulation of cuttings generated by ROP 100ft/hr. And the estimated values of the pressure drop are shown in Appendix A.

4.2.6 **Summary:**

From Figures 13, 14 and 18, the effect of varying the ROP, gas and liquid superficial velocity on pressure drop were observed in the following points.

- ❖ The pressure drop estimated by the simulation gives a reasonable accuracy with the experimental results and the error difference is less that 20% with exception of some few points due to limitations and assumptions considered in this study.

- As the gas superficial velocity increase gradually up to 13.34ft/s, the cuttings bed decreases and the pressure drop decrease also. But once the bed disappeared completely at 21.22ft/s onwards, the pressure drop increases again.
- For increase in ROP, no much change is observed at the trend of the pressure drop maybe due to presence of gas causing turbulence at the annulus.
- Increase in liquid superficial velocity leads to increase in pressure drop due to increase in liquid-gas density when the gas velocity is constant.

4.3 Effects on Cuttings Concentration

In this section, the effect of changes in ROP and liquid velocity on cuttings concentration as gas velocity variation is kept constant is analyzed and verified with experimental data from Ettehadi Osgouei et al (2010).

4.3.1 Effects on Cuttings Concentration due to ROP 50ft/hr and liquid superficial velocity of 2ft/s

Figure 19 below shows a Comparisons of Cuttings Concentration of ANSYS Simulations with Experimental data for ROP 50 ft/hr

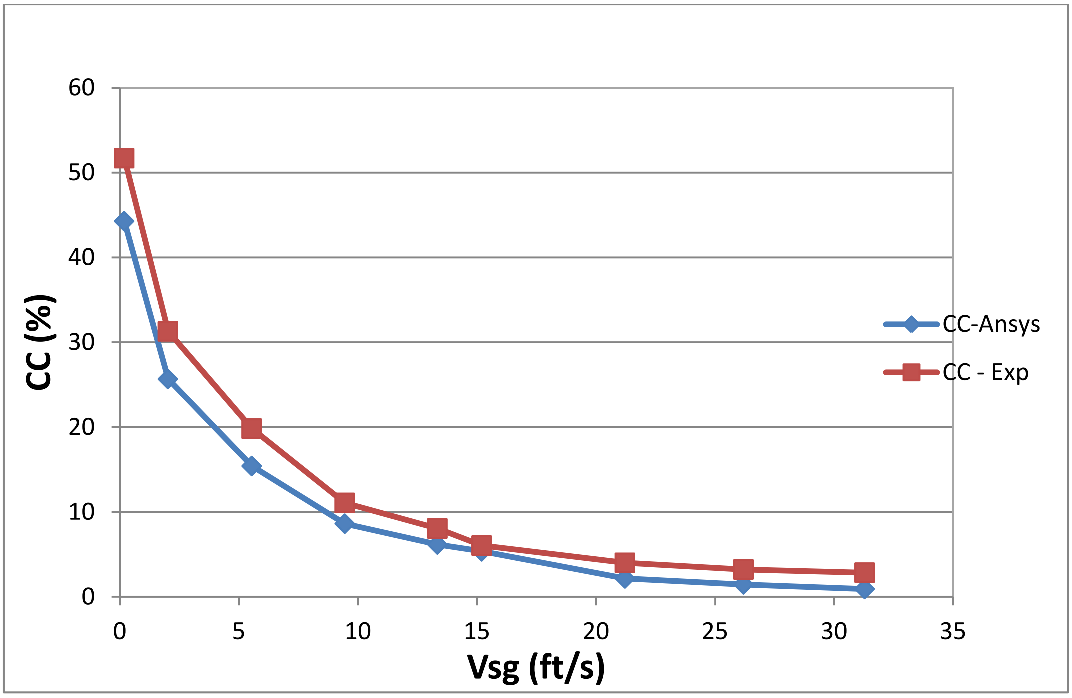


Figure 19: Comparisons of ANSYS Cuttings Concentration with Experimental data Vs. gas superficial velocity for Vsl = 2ft/s and ROP = 50 ft/hr

The simulation results shown above gave an acceptable match with the experimental data especially at gas velocity of 15.2 ft/s and 31.29 ft/s. And the observed error difference between the simulation and the experiment is less than 20% with exception of some few points.

Initially the cutting concentration and accumulation is high at the wellbore due to low annular velocity. But as the gas velocity increases, the cuttings concentration and accumulation decreases significantly. Because the fluid velocity at the annulus reduces the bed developed and increases the flow area of the drilling fluid leads to good carrying of the cuttings to the surface.

