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COMPUTATIONAL FLUID DYNAMICS SIMULATION FOR CUTTINGS-LIQUID FLOW THROUGH HORIZONTAL ECCENTRIC ANNULI

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Computational Fluid Dynamics Simulation For Cuttings-Liquid Flow Through Horizontal Eccentric Annuli

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CERTIFICATION OF APPROVAL

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By

Tham Keat Fu

A project dissertation submitted to the
Petroleum Engineering Programme
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in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
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Approved by,

____

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May 2012

CERTIFICATION OF ORIGINALITY

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

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THAM KEAT FU

ABSTRACT

The interactions between cuttings and drilling fluid in horizontal eccentric annuli were simulated and observed using ANSYS CFX 14 Computational Fluid Dynamics (CFD) software. CFD software program has proven to be a successful tool in studying fluid flow in bit hydraulic and gas liquid flow in pipeline and separator. In this project, the effect of drilling mud flow rate and the impact of the Rate of Penetration (ROP) on flow patterns, cuttings concentration and pressure losses were investigated and validated against flow loop tests conducted by Dr. Reza Ettehadi Osgouei.

It is essential to transport cuttings generated in drilling operations to the surface for disposal. Improper hole cleaning will lead to costly drilling problems such as increase of pipe sticking potential, higher drag and torque, slower rate of penetration, formation of fractures and wellbore steering problems. As the well inclination from vertical axis increases, the cuttings transport is further complicated. In this project, the cuttings transport in horizontal eccentric annulus is investigated.

The results obtained from the simulations are successful. As the drilling mud flow rate increases, the flow pattern was observed changing from stationary bed to dispersed flow, which complies with experimental results and literature findings. Increase in flow rate also increased the annulus pressure drop but decreased the cuttings concentration. The increment in ROP leads to more cuttings generated and poorer hole cleaning. In conclusion, drilling mud flow rate and ROP are both significant factors in hole cleaning operations. The higher the flow rate, the higher the efficiency of hole cleaning, whereas the higher the ROP, the less efficient is the hole cleaning.

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I would like to express my gratitude to those whose their presence have made the completion of this Final Year Project a success. First and foremost would be my Final Year Project supervisor, Dr. Reza Ettehadi Osgouei. Dr. Reza has been very supportive and understanding. He has earnestly guided me through the obstacles, problems and issues faced in this project. I would be looking forward to cooperate with Dr. Reza in near future. In addition to that, I would like to extend my gratitude to Department of Petroleum and Natural Gas Engineering, Middle East Technical University, for allowing me to use their data and Universiti Teknologi PETRONAS, for this is the sole reason I started and completed this project. Next, I would like to thank my mother who has been very understanding and tolerant. Without her moral support, I believe that I would not have the persistence to complete this project till the end. Also, I would like to extend my gratitude to Mr. Zuraimee, the lab technician for CFD Workshop in Block 17-01-05. He has been very helpful and patient in providing me all the facilities I need in this project. I would also like to thank all the guards and maintenance support staffs for attending to me when I worked long hours in the night inside the lab for weeks. Not forgetting of two master students and my coursemate, Haziq, who have kept me company while we are working inside the lab.

TABLE OF CONTENTS

LISTS OF FIGURES

LISTS OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Cuttings Transport in Horizontal Well

When a drilling takes place to produce crude oil or natural gas, cuttings are generated in the process. One of the important functions of drilling fluid in the circulatory system is to provide sufficient hole cleaning by circulating the solid cuttings to the surface. The ability to transport such cuttings is generally referred to as the carrying capacity of the drilling fluid. (Azar & Samuel, 2007)

Cuttings transport is a complex mechanism affected by several parameters. Azar and Samuel (2007), have classified the parameters into cuttings slip velocity, annular mud velocity, flow regime of fluid and cuttings slippage, annular velocity profile, cuttings-bed formation, drill pipe rotary speed, drilling rate, fluid rheological properties and hole inclination. This mechanism is further complicated in horizontal eccentric annulus.

