SHEHAB ABDULWAHID ALHEMYARI B.ENG. (HONS) PETROLEUM ENGINEERING JANUARY2015

CFD SIMULATION OF THE EFFECTS OF DRILL PIPE ROTATION ON CUTTINGS TRANSPORT IN HORIZONTAL WELLBORE USING NEWTONIAN FLUID.

SHEHAB ABDULWAHID ALHEMYARI

PETROLEUM ENGINEERING

UNIVERSITI TEKNOLOGI PETRONAS

JANUARY 2015

CFD Simulation of the Effect of Drill Pipe Rotation on Cuttings Transport in Horizontal Wellbore using Newtonian Fluid.

By

Shehab Abdulwahid Alhemyari

14623

Final report submitted in partial fulfillment of

the requirement for the

Bachelor of Engineering (Hons)

(Petroleum)

January 2015

Supervisor: Mr. Titus Ntow Ofei

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATEION OF APPROVAL

CFD Simulation of the Effect of Drill Pipe Rotation on Cuttings Transport in Horizontal Wellbore using Newtonian Fluid.

By

Shehab Abdulwahid Alhemyari
14623

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

Approved by,

____

Mr. Titus Ntow Ofei

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
January 2015

CERTIFICATION OF ORIGINALITY

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

____

SHEHAB ABDULWAHID ALHEMYARI

ABSTRACT

Good drilling program requires an effective and efficient transportation of cuttings out of the hole. When drilling horizontal wells, hole cleaning process become more complex, therefore proper design of hydraulic parameters is crucial. Cuttings transport through annulus is affected by numerous parameters such as flow rate, eccentricity, drill pipe rotation, angle of inclination, etc. Predicting effective cuttings transport requires simultaneous consideration of all these parameters, which make it essential to study the influence of these parameters in cuttings bed development and erosion. Improper hole cleaning will cause major costly drilling problems such as a slower rate of penetration, increase of pipe sticking potential, higher drag and torque, formation fractures and wellbore steering problems. This project aims to analyze the effect of drill pipe rotation on cuttings transportation in horizontal wellbores. For this purpose, Computational fluid dynamic (CFD) ANSYS 15.0 CFX was utilized to model the design at various pipe rotation speeds, fluid velocities, and a constant rate of penetrations of 60 ft/hr. The performance of the proposed model is compared with an experimental study from literature. By comparing both pressure losses and cuttings concentration at (0, 60) rpm, the outcomes show an excellent agreement for both calculated and experiment results. Simulated pressure loss values deviating slightly from the experimental data with a mean percentage error of 2.18 % and 4.40 % for 0 rpm and 60 rpm respectively. Similarly the calculated cutting concentration value exceeding the experimental results with a mean percentage error of 6.40 % and 11.82 % for 0 rpm and 60 rpm respectively. The analysis of the obtained results shows that increasing the drill pipe rotations significantly reduce the cuttings concentration in the annulus with slight increment in pressure losses. However, at high fluid velocity, drill pipe rotation effect is minimum. It also shows that increasing the flow rate will cause an increment in the annulus pressure losses and rapid decrement in the cuttings accumulation. The use of computer simulation approach eliminates the need for expensive laboratory setups and can be used to study an unlimited number of physical and operational conditions.

Keywords: Cuttings transport, Computational Fluid Dynamic (CFD), Drill pipe rotation, hole cleaning, frictional pressure loss, eccentric annulus, horizontal wells, flow patterns.

ACKNOWLEDGMENTS

First and foremost, all praise is to Allah, the Most Gracious and the Most Merciful, Who through His mercy and grace, I was able to complete my final year project. Next I would like to express my appreciation to Mr.Titus Ntow Ofei, for his endless support. He has provided me with all the necessary data and resources that helped me to enlarge my knowledge and experience in all project related aspects. My ultimate gratitude to him for his guidance, monitoring throughout my project. My deepest heart gratitude to my parents who strived to get me where I'm now, especially my father, Abdul Wahid Alhemyari who helped me in all possible ways to ease my way through this project. His spirit has guided me through my difficult times. Deep appreciation goes to my brothers and sisters. I dedicate this project to them and I highly appreciate their motivation and encouragement and their valuable advices that they provided me through all this period.

Not to forget, I would like to thank Universiti Teknologi PETRONAS (UTP) for their support and for providing me with the necessary equipment and software that were required to run the project smoothly.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

ρ_l	Fluid density (k_g/m^3)
v_l	Fluid velocity (m/s)
ρ_s	Solid density (k_g/m^3)
v_s	Solid velocity (m/s)
K_l	Fluid volume fraction
K_s	Solid volume fraction
e	Eccentricity
δ	Offset distance (m)
OD	Outer pipe diameter (m)
u_l	Specific volume $(\frac{m^3}{k_g})$
Ω	Rotation vector (1/min)
ID	Inner pipe diameter (m)
L_h	Hydrodynamic length (m)
D_h	Hydrodynamic diameter (m)
Re	Reynold number
$\mathcal{M}$	Viscosity $(k_g/m.s)$
M	Interphase momentum transfer
M_d	Drag force per unit volume (N/m^3)
C_D	Drag coefficient
N_{Re_p}	Particles Reynold number
$\mathcal{M}_l$	Fluid viscosity $(k_g/m.s)$
M_L	Lift force per unit volume (N/m^3)

Unit Conversion

$m^3/s = gpm \times 6.31$: E -05

$m/s = ft \times 0.3048$: $E + 00$

$pa/m = psi/ft \times 2.262$: $E + 04$

$kg/m^3 = ppg \times 1.198$: $E + 02$

$m = inch \times 25.4$: E -03

CHAPTER 1

1.0 INTRODUCTION

1.1 Background

In deviated wells, hole cleaning becomes a difficult phenomenon to be carried out due to the accumulation of cuttings at the bottom of the wellbore. Effective cuttings transport out of the hole, through the annulus and up to the surface is required for successful and economic drilling process.

Improper hole cleaning could result in incident which might cause oil companies millions of dollars in revenue [1]. Various problems encountered in the wellbore due to poor hole cleaning are bit wear, slow drilling rate (ROP), increase the pipe sticking potential, higher Equivalent Circulating Density (ECD), excessive required hydraulic power, high drag and torque [2].

When drilling horizontal wells, cuttings transportation efficiency plays important roles when designing hydraulic parameters [3]. Hence, the causes and consequences of cuttings bed development in annulus must be well understood.

There are several parameters that affect hole cleaning including: flow rate, drill pipe eccentricity, hole inclination, fluid rheology, drill-pipe rotation and rate of penetration (ROP) [4-6].

In the past two decades numerous studies associated with the effect of pipe rotation on cuttings transport have been performed by experimental investigations and computational fluid dynamic (CFD) modeling.

Figure (1) shows the level of influence that each parameters has on hole cleaning. It also indicates that flow rate is the most influential parameter with high level of controllability.

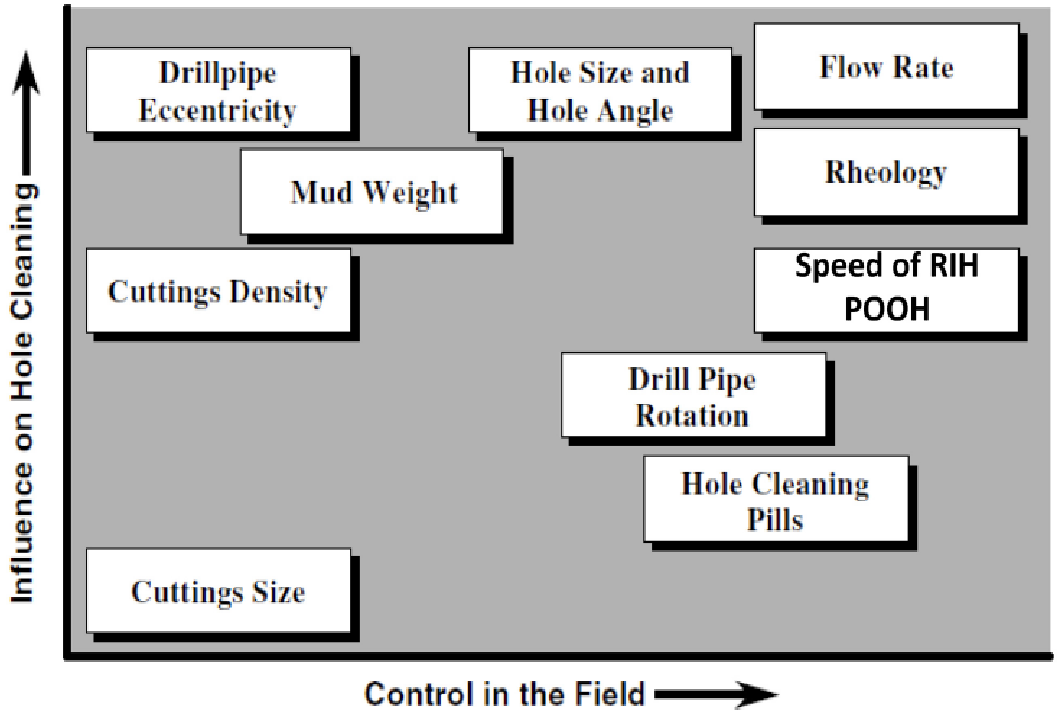


Figure 1: Key variables which effect solids transport services modified from Li and luft [6].

The effects of drilling parameters on cuttings transport are summarized below;

i) Cutting size.

For high angle wellbores, smaller sized cuttings are harder to be transported to the surface due to higher lift force requirements. On other hand, at low angles of inclination, medium sized cuttings are easier to transport than the smaller cuttings [3, 7, 8].

ii) Effect of mud weight.

An increase in mud weight slightly enhances cuttings transport as long as there is not an accompanying increase in viscosity. The effect that mud weight has on hole cleaning is more pronounced for high angle-wells [9].

iii) Pipe rotation.

Rotating the drill pipe can dramatically increase the rate at which cuttings are removed from high-angle and horizontal wells. The mechanism for this increment is not certain but may be related to the redistribution of flow in an eccentric annulus, together with mechanical agitation of the cuttings bed created by rotating the drill pipe. Rotation is the key factor in hole cleaning efficiency for high angle holes where the active flow area is at the top of the hole designated by red spot as seen in Figure (2). Pipe and cuttings lay along bottom of the hole and mechanical agitation is required to get cuttings into the fluid flow [4, 10-12].

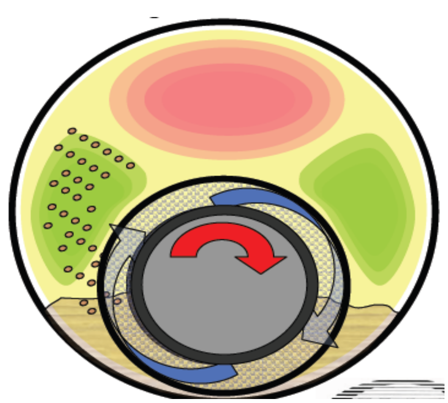


Figure 2: Drill pipe rotation

iv) Eccentricity.

When pipe is not precisely centered (or concentric) in the wellbore; it may be described as partially eccentric or fully eccentric if in contact with the wellbore wall. Eccentricity has more effect if the fluid is viscous. As eccentricity goes from positive (pipe is on the lower side of the wellbore) to negative (pipe is on the higher side of the wellbore), the requirement for hole cleaning decreases. Figure (3) shows the configuration of concentric and eccentric wells.