4.3.2 **Effects on cuttings concentration due to ROP 100ft/hr at liquid superficial velocity of 2ft/s.**

When the ROP is increased to 100ft/hr, the cuttings concentration curve shows the similar trend as 50ft/hr as shown in Figure 20.

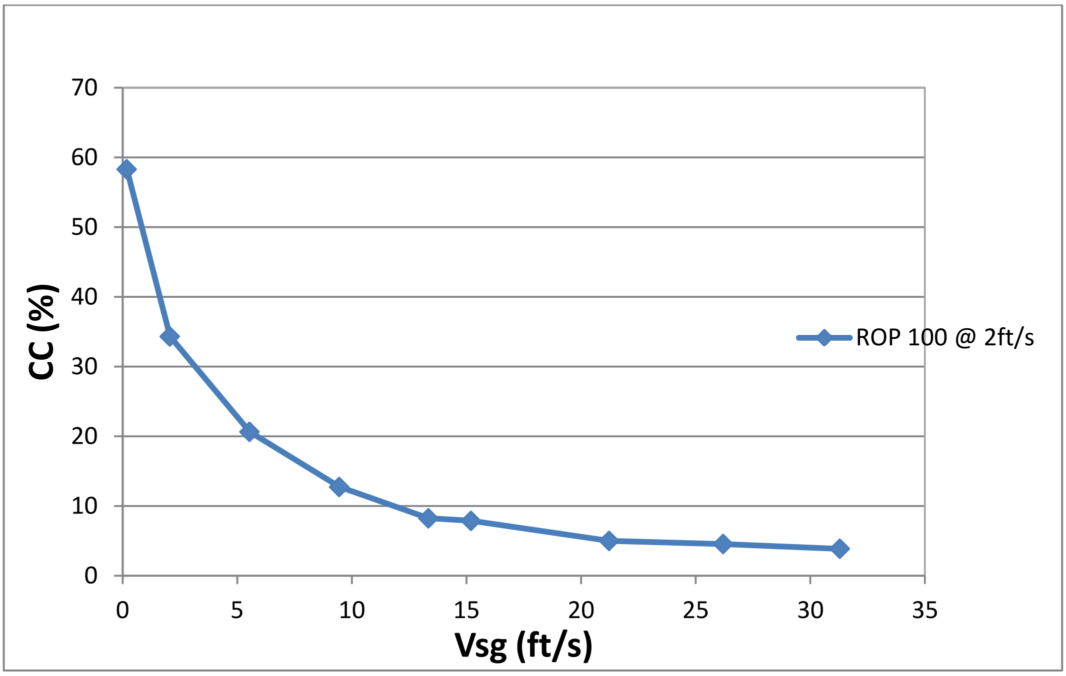


Figure 20: ANSYS Cuttings Concentration Vs. gas superficial velocity for Vsl = 2ft/s and ROP = 100 ft/hr.

From the figure above, it is clearly indicating that the increase in ROP to 100ft/hr shows the similar trend as the ROP 50ft/hr, just that the cuttings concentration increased due to concentration and accumulation of cuttings at the bottom of the well generated by the increased. But to see the increase, it should be compared with ROP 50ft/s as displayed in Figure 21 below.