Various studies, experiments and simulations have been carried out for better understanding of cuttings transport mechanism. Initially, the pioneering studies were experimental studies or as known as flow loop tests initiated at Tulsa University Drilling Research Projects (TUDRP) about two decades ago.

According to Ali et al. (1995)

> A flow loop was built which consisted of a 40-ft long of 5-in. transparent annular test section and means to vary and control: (1) angles of inclination between vertical and horizontal, (2) mud pumping flow rate, (3) drilling rate, and (4) drill pipe rotation and eccentricity.

As more experiments being conducted, various correlations and models have been developed based on the experimental data collected. At present, numerical modelings and simulations are developed to provide a more accurate representation of cuttings transport in the wellbore. Nazari et al. (2010) categorized these models into three categories, which are two layer models, three layer models and dimensionless models.

1.1.2 Computational Fluid Dynamics (CFD)

CFD has been playing a major role in understanding modern fluid dynamics and it has been used considerably in engineering predictions especially to improve process plants applications such as pneumatic transport lines, risers, fluidized bed reactors and hoppers. (Bilgesu, Mishra, & Ameri, 2007). Von Karman Institute (2009) views the role of CFD as a new 'third dimension' in fluid dynamics, the other two dimensions being the classical cases of pure experiment and pure theory. According to Bilgesu, Mishra, & Ameri (2007), CFD provides the flexibilities of changing the design parameters without costly hardware change and a much better turnaround time than experimental runs. Moreover, the use of CFD in petroleum engineering is not a new occurrence. For example, Suarez, Kenyery, & Asuaje (2005) studied water and air flow inside rotary gas separator using CFD. Clem, Coronado & Mody (2006) analyzed velocity, fluid path, erosion and sand concentrations on frac-packing tool inside high profile deepwater well at high pump rates and proppant loads. Yusuf (2006) used CFD to understand the impact of variation of API oil gravity, flow rates and Liquid-

Liquid Hydrocyclones (LLHC) geometry to the performance of LLHC. Bilgesu, Mishra, & Ameri (2007) studied the effects of drilling parameters, which include cuttings particle size, pipe rotation speed, penetration rate and circulation rate, on hole cleaning in horizontal and deviated well using CFD. Hussain et. al. (2010) investigated cleaning performance of laminar, non-Newtonian drilling fluid, different inclination of well from vertical axis, different cuttings size and different cuttings shape factor using CFD.

1.2 Problem Statement

Improper hole cleaning will lead to accumulation of cuttings in the wellbore, which in turn will results in costly drilling problems such as:

a. Increase of pipe sticking potential due to the sedimentation of the cuttings below the drill pipe.
b. Higher drag which requires additional force to rotate the drill pipe and higher torque to drive the drill bit into the formations.
c. Slower rate of penetration due to premature bit wear and higher torque
d. Formation of fractures due to the increment in the frictional pressure losses
e. Wellbore steering problems as a result of pipe sticking

Consequently, the entire drilling operation would be costly and not be profitable. In view of monetary losses resulted from inadequate hole cleaning, it is of the utmost priority to study the phenomenon of cuttings transport.

The negative effects of inadequate hole cleaning are more pronounced in deviated wells, especially horizontal wells. It is proven by many researchers that cuttings transport problem in horizontal wells is much more severe than in horizontal wells.

According to Azar and Samuel (2007),

> The presence of cuttings beds, eccentric flow regimes and the variable impact of gravity make the physics of transport far more complicated. (p.182)

Although many studies have been conducted in order to provide a better understanding in cuttings transport, there are uncertainties and fluctuations in information related to cuttings transport analysis. Therefore, an accurate modeling of cuttings transport phenomenon in horizontal well would provide and promote a better understanding of the liquid and solid interactions. By understanding the interactions, engineers and researchers would be able to address the problems accurately and provide better solutions to trouble shoot the complications in hole cleaning. This project aims to address the flow patterns attributed to variation in drilling fluid flow rate and Rate of Penetration (ROP), annular pressure drop across the eccentric wellbore and maximum cuttings concentration.