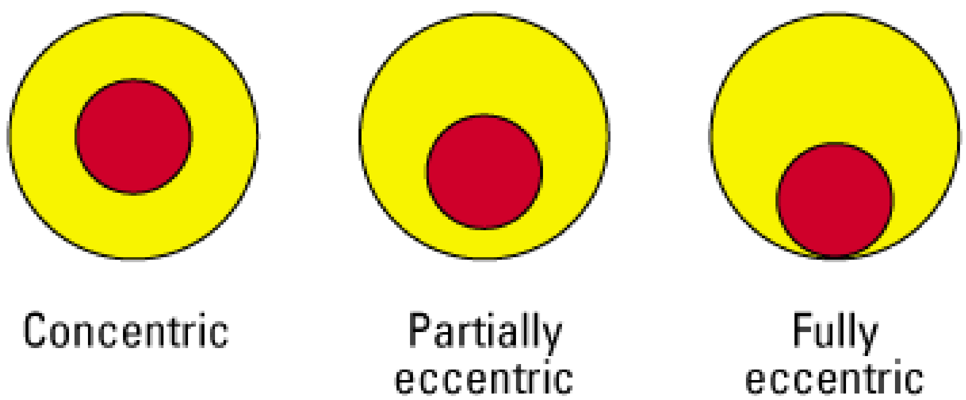


Figure 3: Eccentricity

Bilgesu et al. [13, 14] were one of the first researchers who conducted a simulation study to examine various parameters effecting cuttings transport via CFD. The result was positive, indicating an improvement in cutting transport due to drill pipe rotation and the effect is more prominent for smaller particle size.

1.2 Problem Statement

Several studies have been documented regarding hole cleaning. Both experimental and modeling methods investigating various parameters that governs cuttings transport. Cuttings transport from the bit up the annulus to the surface is a complex process which require a full understanding and simultaneous consideration of all the parameters that effects cuttings transport. If the cuttings cannot be removed from the wellbore, they will soon impede drilling causing several problems that might lead to plug or abandoned the well. Potential problem due to insufficient cuttings removal are increasing pipe sticking potential, formations fracture, excessive hydraulic powered requirement and higher drag and torque forces.

Figure (4) shows the accumulation of cuttings in a deviated wellbore.

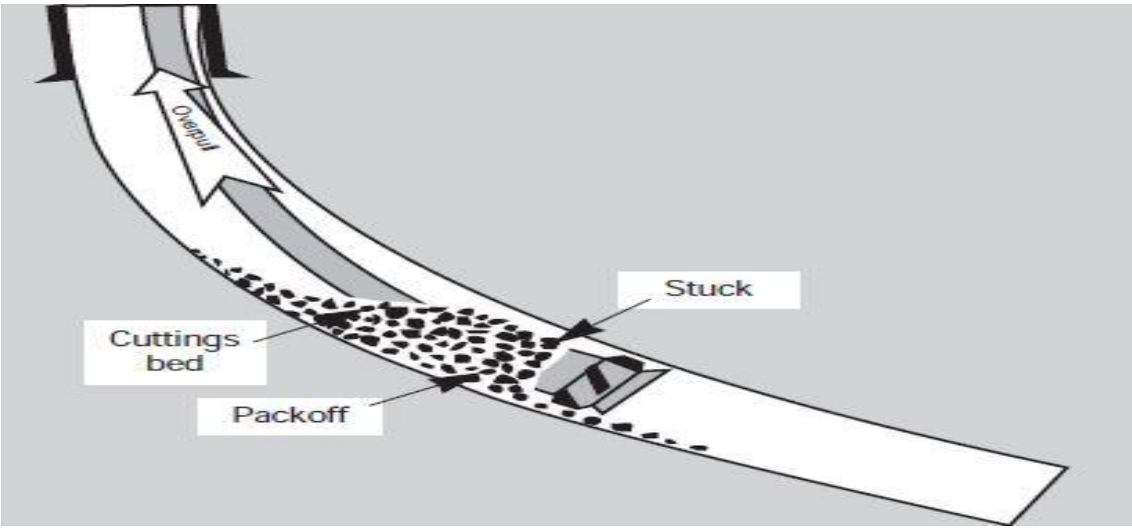


Figure 4: Bed Deposition in deviated wells

Poor hole cleaning is a major risk and it is common in the horizontal drilling. Increasing the fluid flow can ensure an efficient cuttings transport however, it has other consequences such as:

- Stuck pipe requires higher hydraulic power and as a result, this leads to higher operational costs for the industry.
- Increase in the pressure losses which can cause a serious damage to the reservoir formation.

In this case, drill pipe rotation plays an important role in cuttings transportation, moreover computational fluid dynamic (CFD) software can be used to simulate the effects of drill pipe rotation on cutting transport in horizontal wells, more concisely, the effectiveness of hole cleaning under various parameters such as, hole inclination (90°), flow rate, rate of penetration and drill pipe rotation.

1.3 Objectives:

The main objectives of this project are:-

1. To simulate the effects of drill pipe rotation in combination with fluid velocity on cuttings transport in horizontal well using Newtonian fluid.
2. To predict the annular frictional pressure losses, cuttings concentration and flow pattern in the annular space.

1.4 Scope of the study:

The boundaries of this project is to investigate how the rotation of drill pipe can affect the cuttings transport in horizontal wells using Newtonian fluid, assuming steady state conditions and fully developed fluid flow. The model will be designed using Computational Fluid Dynamics (CFD) ANSYS 15.0 workbench and flow equations solved using CFX solver.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Cuttings transport in horizontal wells.

As mentioned earlier, quite a number of studies have been conducted to investigate the effects of various parameters on cuttings transport. The studies were carried out in one of the following approach; empirically, theoretically and experimentally. In this study the focus will be on simulating the effects of drill pipe rotation along with various parameters on cutting transportation to the surface. Sanchez et al. [15] , investigated the effect of drill pipe rotation on hole cleaning during directional-well drilling with a 100ft long wellbore simulator, 8in diameter and 4.5in drill pipe. The drill pipe rotation speed ranged from 0 to 175rpm and four hole inclination 40°, 65°, 80°, and 90° were used. Based on Figure (5) authors observed the following:

1) Hole cleaning is significantly affected by pipe rotation.
2) Low flow rate and high rotary speed in horizontal well tend to reduce cutting concentration significantly.
3) Under similar condition with flow rate of 350gpm when increasing the rotary speed from 50rpm to 90rpm as shown in Figure (5), it is observed that 50rpm is not high enough to fully remove the cuttings while at 90rpm all cuttings were removed.
4) The degree of improvement in cuttings transportation process due to pipe rotation is a function of the instantaneous combination of mud flow rate, cuttings size, and mud rheology.

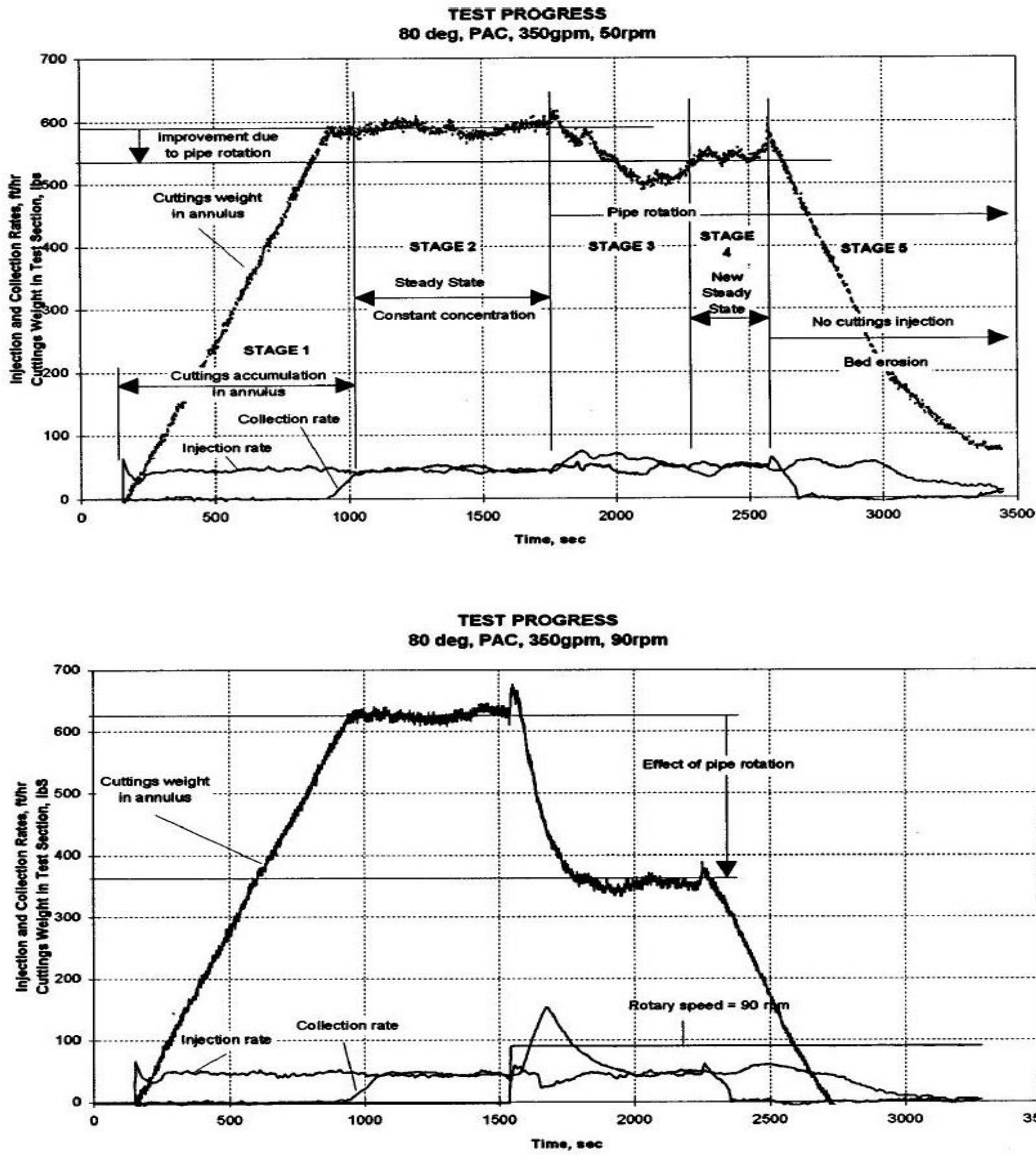


Figure 5: Test progress of hole cleaning under same condition and different pipe rotation speed (Modified from Sanchez et al. [9])

Previous studies have concluded that increasing fluid velocity will lead to decrease in cutting concentration in the annulus [8, 12, 16]. Peden et al. [17] concluded that no major effect on hole cleaning by pipe rotation in large annuli whilst in small annular, significant improvements can be obtained.

Ofei et al. [18] has simulated a two-phase solid-fluid flow employing CFD technique (ANSYS-CFX) to predict the concentration of annular cuttings and pressure losses in eccentric horizontal annuli as a function of varying drilling parameters (pipe rotation speed, fluid type and ratio of inner pipe diameter to outer pipe diameter). The authors observed that increasing in fluid velocity significantly increases pressure losses and it leads to decrement in cuttings concentration. The authors have also concluded that with increasing the drilling pipe rotation from 80rpm to 120rpm, it did not result in any significant increment in pressure loss with noticeable decrement in cuttings concentration.

A comprehensive experimental study was performed by Tomren et al. [8] on cuttings transport in directional well using a 40ft test section. Hole angle effects was evaluated and concluding that hole angle increment will lead to increase in total cutting concentration. The authors also observed that bed thickness increased as the liquid flow rate was decreased.

Sun et al. [19] utilized the computational fluid dynamics (CFD-ANSYS) to study the effects of drill pipe rotation on cuttings transport in complex structure wells. The study was carried out for an inclination varied from 45° to 90°, flow rate from 30 to 50 L/s and drill pipe rotation from 80rpm to 240 rpm. The CFD simulations indicate that significant presence in increasing the tangential velocity of drilling fluid will restrain the cutting bed development. The authors also reported that increasing pipe rotation at low to medium flow rates, can drastically decrease cutting concentration and annular pressure losses as shown in the Figure (6). Another significant impact for the drill pipe rotation was noticed on minimum transport velocity at medium and high viscosity fluid.