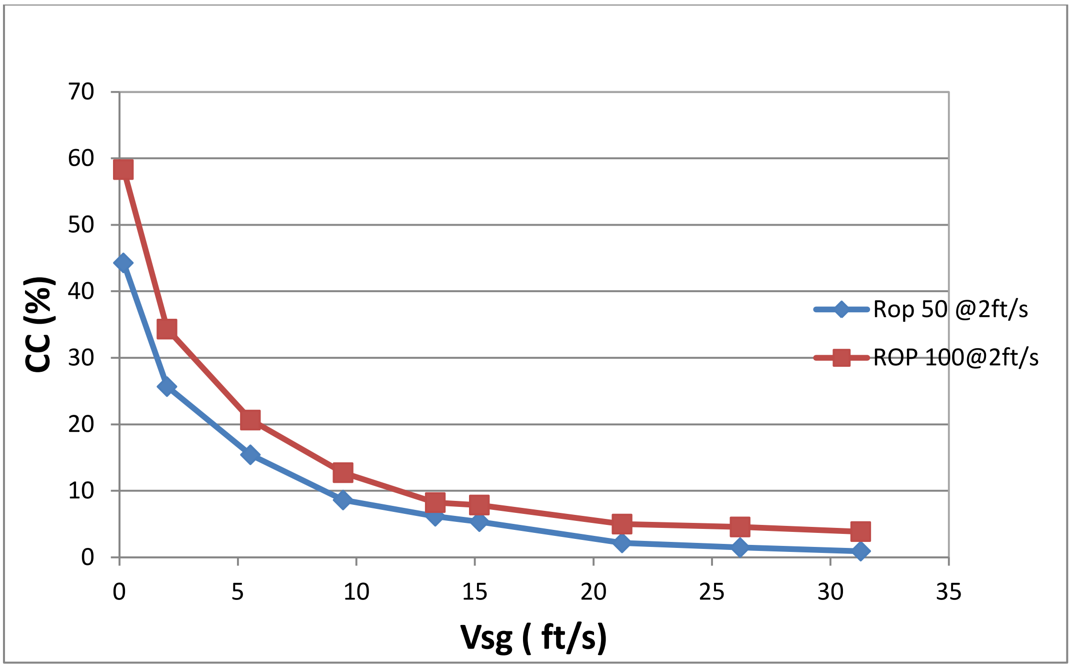


Figure 21: Comparisons of ANSYS Cuttings Concentration Vs. gas superficial velocity for Vsl = 2ft/s and ROP = 50, 100 ft/hr

The simulation results for 100ft/hr shows same trend as the ROP 50ft/hr with an error difference of less than 20 % due to high accumulation of cuttings generated by increase in ROP to 100ft/hr. But as gas velocity increases to 13.43ft/s onwards, the cuttings concentration decreases in both cases.

4.3.3 Effects on cuttings concentration due to ROP 50ft/hr and 100ft/hr at liquid superficial velocity of 4ft/s.

When the liquid velocity is increase to 4ft/s and keeping the gas velocity (0.18ft/s – 31.29ft/s) and ROP (50ft/hr & 100ft/hr) range constant, the following results are observed by the simulation as shown in Figures 22, 23.

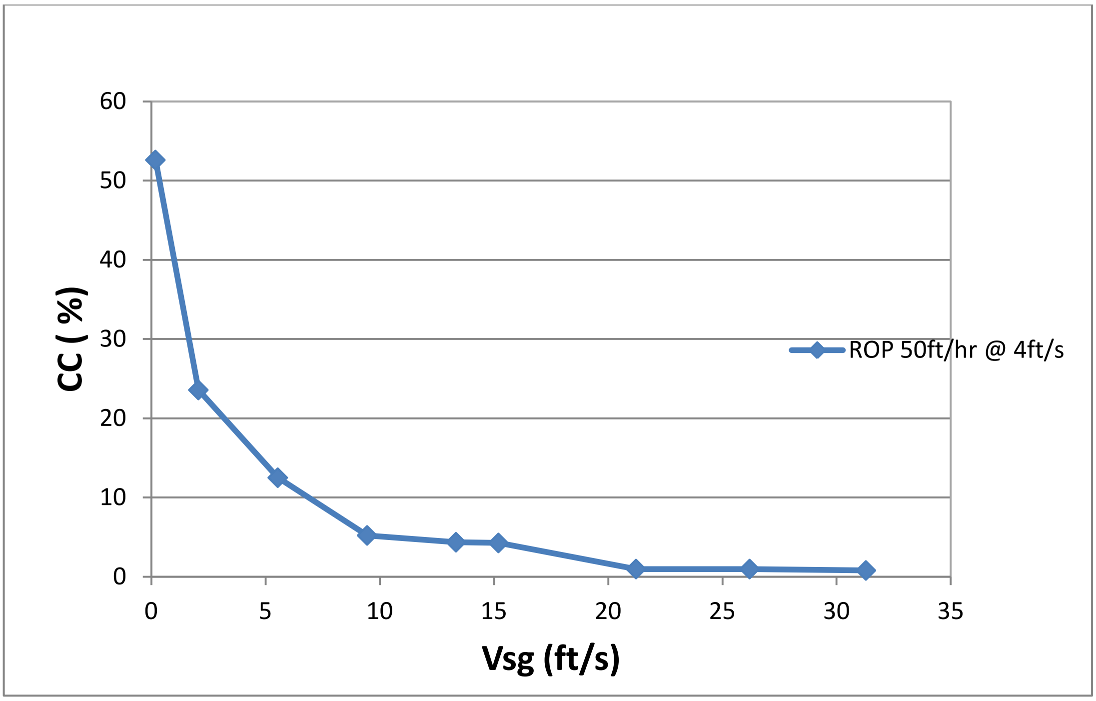


Figure 22: ANSYS Cuttings Concentration Vs. gas superficial velocity for Vsl = 4ft/s and ROP = 50 ft/hr.