1.3 Objectives And Scope Of Study

The primary objectives of this project are as follows:

a. To determine and analyze the effect of different factors on cuttings transport.
b. To predict flow pattern, cuttings concentration and annular pressure drop using Computational Fluid Dynamics (CFD).
c. Compare simulated results with experimental observations.

The scopes of study are as follows:

a. Solid particles tracking in Newtonian fluid, which is pure water in horizontal eccentric annulus using Lagrangian tracking in Eulerian phase.
b. Sensitivity analysis of water flow rate and rate of penetration to flow pattern, maximum cuttings concentration and annular pressure drop.

1.4 The Relevancy Of The Project

As mentioned in previous section, the studies of cuttings transport have been an attention to most researchers for decades. Though experiments are much preferred than modeling and computational simulations for higher accuracy, cuttings transport in wellbore is a complex problem. The interaction between the solid particles and drilling fluid is complicated and there exists various and different wellbore conditions. Expensive laboratory setups are required to simulate each of the physical model dimensions and the operating parameters. Therefore modeling through software is widely accepted. According to Azar and Samuel (2007), these models are typically developed from flow-loop experiments, physically based modeling and field verification. Furthermore, Computational Fluid Dynamics (CFD) has been recognized and verified as a powerful tool that is used in many fields of engineering involving flow of fluids and particulate mixtures (Tu et al., 2008). In this project, the flow of drilling fluid and cuttings particles could be simulated and observed using ANSYS CFX 14. Results and data collected would be able to promote better and clearer understanding of cuttings transport in horizontal well.

1.5 Feasibility Of The Project Within The Scope And Time Frame.

The total duration given for the Final Year Project is 29 weeks. The author is very sure and confident that he could accomplish the project objectives at the end of the period given. The breakdown and proposed timeline for each milestone are further elaborated in Chapter 3.

CHAPTER 2

LITERATURE REVIEW

2.0 Cuttings Transport In Horizontal Eccentric Annulus

In cuttings transport, the solid cuttings particle is subjected to various forces in the flow of drilling fluid. Among the forces that acted on one single solid particle are:

(a) Drag force, F_d
(b) Buoyancy force, F_b
(c) Lift force, F_l
(d) Friction force, F_f
(e) Gravitational force, F_g
(f) Van der Waals force, F_{van}

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

Figure 2.0 shows the schematic diagram of the forces acting on a single cuttings solid particle.