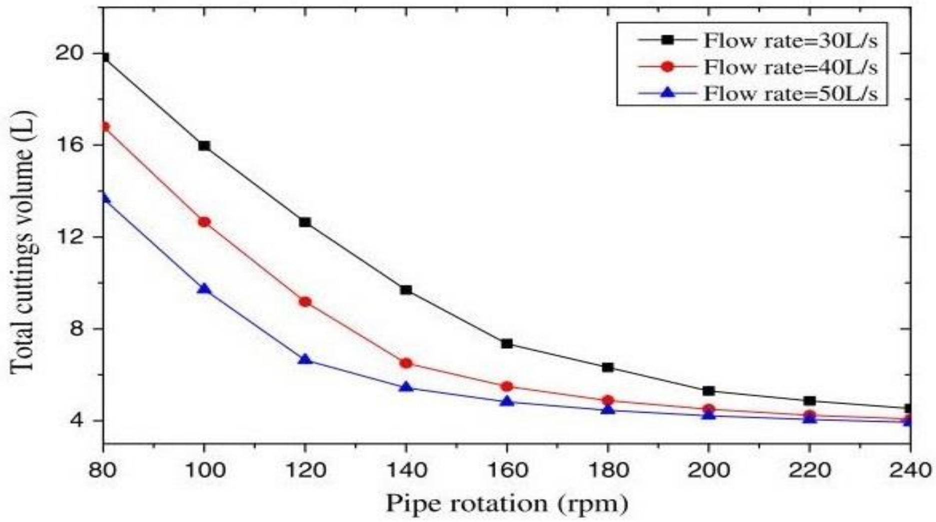


Figure 6: Effects of drill pipe rotation modified from Sun et al. [16]

Experimental researchers have also indicated that small cuttings size are easier to be transported compared to the large cuttings size. Another studies observed that pipe rotation can reduce the cuttings build up in the annulus, the effect is greater for small cuttings with low flow rate [17, 20].

Literature review is summarized in the appendix1

2.2 Physics of cuttings transport;

When transporting cuttings through annulus, cuttings are subjected to various forces that can either support the transportation or drop it down, the forces acting on a single particle are illustrated in Figure (7);

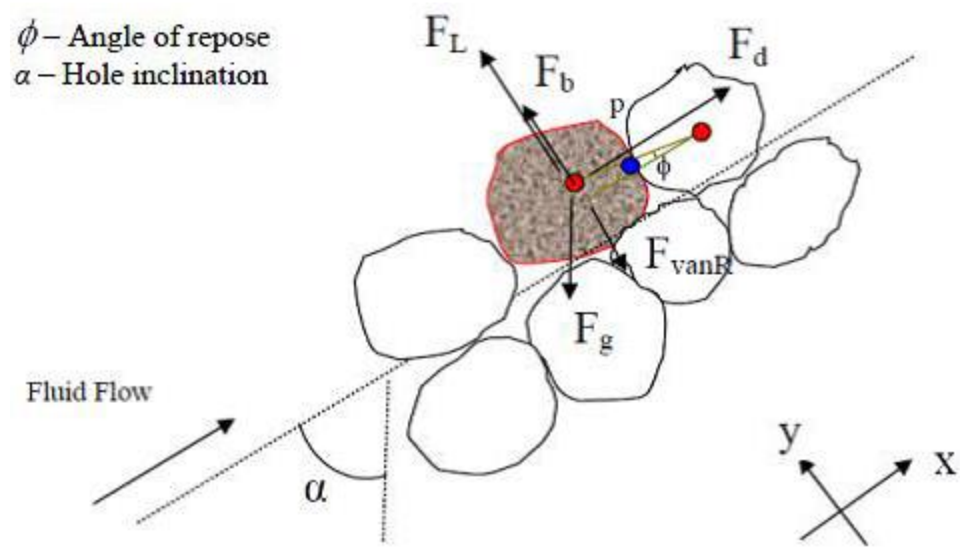


Figure 7: Physical forces acting on particles

i) Forces caused by the properties of the cuttings and it is surrounding fluid refer to the static forces such as Gravity force F_g and Buoyancy force F_b. Static force is independent on fluid flow.

ii) Drag force F_d and Lift force F_L, refer to the hydrodynamic force which is due to fluid flow.

iii) Colloidal force or Van der Waals dispersion F_{van} which exist between any neighboring particles

<u>Gravitational force:</u> This is the apparent weight of the particle.

$$F_g = \pi \frac{{d_p}^3}{6} (\rho_p - \rho_f). g \qquad [2.1]$$

Where d_p is particle size, ρ_p is density of particle and ρ_p density of fluid.

Drag Force:

$$F_D = \frac{\pi}{8} {d_p}^2 \rho_p {v_s}^2). C_D \quad [2.2]$$

Where, v_s is solid Patrice velocity, v_s is the terminal settling velocity and C_D is Drag Coefficient = f (Particle Reynolds No, Particle Shape).

2.3 Flow pattern in horizontal wells;

Fluid velocity, cuttings accumulation and physical properties of both fluid and cuttings are the main parameters that determine the nature of flow pattern through annulus. The solid and liquid flow in horizontal annuli has been classified into three categories as shown in the Figure (8);

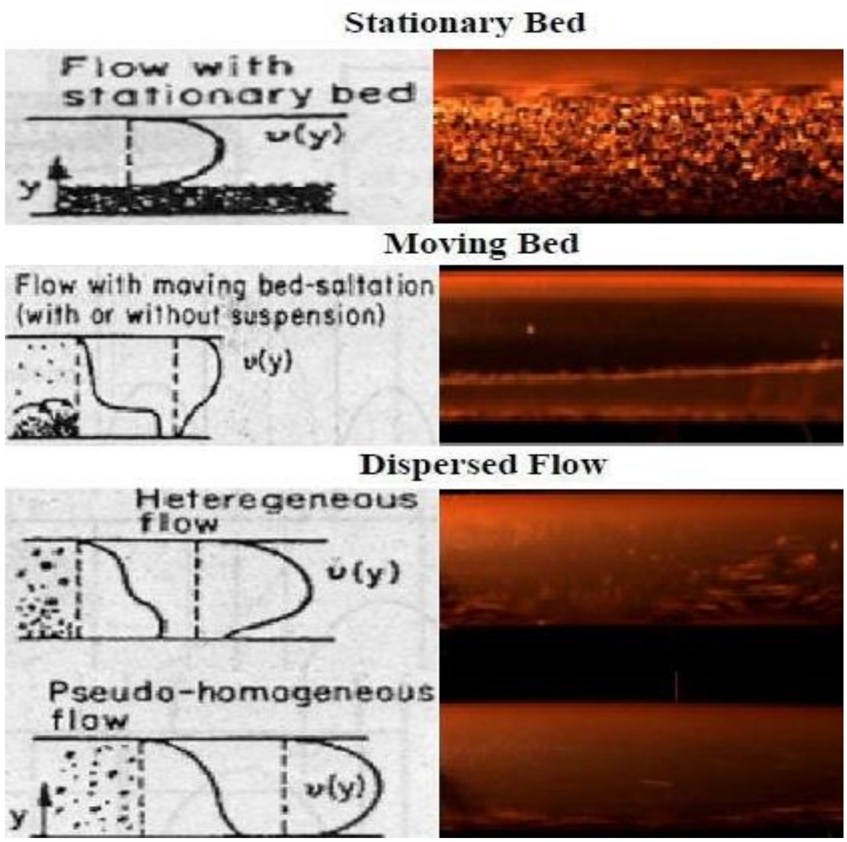


Figure 8: Qualitative solid/ liquid flow pattern modified from Osgouei [22]

Higher superficial velocity has a high impact in flow pattern transition in such way transition from one flow pattern to another occurs noticeably at higher fluid flow. On other hand, at lower velocity, there is no clear transition line between various flow patterns.

CHAPTER 3

3.0 METHODOLOGY

3.1 Research methodology

Methodology is the process undertaken in order to accomplish the objectives of this study that are listed in section 1.3. Simulation implementing CFD technique which will be used in order to achieve the objectives.

Computational Fluid Dynamics (CFD) simulation

Studying the effects of drill pipe rotation in cuttings transport, predicting frictional pressure loss and transport velocities become very critical when modeling a horizontal wells.

In this study and under the assumption that; fluid is incompressible, isothermal and the flow is fully developed and in a steady state condition ,computational fluid dynamics (CFD) model will be used to simulate two phase flow (Solid-Liquid) inside a horizontal wellbores under various drill pipe rotation speeds, fluid velocities and rate of penetration.

3.1.1 Benchmark identification and mathematical equations

An experimental cuttings transport study carried out by Osgouei [2010] was chosen as a benchmark case, to validate the CFD model. Therefore, understanding the case and the fundamental equations of this study is essential.

3.1.2 Meshing and geometry

Model a two phase solid-fluid flow in eccentric horizontal annulus and determining the type, size of the meshing to be simulated.

3.1.3 Grid independence study

Define the optimum element size, with the minimum number of elements and nodes that would produce an accurate results and require less computational time.

3.1.4 Simulation validation

Validating the model by comparing the results obtained from simulation to the results of the benchmark case study.

3.1.5 Parametric studies input simulation

Further studies investigating the effects of drill pipe rotation in cuttings transport under the influence of various parameters.

3.1.6 Data analyzing and report writing

Computing the result and analyzing the data, furthermore all have to be documented in a report form.

3.2 Project Flow chart

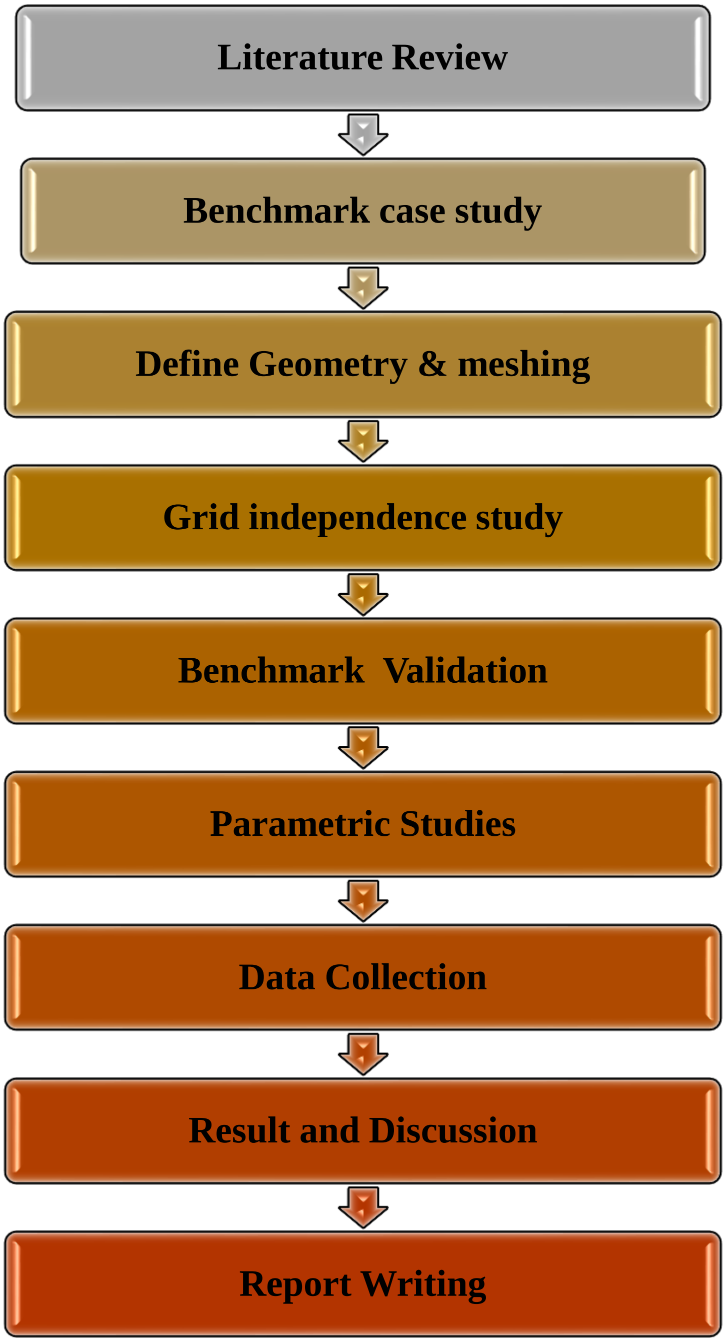


Figure 9: Project Flow Chart

3.3 Parameters

1) Fluid Type:

   Water to be chosen as a Newtonian fluid with density of 998.5k_g/m^3 and viscosity of 0.001 $k_g/m.s$

2) Cutting Size:

   Analyzing the effects of an average cutting size of 0.00201m. in the specified fluid density and viscosity.