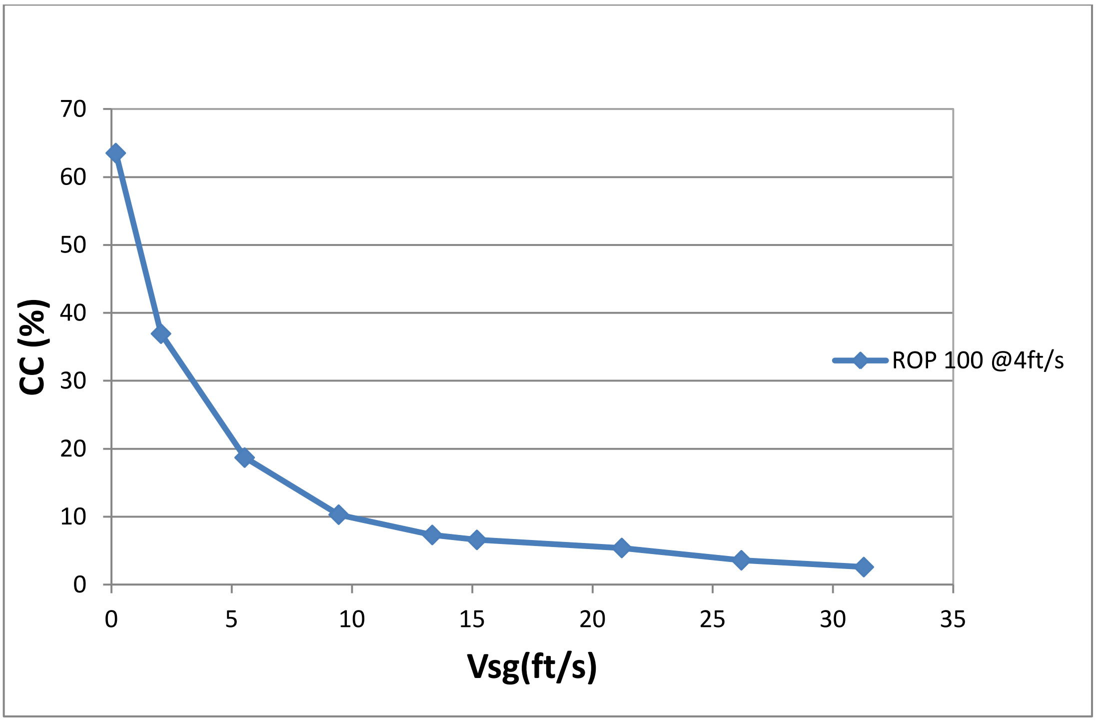


Figure 23: ANSYS Cuttings Concentration Vs. gas superficial velocity for Vsl = 4ft/s and ROP = 100 ft/hr.

4.3.4 Comparisons of ANSYS Cuttings Concentration Vs. gas superficial velocity for Vsl = 4ft/s and ROP = 50, 100 ft/hr

Figure 24 below shows a Comparisons of Cuttings Concentration generated by ANSYS Simulations for ROP 50 ft/hr and 100ft/hr at liquid velocity of 4ft/s.