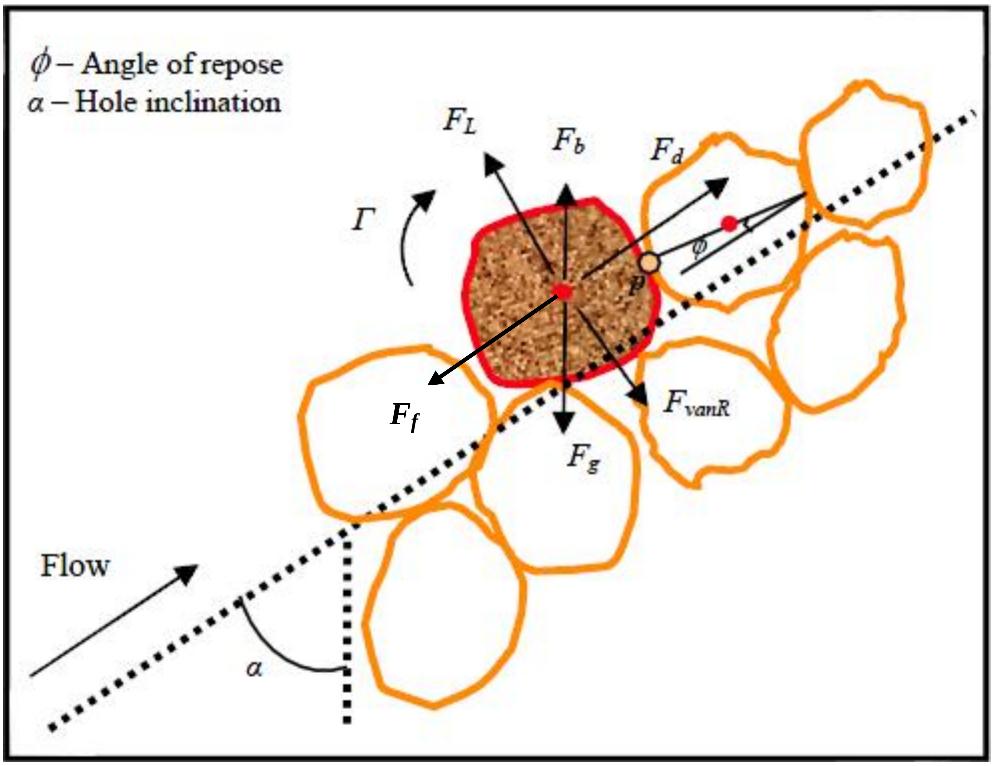


Figure 2.0: Forces acting on solid particle in drilling fluid

There are various factors affecting cuttings transport efficiency in vertical, inclined and horizontal wells. As this project is about cuttings transport in horizontal well, more emphasis will be given to the factors that contribute significantly in the transport efficiency in the horizontal wells. Apart from this, more focus would be given to annular drilling fluid velocity, annular eccentricity, rate of penetration and flow pattern.

2.0.1 The Effect Of Drilling Fluid Velocity

In all experimental and numerical studies that have been conducted, it is concluded that drilling fluid velocity is the most important factor in hole cleaning other than the drilling fluid rheology. (Cho et al, 2002). Sufficient annular velocity is required to transport these cuttings to the surface and avoid accumulation at the bottom of the well.

The in-situ fluid velocity must exceed the minimum transport velocity (MTV) to prevent the cuttings depositing downward. MTV is the measure of the drilling fluid carrying capacity.

Ford et al (1990) mentioned that the lower the MTV, the higher the drilling fluid carrying capacity and vice versa. Nevertheless, other factors such as pressure drop should be considered. As the velocity increased, the pressure would drop.

Cho et al (2002) recommended:

> The conventional drilling fluid velocity range of 0.6 to 0.9 m/s should be avoided while drilling horizontal wells with coiled tubing. It is recommended that the nominal annular velocity range of 1.0 to 1.2 m/s be used for a well having long horizontal section, because a lower pressure gradient and a less stationary bed area are predicted than for those of conventional velocity range.

On the other hand, Bilgesu et al (2007) observed that the increment in annular drilling fluid velocity has more pronounced cleaning effect for smaller particles than larger particles in horizontal well.

2.0.2 Annular Eccentricity

The eccentricity, ε is defined by:

$$\varepsilon = \frac{e}{R_o - R_i} \qquad (2.0)$$

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 2.1 depicts concentric and eccentric annular geometries.