3) Pipe Rotation:

   Various speed will be taken under consideration starting from static position 0rpm to 120 rpm to simulate the effects of pipe rotation on cuttings transport through annulus.

4) Diameter Ratio:

   It is the ratio of the inner pipe to the outer pipe. 0.64 will be chosen for this model.

Table 1 Experimental Parameters [22]

Fluid-Sold Parameters	**Range**
Fluid Type	Newtonian fluid (Water)
Fluid Density (k_g/m^3)	998.5
Fluid Viscosity ($k_g/m.s$)	0.001
Fluid flow rate (m^3/s)	0.00119 – 0.01577
Cuttings Size (m)	0.079
Cuttings Density (k_g/m^3)	2761.4
Drilling parameters	**Range**
Rotation Speed of the pipe (rpm)	0, 20, 40, 60, 80, 100, 120
Penetration Rate (m/s)	0 – 0.01016
Diameter ratio (di/do)	0.64
Geometry parameters	**Range**
Length (m)	6.4008
Casing Diameter (m)	0.073914
Drill pipe Diameter (m)	0.04699
Eccentricity	0.623

3.4 ANSYS Workbench and ANSYS CFX

Computational Fluid Dynamics (CFD) software is broadly used in numerous engineering sectors such as petroleum, chemical, mechanical, civil and aerospace engineering to set up simulation. In this study, prediction of frictional pressure losses of Newtonian fluid in annulus with pipe rotation with the presence of cuttings in horizontal wellbore will be performed using ANSYS WOKRBENCH and ANSYS 15.0 CFX.

Simulation Procedure is in the appendix2

3.4.1 Navier-Stokes Equation

To solve any fluid problem, the physical properties of the fluid should be determined implementing fluid mechanics. Navier-Stokes equations can be used to describe the physical properties of the fluid mathematically applying the conservation law of physical properties of fluid.

3.4.1.1 Continuity equation

Mass conservation is the physical principle of continuity equation, where the rate at which mass entering the system is equal to the rate at which mass leaves the system assuming isothermal flow condition. For the fluid phase the equation can be expressed as follow:

$$\frac{\partial \rho_l}{\partial t} + \nabla \cdot (\rho_l v_l) = 0 \qquad [3.1]$$

For the solid phase the equation is given as:

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_s v_s) = 0 \qquad [3.2]$$

The sum up of the volume fraction for both phases should equal to 1

$$k_l + k_s = 1 \qquad [3.3]$$

At steady state condition; $\frac{\partial \rho}{\partial t} = 0$

3.4.1.2 Momentum equation

It implies that forces acting on each phase and interphase momentum, it models the interaction between each phase, the below expressed equation is for the fluid phase:

$$\rho_l \, k_l \left[\frac{\partial \mathrm{v}}{\partial \mathrm{t}} + \mathrm{v}_l \, . \nabla \mathrm{v}_l\right] = -k_l \, \nabla \mathrm{P} \; + k_l \, \nabla \tau_l + \rho_l \, k_l \, \mathrm{g} - \mathrm{M} \qquad [3.4]$$

Correspondingly, for the solid phase,

$$\rho_s \, k_s \left[\frac{\partial \mathrm{v}}{\partial \mathrm{t}} + \mathrm{v}_s \, . \nabla \mathrm{v}_s\right] = -k_s \, \nabla \mathrm{P} \; + k_s \, \nabla \tau_s + \rho_s \, k_s \, \mathrm{g} + \mathrm{M} \qquad [3.5]$$

$\frac{\partial}{\partial \mathrm{t}} = 0$, in the case of steady state condition.

3.4.2 Closure models

3.4.2.1 Interphase Drag force model

Assuming particles with spherical shape, the equation to compute the drag force per unit volume is expressed as;

$$M_d = \frac{3C_D}{4d_s} K_s \rho_l |v_s - v_l| (v_s - v_l) \qquad [3.6]$$

Based on the calculated solid volume fraction if the value $k_s < 0.2$, the Wen and Yu drag coefficient model should be employed. This model is pre-defined in ANSYS CFX and can be directly implemented. The below expression is for calculating C_D;

$$C_D = K_l^{-1.65} \max[\frac{24}{N'_{Re_p}}\left(1 + 0.15 {N'_{Re_p}}^{0.687}\right), 0.44] \qquad [3.7]$$

In such way that, $N'_{Re_p} = k_l N_{Re_p}$ and $N_{Re_p} = \rho_l |v_l - v_s| d_s / \mathcal{M}_l$

In other hand, if the solid volume fraction $k_s > 0.2$, another coefficient drag model should be implemented such as the Gidaspow model, Drag force per unit volume can be calculated using the following equation;

$$M_d = \frac{150(1-k_l)^2 \mathcal{M}_l}{4d_s} + \frac{7}{4} \frac{(1-k_l) N_{Re_p}}{\mathcal{M}_l d_s} K_s \rho_l |v_s - v_l| (v_s - v_l) \qquad [3.8]$$

3.4.2.2 Lift force model

In two phase flow, the force acting perpendicular to the motion of the fluid is called lift force, unlike the drag force in which the direction is parallel to the flow. ANSYS 15.0 CFX utilizes the Mei lift and Saffman model, expressed as:

$$M_L = \frac{3}{2\pi} \frac{\sqrt{u_l}}{d_s\sqrt{|\nabla \times v_l|}} C'_L k_s \rho_l (v_s - v_l) \times (\nabla \times v_l + 2\Omega) \quad [3.9]$$

3.4.3 Physical model of horizontal section.

Two phase solid-fluid flow in eccentric horizontal annulus was simulated in an annular test structure consist of 0.9080m long with 0.073914m.O.D hole (casing) and 0.04699m.I.D drill pipe. The eccentricity between the stationary outer pipe and the rotation inner pipe was set to be 0.623, where the eccentricity from the center point was calculated using equation

$$e = \frac{2 * \delta}{\mathrm{OD} - \mathrm{ID}} \quad [3.10]$$

For the length of the annular pipe, it must be longer than the hydrodynamic entrance length in order to ensure a fully developed flow. For a single phase Newtonian fluid flowing in a pipe under turbulent condition, the hydrodynamic length can be calculated using the expression below;[18]

$$\mathrm{L_h} = 4.4 * \mathrm{Re}^{\frac{1}{6}} * \mathrm{D} \quad [3.11]$$

However, for two phase flowing in the annular space, there is no specified term that can be used to calculate the hydrodynamic length, however the author has adopted the above expression and replace the pipe diameter with hydraulic diameter;

$$\mathrm{D_h} = OD - ID \quad [3.12]$$

For Reynold number calculation, such expression can be used;

$$\mathrm{Re} = \frac{\rho \mathrm{vD}}{\mathcal{M}} \quad [3.13]$$

To eliminate the doubt, the maximum velocity and the outer diameter were used in calculating Reynold number.

The concept of the physical model is shown in Figure (10);

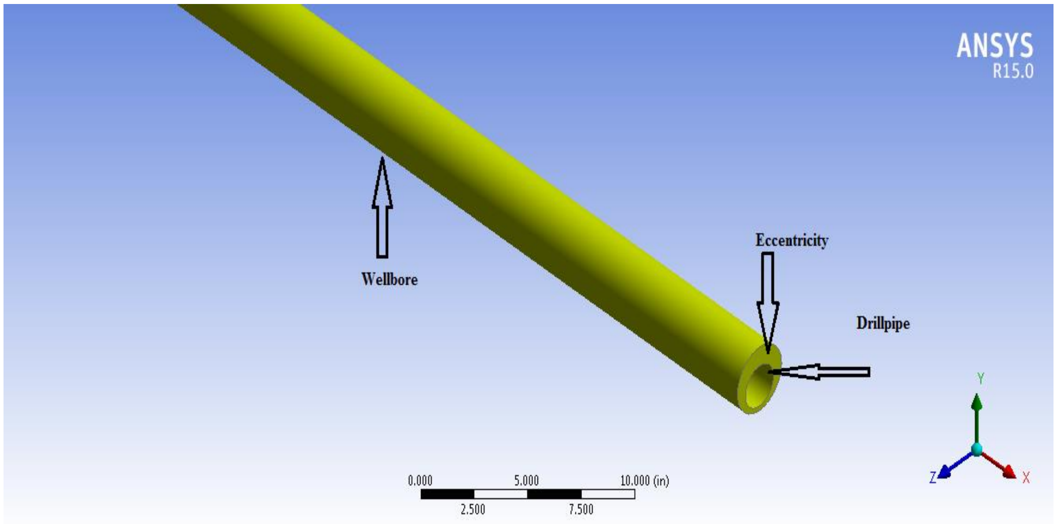


Figure 10: Physical model of horizontal section

3.4.4 Meshing and grid independence study.

The designed geometries were meshed using tetrahedral grids with approximately 1.74×10^{6} elements. Inflation layers were created in near wall regions to resolve the meshing around the near wall region and accurately capture the flow effects in that region as shown in Figure (11). Grid independence refers to the optimum use of the number of elements, thus resulting in reduction in the computational cost without compromising the accuracy of the solution. Several runs have been conducted under different elements sizes varying from (0.0020-0.0028) m, the purpose is to find the optimum element size in which the computed result will be insignificantly dependent on mesh size. The meshing with element size 0.0025 was chosen since it gives the most accurate results and irrelevant difference with smaller elements size as shown in Figure (12).

The fluid used is water with velocity of 2.75m/s, where the amount of cuttings represented by the cuttings feed concentration was calculated using the equation below;

$$C_{cf} = \frac{(ROP)A_{bit}}{R_T * Q} \quad [3.14]$$

Transport ratio R_T is defined as the transport velocity divided by the critical mud velocity where the critical mud velocity is the minimum mud velocity required to carry drill cuttings to the surface, and below which cuttings will settle in the wellbore. In this study and based on previous experimental studies, R_T is considered to be 0.5. [21]