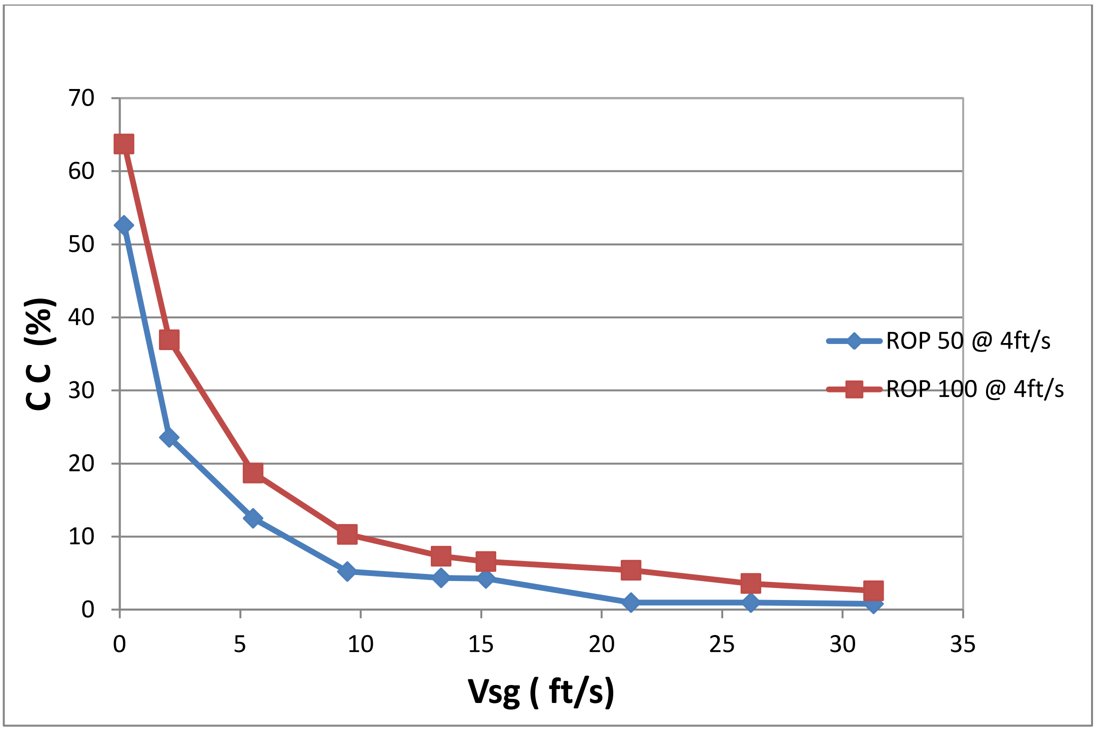


Figure 24: Comparisons of ANSYS Cuttings Concentration Vs. gas superficial velocity for Vsl = 4ft/s and ROP = 50, 100 ft/hr

As the liquid velocity increase, the cuttings concentration decreases due to increase in flow rate at the annulus. The higher the liquid velocity, the lower the cuttings concentration and accumulation. Thus, the cuttings transport is so sensitive to the liquid velocity.

4.3.5 **Comparison between ANSYS cuttings concentration with experimental results.**

The figure below shows the Comparison between the ROP 50ft/s and 100 ft/hr at liquid velocity of 2ft/s and 4ft/s generated by ANSYS with experimental data of ROP 50ft/s at velocity of 2ft/s as gas superficial velocity varies from 0.18 – 31.29ft/s.

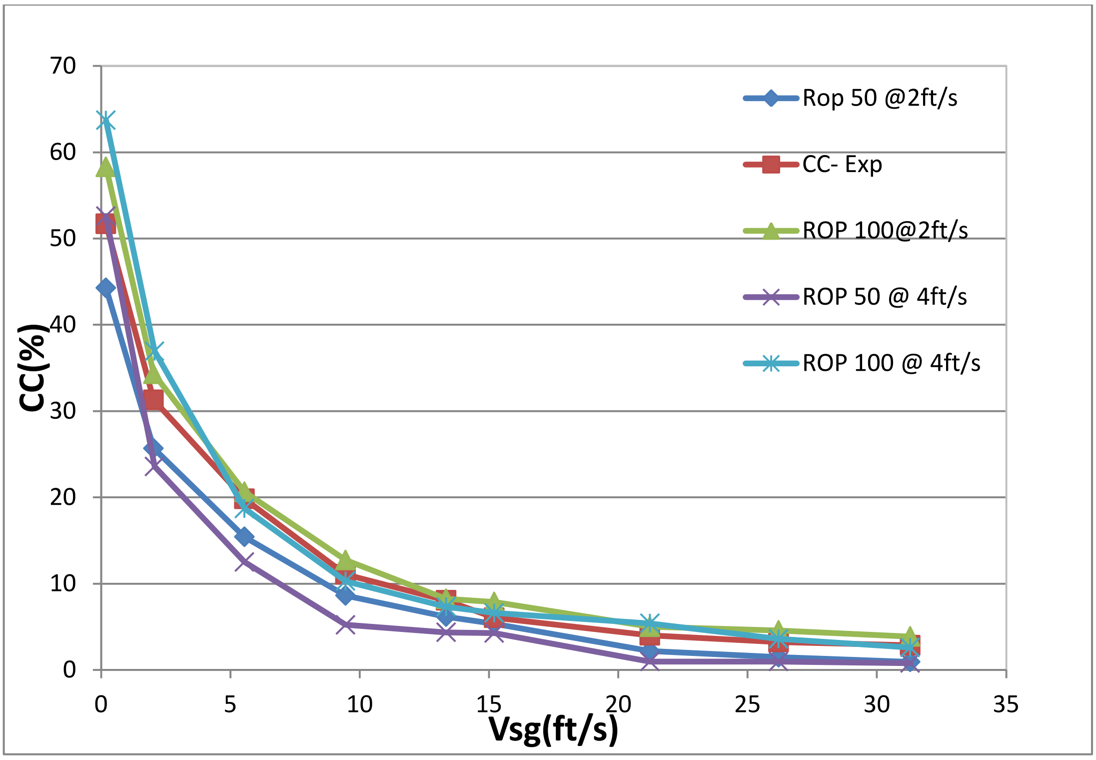


Figure 25: Comparisons of ANSYS Cuttings Concentration with Experimental data Vs. gas superficial velocity for Vsl = 2, 4ft/s and ROP = 50, 100ft/hr