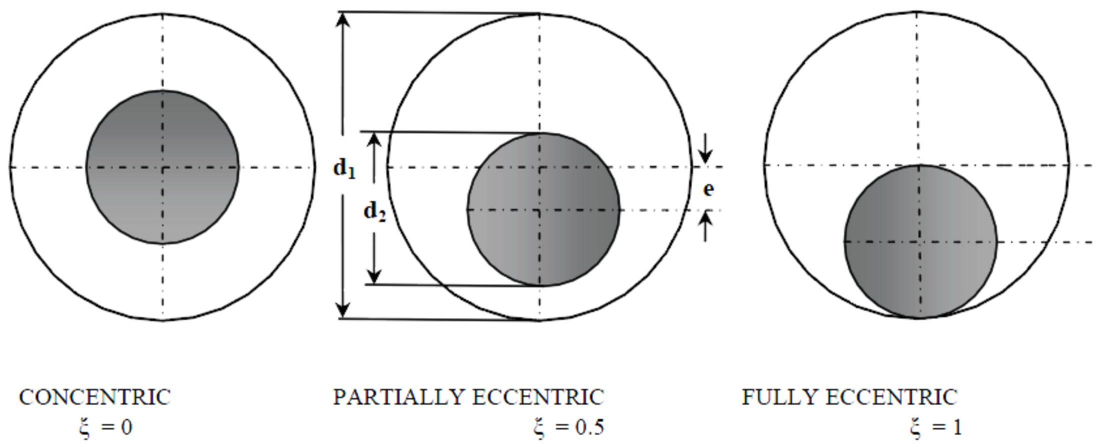


Figure 2.1: Concentric and eccentric annular geometries

In horizontal well, the drill pipe has higher tendency to be displaced to the lower wall of the annulus due to the gravitational effect. As the result, the eccentricity increases the velocity maximum in the larger areas while reducing it in the constricted area. Consequently, the latter area is less fitted for cuttings transport. Thus, for horizontal well with positive eccentricity cuttings-transport problems are accentuated.

Figure 2.2 shows the velocity profile of a concentric annular geometry and eccentric annular geometry.

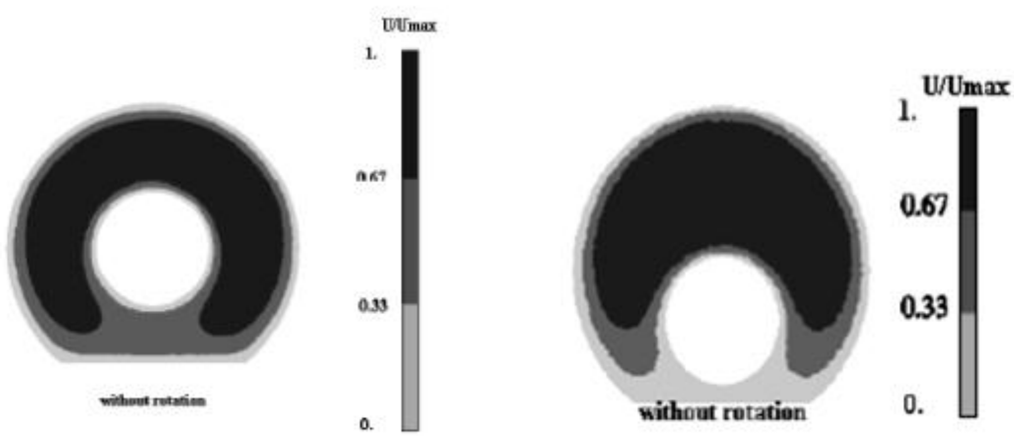


Figure 2.2: Velocity profile in concentric annular geometry (left) and in eccentric annular geometry (right)

From Figure 2.2, we can observe that the velocity is higher in the larger area and approaching zero at the narrow area for eccentric annulus. According to Ogugbue et al (2010), the frictional pressure losses depend significantly on eccentricity. Experimental results showed that pressure losses declined with the increased of eccentricity.

2.0.3 The Effect Of Rate of Penetration

Ettehadi Osgouei (2010) mentioned that there exists a direct relationship between the total cuttings concentration with rate of penetration (ROP). As the rate increases, more cuttings solid particles are generated. The existing drilling fluid velocity is unable to transport all the cuttings to the surface in time. Hence, it can be observed that the increment of drilling rate causes the decrease in cuttings transport efficiency. Nazari et al (2010) summarizes as the increase in rate of penetration (ROP), the hydraulic requirement for effective hole cleaning is increased.

Ettehadi Osgouei (2010) also observed that ROP has direct impact on annular pressure losses. As ROP increases, cuttings concentration in the well increases. As a result of the cuttings concentration increment, annular pressure loss increases.

2.0.4 Flow Patterns In Horizontal Well

The variation of the parameters discussed above sections will result in different flow patterns in the annulus. The effect is more accentuated in horizontal well than the vertical well due to the gravitational forces and the maximum radial slip velocity. Azar and Samuel (2007) classified solid and liquid flow in horizontal annuli into four groups. Figure 2.3 shows the four types of flow with their velocity profiles.