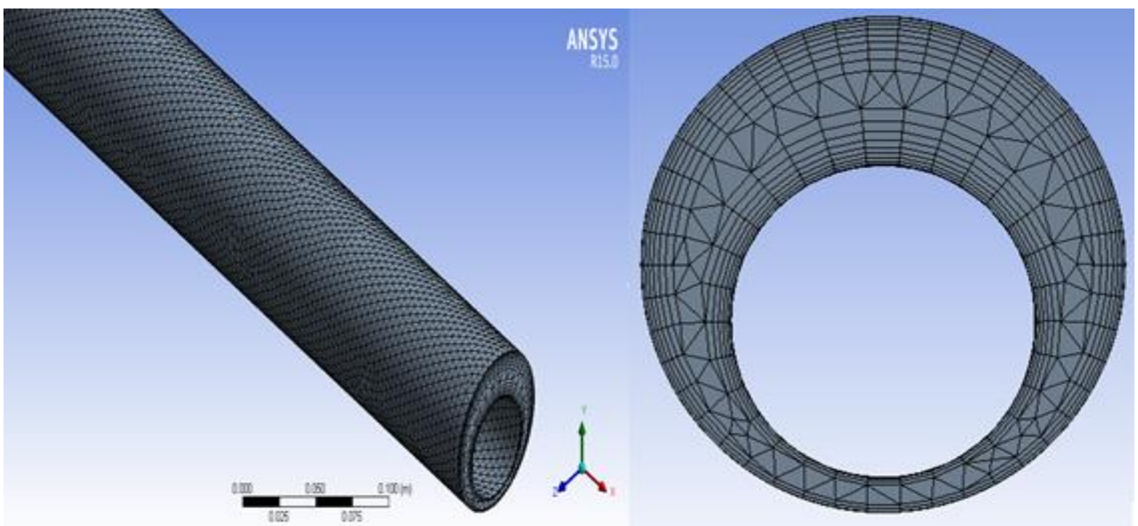


Figure 11: Meshing design

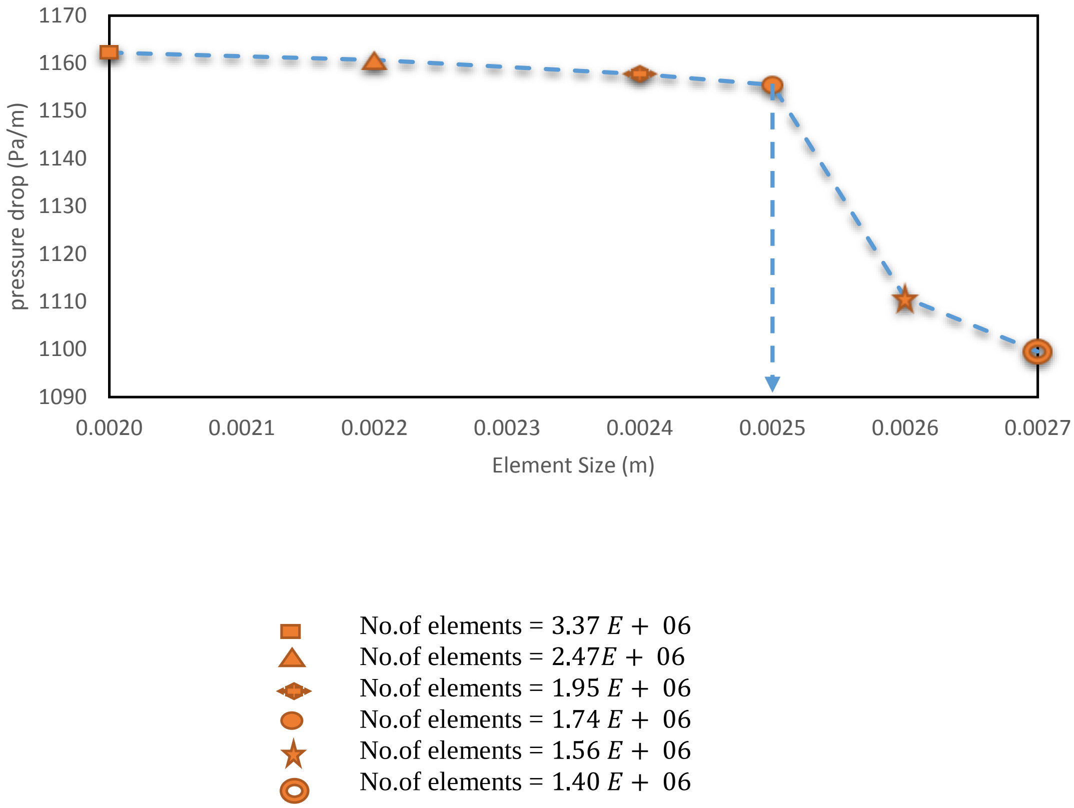


Figure 12: Grid independence study

3.4.5 Initial conditions and boundary conditions.

In this simulation, a specified velocity was applied at the inlet and zero gauge pressure defined at the outlet. Various values can be applied in both inlet velocity and outlet gauge pressure to simulate the rotation affects at different speeds. In the settings, no slip boundary conditions were imposed on both inner and outer pipe walls for fluid and free slip velocity was set for particles. Water was used as a drilling fluid with density of 998.5 k_g/m^3, and the cuttings density is 2761.4 k_g/m^3 with diameter of 0.00201m.

3.5 Gantt chart

Table 2: Gantt chart Final Year Project

	FYP1														FYP2													
Mission/Week (FYP)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Preliminary research objective and scope determination				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Mathemetical equations								■	■	■																		
Benchmark problem identification										■	■	★																
ANSYS CFX (Geometry & Mishing)											■	■	■															
Gridding independence Study													■	■														
Model Validation of benchmark case														■	■	★												
Parametric Studies of the effects of drillpipe rotation																■	■	■	■	■	■	★						
Studying the pressure drop/cuttings concentration in the anulus																					■	■	■	■	★			
Data collection & results Analysis																									■	■		
Report Writing																									■	■	■	■

★ Key Milestone

Please refer to the key milestone in Figure (13).

3.6 Project Key Milestones

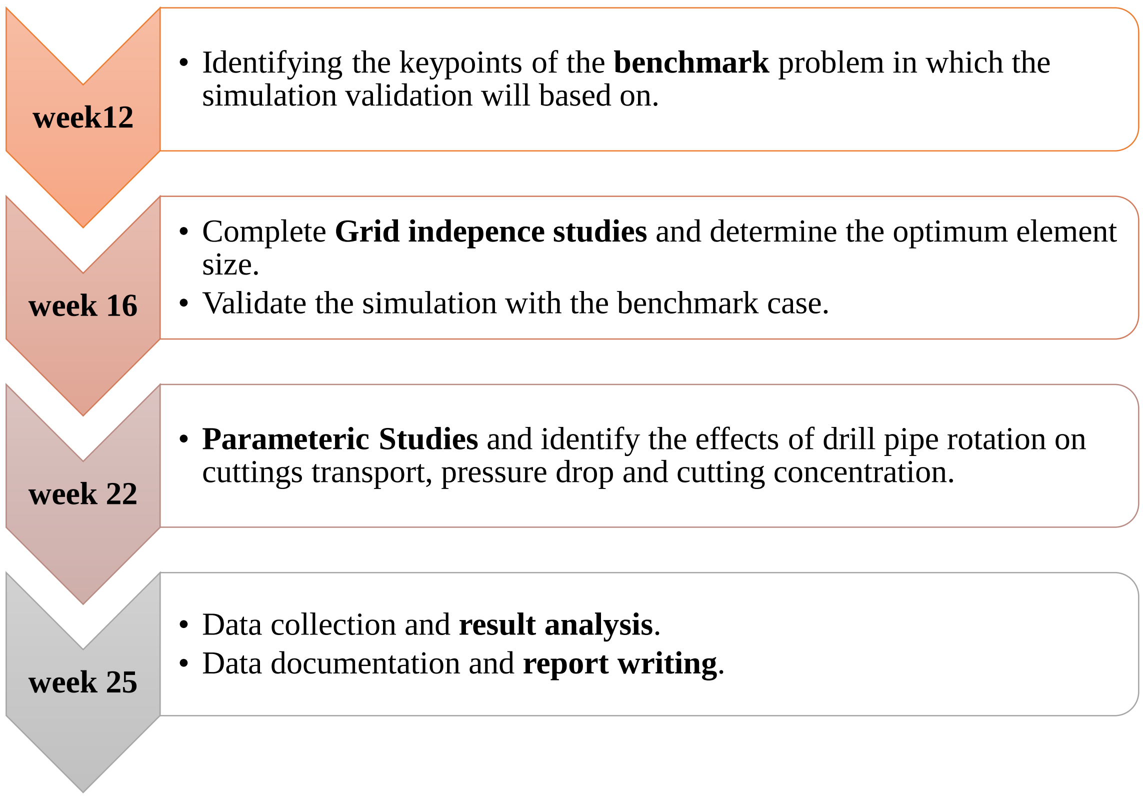


Figure 13: Key Milestones

CHAPTER 4

4.0 RESULTS AND DISCUSSION

4.1 Model setup validation

The benchmark study has been identified and deliberated in which the designed model will be validated against.

The table below summarizes the operation parameters, rheological properties for the experimental studies and the model simulation results;

Table 3: Summary of Experimental and simulation data

Experimental Data							CFD Data			
flow rate (m^3/s)	**Mud Sup.Vel** (m/s)	**Average Cc (%)**	**Dp** (Pa/m)	**ROP** (m/s)	**RPM**	**Flow Pattern**	**Model pressure drop** (Pa/m)	**Model Average Cc (%)**	**DP Error (%)**	**Cc Error (%)**
0.003119	1.2101	12.99	678.62	0.00508	0	Dispersed	716.773	12.20	5.32	-6.48
0.003549	1.3746	10.11	927.44	0.00508	0	Dispersed	942.255	9.54	1.57	-5.97
0.00393	1.5240	7.97	1221.51	0.00508	0	Dispersed	1205.8	7.21	-1.30	-10.54
0.004718	1.8288	5.94	1900.13	0.00508	0	Dispersed	1848.07	6.01	-2.82	1.16
0.005498	2.1306	3.87	2533.51	0.00508	0	Dispersed	2522.14	4.20	-0.45	7.86
0.003172	1.2283	11.08	904.82	0.00508	60	Dispersed	798.317	9.81	-13.34	-12.95
0.003944	1.5301	8.09	1311.99	0.00508	60	Dispersed	1276.85	7.01	-2.75	-15.41
0.004723	1.8318	5.55	1832.27	0.00508	60	Dispersed	1847.08	4.98	0.80	-11.45
0.005507	2.1366	3.46	2329.92	0.00508	60	Dispersed	2346.67	3.22	0.71	-7.45

The model setup was validated against a chosen benchmark experimental data obtained from previous study by comparing both pressure loss and cuttings concentration in the annular gap of the horizontal wellbore.

Figure (14-17) shows the comparison between experiment and simulated results at (0-60) rpm. Excellent agreement is observed. Figure (14) and (15) show simulated pressure loss values deviating slightly from the experimental data with a mean percentage error of 2.18 % and 4.40 % for 0 rpm and 60 rpm respectively. Similarly in figure (16) and (17) the calculated cutting concentration value exceeding the experimental results with a mean percentage error of 6.40 % and 11.82 % for 0 rpm and 60 rpm respectively.

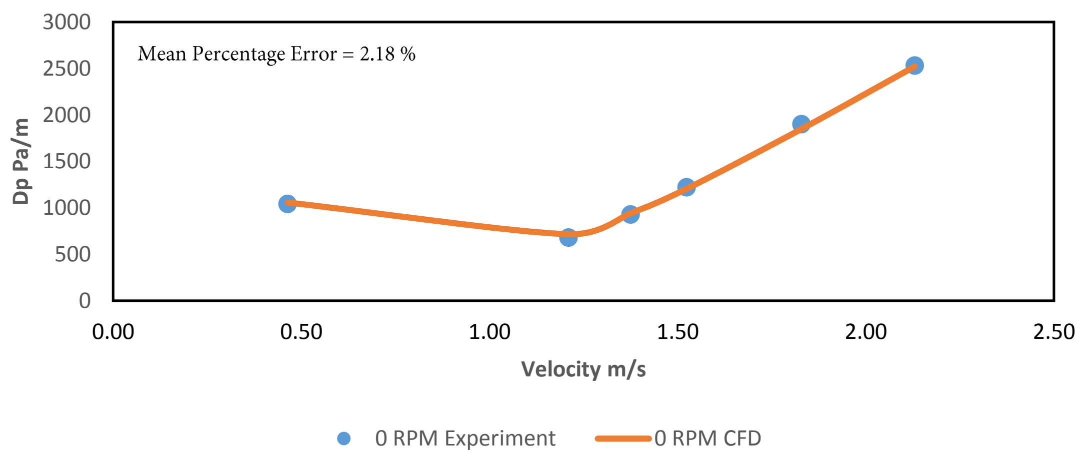


Figure 14: Simulation & experimental Pressure drop vs fluid velocity at (0rpm & $\theta = 0$)