It is clearly indicating from the above figure that, as the ROP increase, the cuttings concentrations increases, especially at low gas and liquid velocity at the annulus. While as the gas and liquid superficial velocity increase, the cuttings concentration decreases due to increase in flow area of the drilling fluid. And the estimated values of the cuttings concentration are shown in Appendix A

4.3.6 **Summary:**

From Figures 19, 21, 23 and 25 the effect of varying the ROP, gas and liquid superficial velocity on cuttings concentration were observed in the following points.

- ❖ Cuttings concentration estimated by the simulation model at the horizontal section of the wellbore are in good agreement with the experiment trend. And the error difference is less than 20% with exception of some few points due to limitations and assumptions considered in this study
- ❖ As the gas superficial velocity increase to 15.2 ft/s onwards, the cuttings concentration decreases and dispersed coarsely into the continue phase (water) in all case because gas superficial velocity increases the annular velocity and hence the flow area of the fluid increases.
- ❖ When the ROP is increase, the cuttings concentration increases. Thus, there is a linear relationship between them.
- ❖ Increase in liquid velocity is so effective to cuttings concentration reduction by increasing the carrying velocity of the fluid at the annulus.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The main objective of this project is to simulate the three phase (cuttings-gas-water) flow in a horizontal section of wellbore to estimate the pressure drop and cuttings concentration by using software called ANSYS-CFX 14. Here parameters like rate of penetration and gas and liquid superficial velocity are mainly considered to observe their effect. The liquid superficial velocity is constant in each case, while the gas superficial velocity varies. As a result of running the simulation, the following points are summarized as conclusion:

- The software ANSYS managed to simulate the cuttings-gas-liquid three phase flow in the horizontal section of the wellbore with an error difference of less than 20% when compared with the experimental results with exception of some few points due to limitations and assumptions considered in this study.
- Due to increase in gas superficial velocity, the annular velocity increase causing the carrying capacity to increase, which reduces the cuttings bed and hence improve cuttings transport
- The cuttings concentration has a linear relationship with rate of penetration (ROP). Thus, as the rate of penetration increase, the cuttings concentration and accumulation increases.
- As the gas superficial velocity increase, annular velocity increases causing the cutting beds to decrease and pressure drop decreases as well. But once the bed disappeared completely, the pressure drop increases again due to density of the mixture fluid.
- For increase in ROP, no much change is observed at the trend of the pressure drop due to presence of gas causing turbulence at the annulus.
- Based on local observation, three flow patterns are identified namely: Stationary bed, Moving bed and dispersed bed.

  The results got from applying ANSYS-CFX14 can be considered reasonable ; therefore this software can be used to designed cutting transport program along the horizontal wellbore during underbalanced drilling.

As part of recommendation for future work of this project, the following points can be considered:

- Cuttings should be simulated as dispersed phase using Eulerian-Eulerian model instead of particle transport model.
- Effect of inner pipe rotation (RPM) and hole inclination should be considered.
- Gas-cuttings two phase should be simulated using this software to determine the minimum gas injection rate to lift the cuttings.
- For more accurate results the mesh geometry should be finer and velocity profile should be introduced into the model.

REFERENCES

A.L. Martins, A.M.F. Lourenço, and C.H.M. de Sá: "Foam Property Requirements for Proper Hole Cleaning While Drilling Horizontal Wells in Underbalanced Conditions", SPE 74333 (2001)

A.A. Sunthankar, S.Miska, and E. Kuru; A. Kamp: "New Developments in Aerated Mud Hydraulics for Horizontal Well Drilling" SPE 62897 (2000).

Adari R.B: "Development of Correlations Relating Bed Erosion to Flowing time for Near Horizontal Wells", M.S. Thesis, The University of Tulsa, Tulsa (2000).

Ansari A.M.Sylvester N.D.Cem Sarica, Ovadia Shoham, J.P.Brill, ''A Comprehensive Mechanistic Model for Upward Two-phase Flow in Wellbores'' Journal SPE Production & Facilities, Volume 9 (1994).

B.K.Datta et al : " Hole cleaning and pressure loss prediction from a bulk transport perspective",SPE 96315 (2005).

Barkim Demirdal and J.C.Cunha: "Pressure losses of non-newtonian fluids in drilling operations", SPE 108711 (2007).