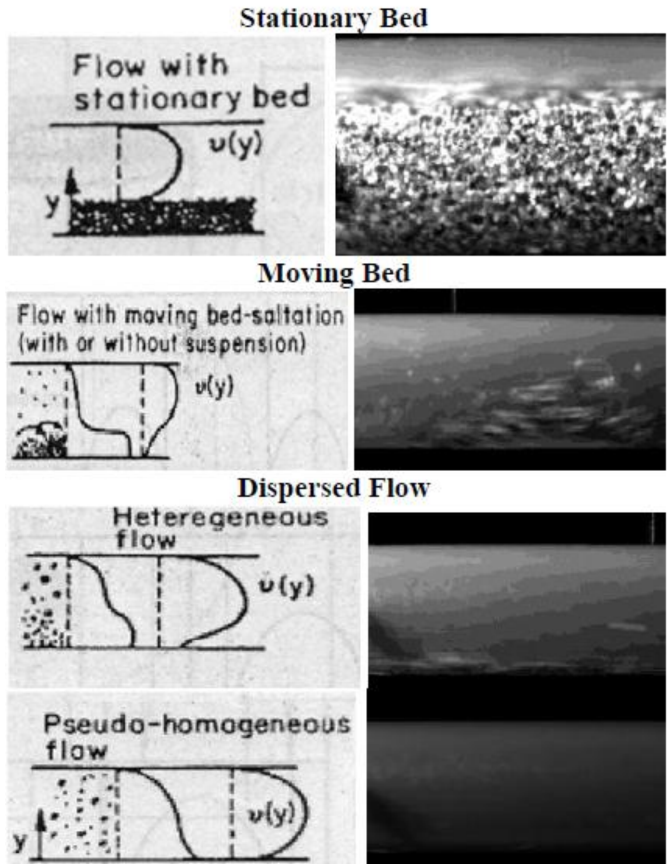


Figure 2.3: Qualitative solid/ liquid flow pattern

Ford et al. (1990) identified two distinctly different cuttings transport mechanisms in the four flows. First, the cuttings are transported by rolling and saltating along the low side wall of the annulus. Second, the cuttings are dispersed and suspended in the drilling fluid. The second mechanism requires higher annular velocity than the first.

The first mechanism of transport is observed in flow with stationary bed and flow with moving bed-saltation without suspension whereas the second mechanism is observed in flow with moving bed-saltation with suspension, heterogeneous flow and pseudo-homogeneous flow.

In stationary bed, a continuous stationary sand bed is formed along the lower wall of the annulus with the sand on the surface rolling and sliding. In the flow with moving bed – saltation, the sand is transported by "jumping" forward or saltating on the surface of the lower wall of the annulus. Some of the sand particles may be dispersed and suspended in the above drilling fluid. In pseudo-homogeneous suspension, the sand is transported in suspension and dispersed uniformly over the annular space while in heterogeneous suspension, the sand is still being transported in suspension save there is a concentration gradient across the annulus.

2.1 Theories Behind Computational Fluid Dynamics

In this project, a commercial software package ANSYS CFX 14.0 would be used to simulate the cuttings transport in horizontal well under the influence of the variables. The same software would be used to plot the flow pattern in the horizontal well.

According to ANSYS CFX-Solver Theory Guide, the two governing equations are the continuity equation and the momentum equation. The continuity equation is used for the calculation the mass transfer of the solid-liquid flow and the momentum equation is to observe the motion of the solid particles in the liquid.

The continuity equation is defined as follows:

$$\nabla . (r_\alpha \rho_\alpha U_\alpha) = \sum_{\beta=2}^{2} \Gamma_{\alpha\beta} \tag{2.1}$$

$$\Gamma_{\alpha\beta} = \dot{m}_{\alpha\beta} A_{\alpha\beta} \tag{2.2}$$

$$A_{\alpha\beta} = \frac{r_\alpha r_\beta}{d_{\alpha\beta}} \tag{2.3}$$

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 momentum equation is defined as follows:

$$\nabla.\left(r_\alpha(\rho_\alpha U_\alpha \otimes U_\alpha)\right) + r_\alpha \nabla p_\alpha = \nabla.\left(r_\alpha \mu_\alpha(\nabla U_\alpha + (\nabla U_\alpha)^T)\right) + \sum_{\beta=1}^{2}\left(\Gamma^{+}_{\alpha\beta}U_\beta - \Gamma^{+}_{\beta\alpha}U_\alpha\right) \quad (2.4)$$