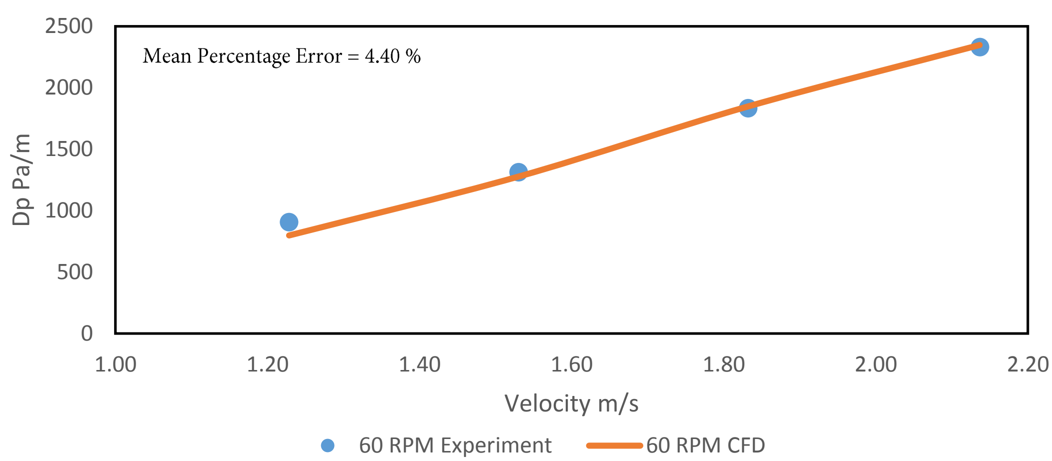


Figure 15: Simulation & experimental Pressure drop vs fluid velocity at (60rpm & θ=0)

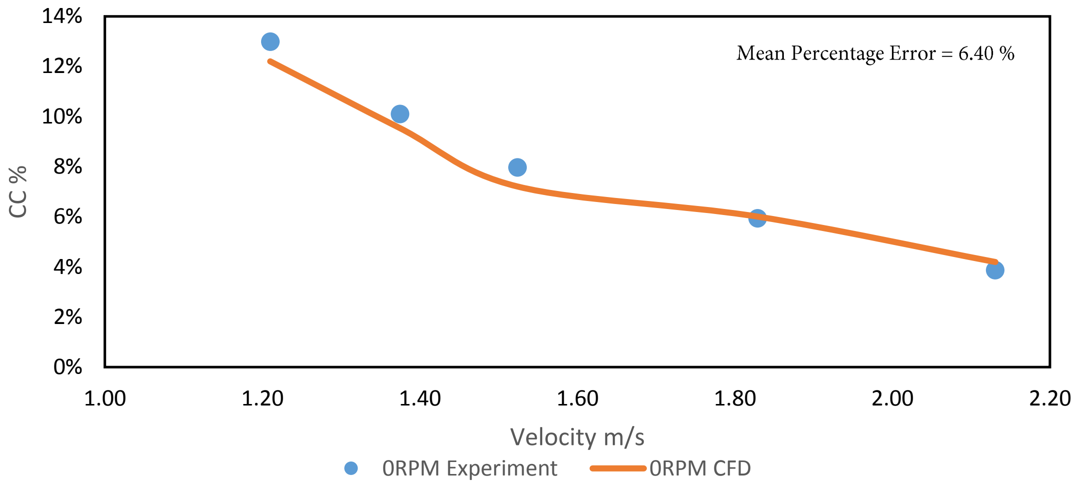


Figure 16: Simulation & experimental Cuttings concentration vs fluid velocity ($0rpm$ & $\theta = 0$)

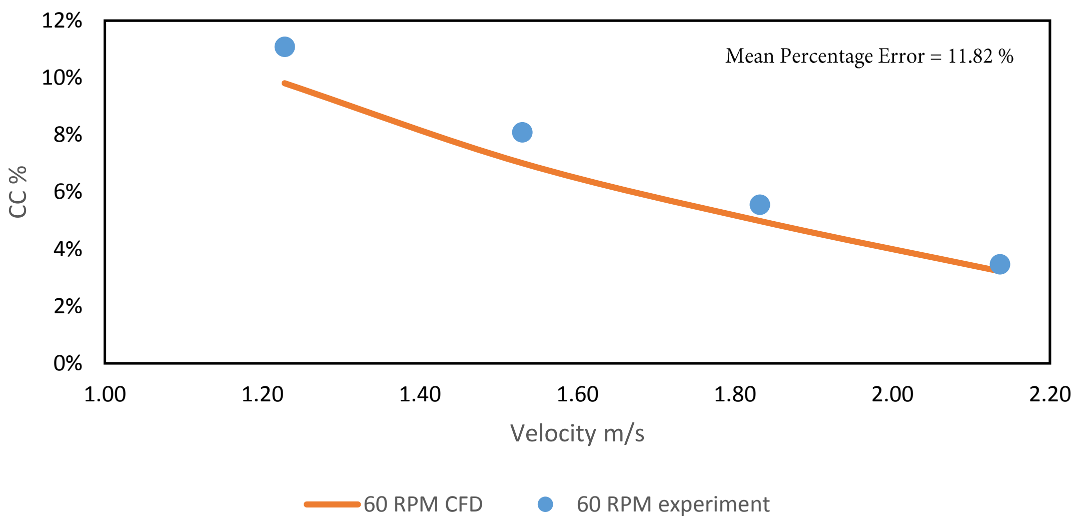


Figure 17: Simulation & experimental Cuttings concentration vs fluid velocity ($60rpm$ & $\theta = 0$)

The above graphs show a direct relationship between velocity and cuttings transport through the annulus, in such way with increasing fluid flow velocity more cuttings are transported to the surface. The above graphs indicate a very close agreement between both calculated and experimental data, hence the model setup is confirmed to be validated. The total cuttings concentration is defined as

$$C_{cT} = \frac{Net\ volume\ occupied\ by\ particles}{Total\ volume\ of\ annulus} \times 100. \qquad [4.1]$$

4.2 Flow pattern investigation

Figure (18) indicates the flow pattern that was observed and obtained from ANSYS CFX 15.0 simulation. The flow pattern was investigated at various fluid flow velocity, various pipe rotation and constant Rate of penetration (60 ft/hr). Rainbow spectrum was chosen as legends and as color descend from red to blue, the cuttings concentration decreases.

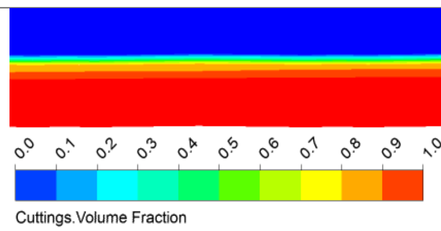
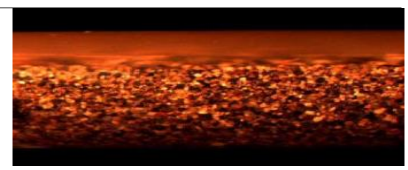
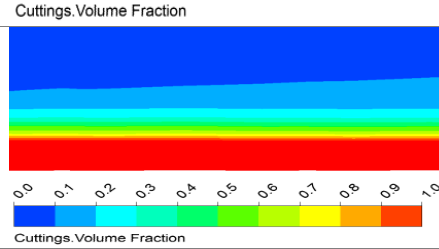
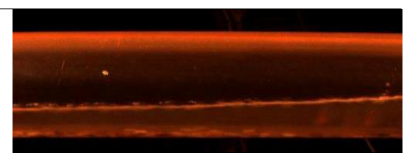
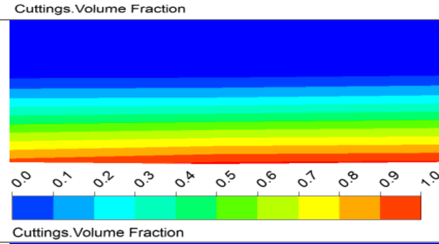
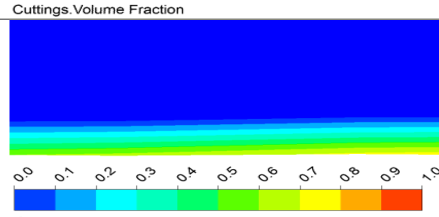
Parameters	Simulation flow pattern	Experimental flow pattern
(0RPM) 2.4384 m/s Stationary bed		
(35RPM) 2.4384 m/s Moving bed		
(80RPM) 2.4384 m/s Heterogeneous Dispersed flow		
(120RPM) 2.4384 m/s Pseudo- homogeneous Dispersed flow		

Figure 18: compares the flow patterns obtained from ANSYS CFX 15 simulations to flow patterns observed in flow loop test modified from Osgouei [22].

Figure (18) indicates that as the drill pipe rotation increases, the flow patterns change from stationary bed into dispersed flow with noticeable moving beds in between. The stationary bed rests at the bottom of the wall at 0 rpm indicated by red color. Moving bed is observed at 35 rpm indicated by mixture colors of yellow and green. Then at rotation speed of of 80 rpm, dispersed flow (Heterogeneous flow) is observed. Finally at 120 rpm, dispersed flow (Pseudo-homogeneous flow) is observed. In such case, as fluid velocity increases along with drill pipe rotation, the concentration of the cuttings decreases.

4.3 Parametric study

After the model was validated with an experimental data, a parametric study was carried out to investigate the effects of pipe rotation in cuttings transport and to determine the pressure loss and cuttings concentration in the annulus.

4.3.1 Annular pressure loss

Figure (19) shows that as the pipe rotation increases, the annular pressure loss is observed to be slightly increased. On the contrary, as the fluid velocity increases, the annular pressure loss increases significantly. From the graph, it is also observed that at high velocity, the annular pressure loss due to increasing pipe rotation is very small and negligible.

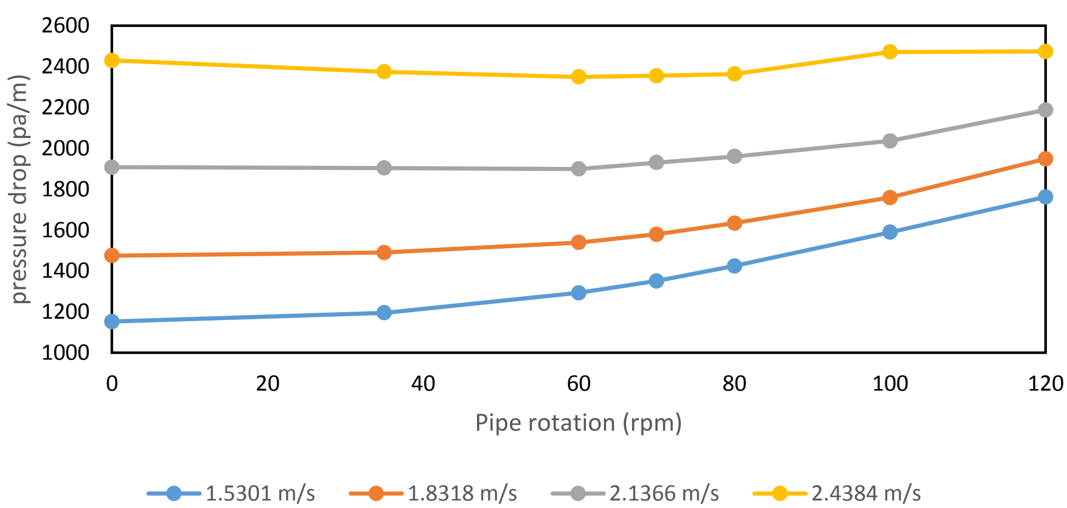


Figure 19: Pressure loss at various pipe rotation

4.3.2 Cuttings concentration

Figure (20) shows the contours of cuttings volume fraction at various pipe rotations and fluid velocity. The cuttings concentration accumulates in the narrowest gap of the eccentric annuli forming a bed. However, the drill pipe rotation various from (0-120) rpm reduces the cuttings concentration by sweeping it into the fluid flow domain at the widest gap where the velocity is high enough to carry out the cuttings to the surface.