C.Ercan amd E.M.Ozbayoglu: "PHPA as a frictional pressure losses reducer its pressure loss estimation", SPE 125992 (2009).

C.Omurlu.Metin and E. M. Ozbayoglu: "Two-phase fluid flow through fully eccentric horizontal annuli: A mechanistic Approach" SPE 107076 (2007).

C.Perez and J. R. Smith: "New mechanistic model for UBD improves wellbore pressure predictions" SPE 85110 (2003).

Dongping. Y and S.G.Robello: "Annular pressure loss predictions for various standoff devices". SPE 112544 (2008).

Doan Q.T.,M. Oguztoreli, Y. Masuda, T. Yonezawa, A. Kobayashi, S. Naganawa,'' Modeling of Transient Cuttings Transport in Underbalanced Drilling (UBD)'' SPE Journal Volume 8(2003).

Desmond Nguyen, and S.S. Rahman : "A Three-Layer Hydraulic Program for Effective Cuttings Transport and Hole Cleaning in Highly Deviated and Horizontal Wells" , SPE 51186 (1998).

Evren.M.Ozbayoglu Osgouei R & M.A.Ozbayoglu: "Estimation of very-difficult to identify data for hole cleaning, cuttings transport and pressure drop estimation in directional and horizontal drilling", SPE 136304 (2010).

H.I. Bilgesu et al : "computational fluid dynamics (CFD) as a tool of study cutting transport in wellbores", SPE 78716, (2002).

Iyoho, A.W. and Azar, J.J.:"An Accurate Slot-Flow Model for Non-Newtonian Fluid Flow through Eccentric Annuli," SPE 9447 (1981).

L.Zhou et al:" Measurement of in-situ cuttings concentration using nuclear densitometers in a horizontal annulus at simulated downhole conditions" , SPE 94261 (2005).

Li J., Walker S., ''Sensitivity analysis of hole cleaning parameters in directional wells'' SPE Journal, Vol. 6, No.4, (2001).

M.E.Ozbayoglu, M.Sorgun and K.Sveen: "Hole cleaning performance of light-weight drilling fluids during horizontal underbalanced drilling", SPE-Journal (2010).

Martins, A.L., Sa, C.H.M., Lourenco, A.M.F. and Campos, W.: "Optimizing Cuttings Circulation In Horizontal Well Drilling," SPE 35341 (1996).

Mukherjee H: "An experimental study of inclined two-phase", Phd dissertation, University of Tulsa (1979).

N. Singhal et al: "Friction pressure corrections for Newtonian and Non-Newtonian fluids in concentric annuli", SPE 94280, (2005).

Osgouei R, Evren.M.Ozbayoglu & M.A.Ozbayoglu: "Hole cleaning process during gasified fluid flow through horizontal annulus" SPE 131378 (2010).

Reza Ettehadi O: “Determination of cuttings transport properties of gasified drilling fluids”, Phd dissertation, METU (2010).

Reza Ettehadi, Evren.M.E Ozbayoglu and Murat .A.Ozbayogly : “ Flow pattern identification of Gas-liquid flow through horizontal Annular geometries”, SPE 129123 (2010).

Subramanian.R. and Azar. J. J’’ Experimental Study on Friction Pressure Drop for Non-Newtonian Drilling Fluids in Pipe and Annular Flow’’ SEP 64647, (2000).

S.T.Johansen and J. Sveen : " Generic model for calculation of frictional losses in pipe and annular” SPE –Journal (2003).

T.Hemphill and K. Ravi: “Pipe rotation and hole cleaning in an eccentric annulus”, SPE 99150 (2006).

Ternyik .J, Bilgesu H.I and S. Mohaghegh: “Virtual measurement in pipe (part-2), liquid holdup and flow pattern correlations”, SPE 30976 (1995).

Y. Li, N. Bjorndalen, E. Kuru: “Numerical Modelling of Cuttings Transport in Horizontal Wells Using Conventional Drilling Fluids”, SPE 227 (2004).

Y.Peysson and B. Herzhaft: “Lubrication Process at the Wall in Foam Flow—Application to Pressure Drop Estimation While Drilling UBD Wells” SPE –Journal (2008).

Zhou Yingcao et al: “A New Method to Measure the Downhole Pressure in UBD” SPE 88002 (2004).

Zhou L., Wang J., Hao J., ‘’Calculation and Design of Flow Parameters for Two-Phase Flow in Aerated Drilling’’, SPE 37044 (1996).

APPENDICES

Appendix A:

Simulation results for three phase (cuttings-gas-water) flow for horizontal eccentric annulus.