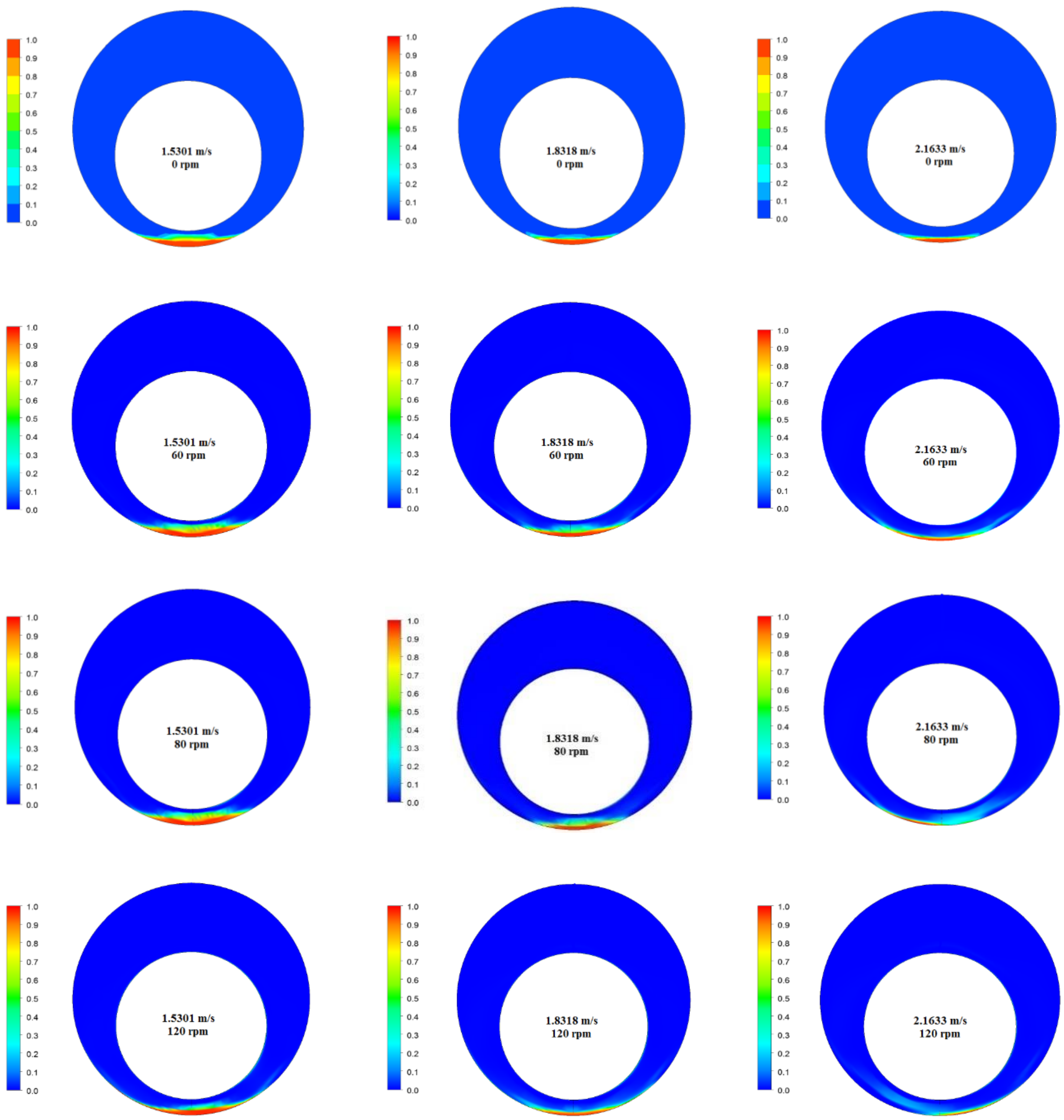


Figure 20: Cuttings concentration at the outlet with various pipe rotation and various fluid velocity.

It is observed that the cuttings concentration is at the highest when the fluid flow velocity and pipe rotation is at the lowest. Pipe rotation causes the particle to be redistributed and mechanically agitated into the fluid flow domain. When increasing the fluid velocity, it prevents the cuttings from slipping downward and prevent cuttings accumulation. Figure (21) shows significant differences in particle concentration along the pipe cross section.

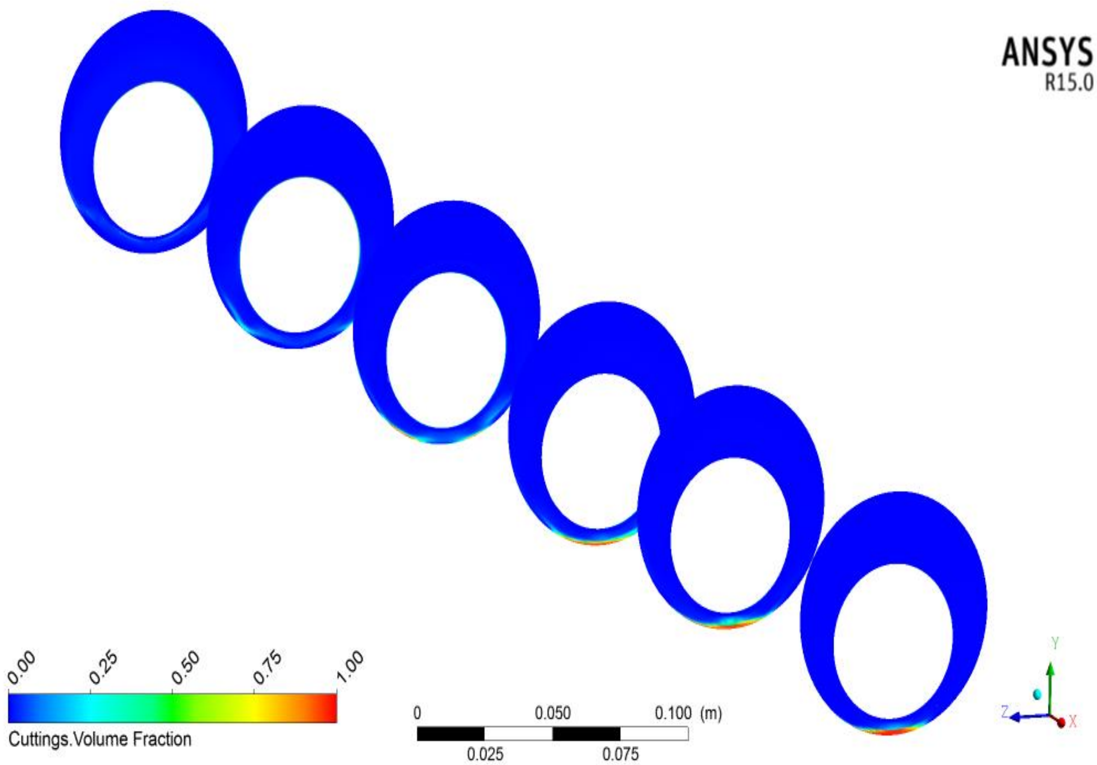


Figure 21: Contour plots for cuttings concentration taken at 60RPM and velocity of 1.5301m/s over the horizontal pipe.

The results obtained from the simulation indicate that with increasing pipe rotation the cuttings concentration will be significantly reduced. Similarly, at a high fluid flow velocity less cuttings are accumulated in the annulus. It also observed that at a high fluid flow velocity, increasing pipe rotation has a slight to negligible effects in reducing cuttings concentration as shown in Figure (22).

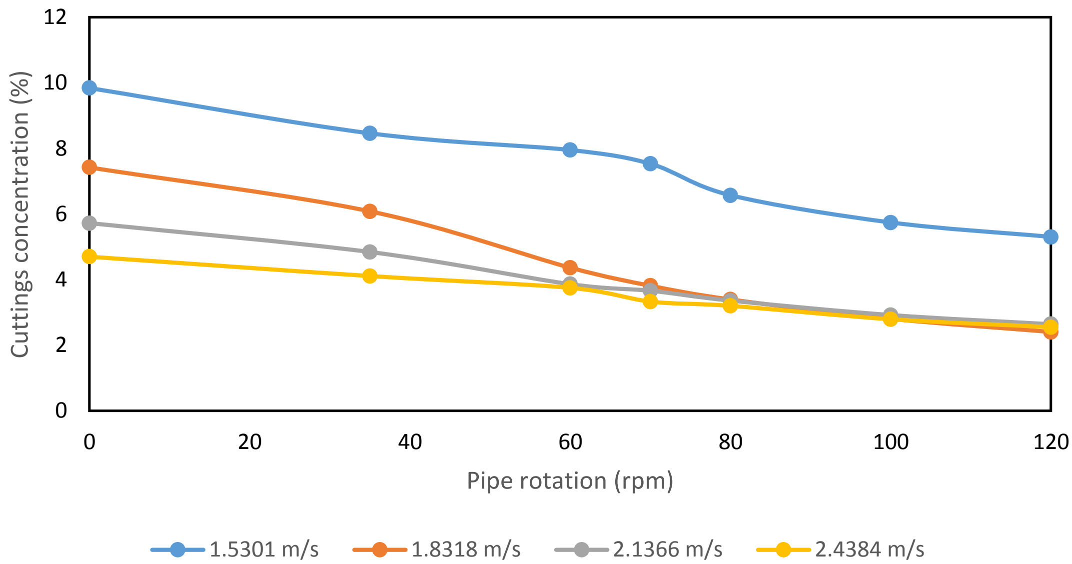


Figure 22: Cuttings concentration at various pipe rotation

CHAPTER 5

5.0 CONCLUSION AND RECOMMENDATION

For a successful drilling operation, good hole-cleaning operations is required. Hole cleaning is very complicated since it requires an integrated process of fluid mechanics, thermodynamics, mechanics and fluid rheology. The present project implied the use of CFD simulation, and validated with experimental measurements to predict the impact of the drill pipe rotation in cuttings transport and well cleaning performance. The benchmark study has been defined to validate the model setup.

The model has been designed using Workbench in ANSYS 15.0. Grid independence studies have been performed in order to optimize the mesh design and save computational time. Model setup was validated with experimental measurements. Excellent agreement was achieved for both calculated and experimental results. Simulated pressure loss values deviating slightly from the experimental data with a mean percentage error of 2.18 % and 4.40 % for 0 rpm and 60 rpm respectively. Similarly the calculated cutting concentration value exceeding the experimental results with a mean percentage error of 6.40 % and 11.82 % for 0 rpm and 60 rpm respectively. Based on the listed objectives, the effects of pipe rotation have been investigated and the results have been collected, analyzed and concluded in the following;

i) Increasing pipe rotation has a significant impact in reducing cuttings concentration, with slight increment in pressure losses.
ii) As velocity increases, more cuttings are transported, however the pressure loss increases rapidly.
iii) The effects of pipe rotation at high velocity is negligible.
iv) Three types of flow pattern have been identified in the horizontal eccentric wall (stationary bed, moving bed and dispersed flow).

The author has proposed several recommendations in order to enhance the study;

i) Further studies can be conducted utilizing a Non-Newtonian fluid flow instead of water.
ii) Additional studies can be run on the effects of well inclination from the vertical axis.

REFERENCES

[1] N. B. Egenti, "Understanding Drill-cuttings Transportation in Deviated and Horizontal Wells." paper SPE-172835-MS, presented at the SPE Nigeria annual interntaional conference and exhibition (Aug. 05-07 2014).

[2] N. M. Z. Hussain H. Al-Kayiem, Muhamad Z. Asyraf and Mahir Elya Elfeel, "Simulation of the Cuttings Cleaning During the Drilling Operation," American Journal of Applied Science P vol.7 ISSN 1546-9239 //2010.

[3] G. Jiimaa, "Cutting transport models and parametric studies in vertical and deviated wells," p. 109, MS thesis, U. of Stavanger faculty of science and technologu (2013).

[4] M. E. Ozbayoglu, A. Saasen, M. Sorgun, and K. Svanes, "Effect of Pipe Rotation on Hole Cleaning for Water-Based Drilling Fluids in Horizontal and Deviated Wells.", IADC/SPE 114965, presented at the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, Jakarta, Indonesia (Aug 25-27 2008).

[5] S. S. Costa, S. Stuckenbruck, S. A. B. Fontoura, and A. L. Martins, "Simulation of Transient Cuttings Transportation and ECD in Wellbore Drilling.", paper SPE 113893 presented at the annual conference and exhibition, Roma, Italy (Jun 9-12 2008).

[6] J. Li and B. Luft, "Overview of Solids Transport Studies and Applications in Oil and Gas Industry - Experimental Work."

[7] Y. M. Na Wei, 1 Gao Li,1 LiPing Wan,1 ZhaoYang Xu,1 and a. Y. Z. XiaoFeng Xu, "Cuttings Transport Models and Experimental Visualization of Underbalanced Horizontal Drilling," Hindawi Publicating Cororation, p. 6, 25 June 2013 2013.

[8] P. H. Tomren, A. W. Iyoho, and J. J. Azar, "Experimental Study of Cuttings Transport in Directional Wells," paper SPE 12123, presented at the 1983 SPE Annual Technical Conference and exhibition, San Francisco (Oct 5-8 1984).

[9] X.-H. Zhu, C. Sun, and H. Tong, "Distribution features, transport mechanism and destruction of cuttings bed in horizontal well," *Journal of Hydrodynamics, Ser. B*, vol. 25, pp. 628-638, 9// 2013.

[10] T. Hemphill, P. A. Bern, J. Rojas, and K. Ravi, "Field Validation of Drillpipe Rotation Effects on Equivalent Circulating Density."Paper SPE 110470, presented at the 2007 SPE annual Technical Conference and Exhibition, Anahiem, California (Nov 11-14 2007).

[11] T. J. Lockett, S. M. Richardson, and W. J. Worraker, "The Importance of Rotation Effects for Efficient Cuttings Removal During Drilling." Paper SPE 25768, presented at the 1993 SPE.IADC Drilling Conference, Amsterdam (feb 23-25 1993).

[12] B. V. Loureiro, R. S. Paula, M. Serafim, and A. L. Martins, "Experimental Evaluation of the Effect of Drillstring Rotation in the Suspension of a Cuttings Bed." paper SPE 122071 presented at the SPE Latin American & Caribbean Petroleum Engineerign Conference, Lima, Peru (Dec 1-3 2010).

[13] H. I. Bilgesu, M. W. Ali, K. Aminian, and S. Ameri, "Computational Fluid Dynamics (CFD) as a Tool to Study Cutting Transport in Wellbores.", paper SPE 78716 presented at the SPE Eastern Regional Meeting, Lexington, Kentucky, USA (Oct 23-25 2002).

[14] E. Della-Giustina, "investigation of hole cleaning parameters using computational fluid dynamics in horizontal and deviated wells," p. 76, 2007, MS thesis, U. of west Virginia, Morgantown, West Virginia (2007).

[15] R. A. Sanchez, J. J. Azar, A. A. Bassal, and A. L. Martins, "Effect of Drillpipe Rotation on Hole Cleaning During Directional-Well Drilling," paper SPE 56406 presented at SPE/IADC Drilling Conference, Amsterdam (Mar 4-6 1997).

[16] M. N. Belavadi and G. A. Chukwu, "Experimental Study of the Parameters Affecting Cutting Transportation in a Vertical Wellbore Annulus.", paper SPE 27880 presented at the western regional meeting, Long Beach, California, USA (Mar 23-25 1994).

[17] J. M. Peden, J. T. Ford, and M. B. Oyeneyin, "Comprehensive Experimental Investigation of Drilled Cuttings Transport in Inclined Wells Including the Effects of Rotation and Eccentricity.", paper SPE 20925 presented at Europec 90, Netherlands (Oct. 22-24 1990).

[18] T.N. Ofei, S. Irawan and W. Pao, "CFD Method for Predicting Annular Pressure Losses and Cuttings Concentration in Eccentric Horizontal Wells,", Journal of Petroleum Engineering Volume16, ID 486423 (2014).

[19] X. Sun, K. Wang, T. Yan, S. Shao. and J. Jiao, "Effect of drillpipe rotation on cuttings transport using computational fluid dynamics (CFD) in complex structure wells,", Paper of J Petrol Explor Prod Technical, U. of Northeast Petroleum, China (2014).

[20] T. R. Sifferman and T. E. Becker, "Hole Cleaning in Full-Scale Inclined Wellbores,", paper SPE 20422, presented at SPE annual technical conference and exhibition, New Orleans (Sept 23-26 1991).

[21] M. Sorgun, I. Aydin, and M. E. Ozbayoglu, "Friction factors for hydraulic calculations considering presence of cuttings and pipe rotation in horizontal/highly-inclined wellbores," Journal of Petroleum Science and Engineering, vol. 78, pp. 407-414, 8// 2011.

[22] R. E. OSGOUEI, "Determination of Cuttings Transport Properties of Gasified Drilling Fluids," p. 236, PhD thesis, U. of middle east technical, the graduate school of natural applied science, 13. OCTOBER 2010.

APPENDIX 1

Table 4: Summery literature Review

Source	Rotary Speed	Additional Factors	Methods	Conclusion
Sanchez et al. [15]	0-175 rpm	Hole inclination, flow rate & Cutting size	Experimental TUDRP	High rotary speed and low flow rate in horizontal well tend to reduce cutting concentration significantly especially for smaller cuttings size.
Tomren et al. [8]	0-100 rpm	Hole inclination, viscosity & flow regimes	Experimental	Pipe rotation produced only slight effects on transport performance in inclined annulus, conflicting with other studies.
Ofei et al. [18]	0-120 rpm	Fluid velocity, fluid type & diameter ratio	Simulation CFD	Increasing drilling pipe rotation from 80rpm to 120rpm, it did not result in any significant increment in pressure lose with noticeable decrement in cuttings concentration.
Sun et al. [19]	80-240 rpm	Fluid flow rate	Simulation CFD-ANSYS	Increasing pipe rotation at low to medium flow rates, can drastically decrease cutting concentration and annular pressure losses.
Li et al. [6]	0-200 rpm	Pipe rotation	Simulation CFD-ANSYS	Pipe rotation between 80-120 rpm has a significant effects on hole cleaning.
Bilgesu et al. [6]	0-60 rpm	Particle size	Simulation CFD	Drill pipe rotation can improve cutting transport more for smaller sized particles.
Jiimaa et al. [3]	0-160 rpm		Experimental	Pipe rotation improves the transport efficiency of smaller cuttings compared with larger-sized cuttings.

APPENDIX 2

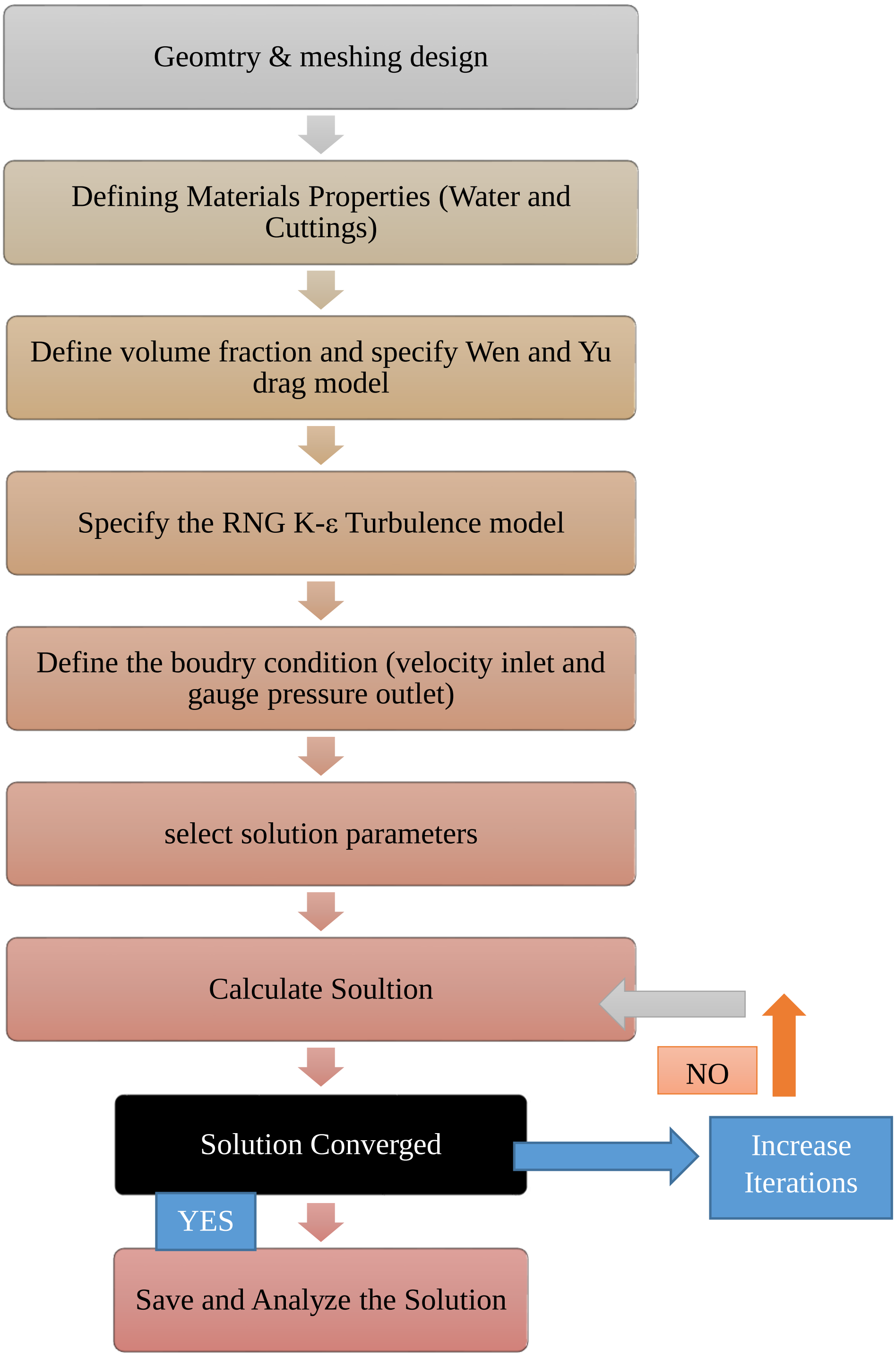


Figure 23: Simulation Procedure

APPENDIX 3

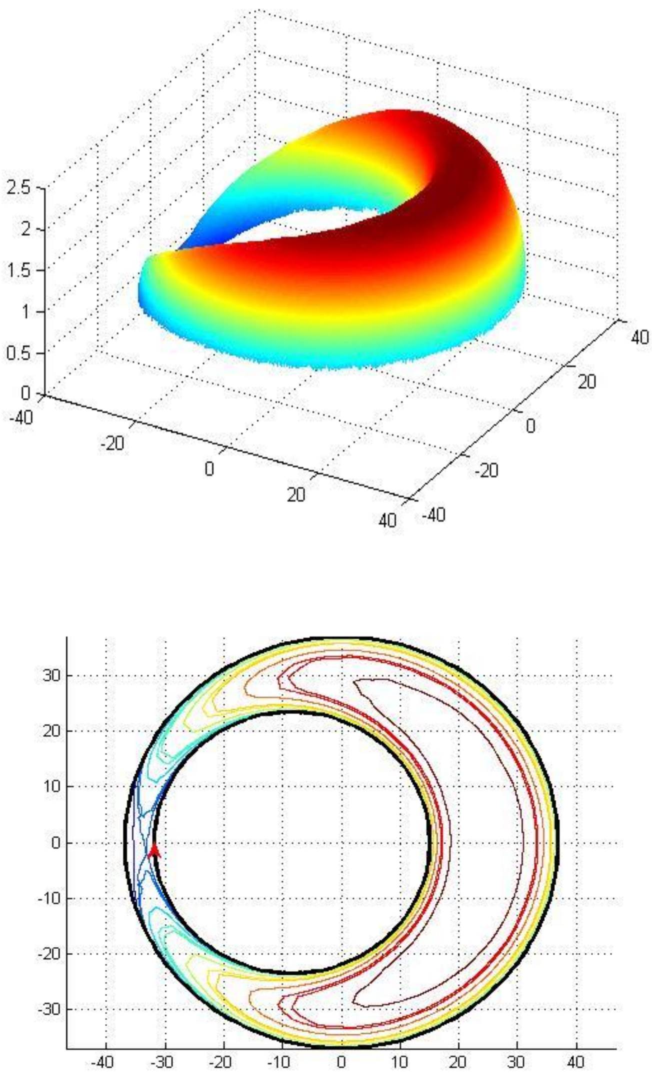


Figure 24: 3D model for the cuttings velocity of 1.5301m/s and 0rpm at the outlet