Table 3: pressure drop and cuttings concentration estimation for liquid velocity = 2ft/s and ROP = 50ft/hr

Inlet pressure (psi)	Outlet pressure (psi)	Gas sup. vel(ft/s)	Liquid sup. vel(ft/s)	CC(%)	ROP (ft/hr)	DP Ansys
18.42	18.42	0.18	2.02	44.278	50	0.054
19.25	18.79	2.06	2	25.67	50	0.058
18.48	18.11	5.54	2.01	15.4174	50	0.046
18.21	17.86	9.45	2.02	8.619	50	0.054
17.78	17.47	13.34	2	6.16878	50	0.0352
17.7	17.4	15.2	2.01	5.3578	50	0.0389
17.54	17.25	21.22	2	2.16878	50	0.0286
17.41	17.14	26.2	2.01	1.4621	50	0.0269
17.28	17.02	31.29	2	0.9259	50	0.0271

Table 4: pressure drop and cuttings concentration estimation for liquid velocity = 2ft/s and ROP = 100ft/hr

Inlet pressure (psi)	Outlet pressure (psi)	Gas sup. vel(ft/s)	Liquid sup. vel(ft/s)	CC(%)	ROP (ft/hr)	DP Ansys
18.42	18.42	0.18	2.02	58.309	100	0.0565
19.25	18.79	2.06	2	34.3195	100	0.0635
18.48	18.11	5.54	2.01	20.64	100	0.0525
18.21	17.86	9.45	2.02	12.72938	100	0.0595
17.78	17.47	13.34	2	8.23264	100	0.0405
17.7	17.4	15.2	2.01	7.8641	100	0.04
17.54	17.25	21.22	2	4.99593	100	0.03325
17.41	17.14	26.2	2.01	4.564714	100	0.0305
17.28	17.02	31.29	2	3.86826	100	0.03235

Table 5: pressure drop and cuttings concentration estimation for liquid velocity = 4ft/s and ROP = 50ft/hr

Inlet pressure (psi)	Outlet pressure (psi)	Gas sup. vel(ft/s)	Liquid sup. vel(ft/s)	CC(%)	ROP (ft/hr)	DP Ansys
18.42	18.42	0.18	4	52.5968	50	0.05385
19.25	18.79	2.06	4	23.5682	50	0.0595
18.48	18.11	5.54	4	12.49625	50	0.05
18.21	17.86	9.45	4	5.21238	50	0.0601
17.78	17.47	13.34	4	4.35323	50	0.0422
17.7	17.4	15.2	4	4.26082	50	0.0406
17.54	17.25	21.22	4	0.964944	50	0.0395
17.41	17.14	26.2	4	0.964645	50	0.03625
17.28	17.02	31.29	4	0.788597	50	0.0375

Table 6: pressure drop and cuttings concentration estimation for liquid velocity = 4ft/s and ROP = 100ft/hr

Inlet pressure (psi)	Outlet pressure (psi)	Gas sup. vel(ft/s)	Liquid sup. vel(ft/s)	CC(%)	ROP (ft/hr)	DP Ansys
18.42	18.42	0.18	4	63.7205	100	0.0575
19.25	18.79	2.06	4	36.9337	100	0.06115
18.48	18.11	5.54	4	18.6964	100	0.0545
18.21	17.86	9.45	4	10.2966	100	0.067
17.78	17.47	13.34	4	7.31269	100	0.04225
17.7	17.4	15.2	4	6.586882	100	0.04495
17.54	17.25	21.22	4	5.395257	100	0.041
17.41	17.14	26.2	4	3.585928	100	0.039125
17.28	17.02	31.29	4	2.585624	100	0.03975

Table 7: Experiment data for pressure drop and cuttings concentration estimation at liquid velocity = 2ft/s and ROP = 50ft/hr.

Inlet pressure (psi)	Outlet pressure (psi)	Gas sup. vel(ft/s)	Liquid superl vel(ft/s)	Annulus pressure Trans.	ROP (ft/hr)	CC(%)	DP Exp. (psi/ft)
18.42	18.42	0.18	2.02	4.14	50	51.70658	0.05
19.25	18.79	2.06	2	4.55	50	31.29136	0.06
18.48	18.11	5.54	2.01	3.78	50	19.8245	0.05
18.21	17.86	9.45	2.02	3.51	50	11.06994	0.06
17.78	17.47	13.34	2	3.08	50	8.057709	0.04
17.7	17.4	15.2	2.01	3	50	6.04139	0.04
17.54	17.25	21.22	2	2.84	50	4.005597	0.03
17.41	17.14	26.2	2.01	2.71	50	3.224457	0.03
17.28	17.02	31.29	2	2.58	50	2.847587	0.03