Where,

$$\Gamma^{+}_{\alpha\beta}U_\beta - \Gamma^{+}_{\beta\alpha}U_\alpha = \Gamma_{\alpha\beta} \quad (2.5)$$

2.1.1 Particles Transport Theory In ANSYS CFX 14

In this project, the cuttings particles are modeled as particle transport solid rather as an additional Eulerian phase. The particles are tracked through the water flow individually using Lagrangian way.

According to ANSYS CFX-Solver (2011), the implementation of Lagrangian tracking in ANSYS CFX 14 involves integration of particle paths through the discretised domain where each of the particles is tracked from their injection point until they leave the domain or some integration limit criterion is met. The following sub sections explain the methodology to track the particles.

Integration

Using forward Euler integration of particle velocity over time step, the particle displacement is calculated.

$$x_i^n = x_i^o + v_{pi}^o \delta t \quad (2.6)$$

Where,

x = particle displacement

n = new

o = old

v_p = particle velocity

δt = time step

Using forward Euler integration, particle velocity is calculated using the following equation.

$$v_p = v_f + \left(v_p^o - v_f\right) \exp\left(-\frac{\delta t}{\tau}\right) + \tau F_{all}(1 - \exp\left(-\frac{\delta t}{\tau}\right)) \quad (2.7)$$

Where,

v_f = fluid velocity

τ = shear stress

F_{all} = sum of all forces

CHAPTER 3

METHODOLOGY

3.1 Project Flow

Figure 3.0 shows the approaches taken to conduct and complete this project.

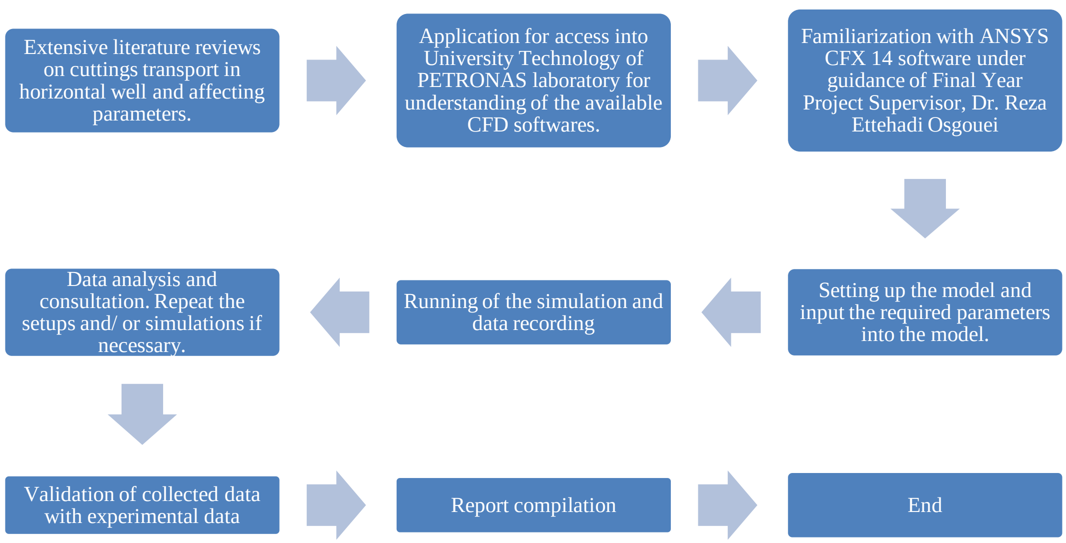


Figure 3.0: Flow chart in completing the project.

3.1.1 Project Activities

As depicted in previous section, the activities of the project can be broken down into the followings:

a) Extensive literature reviews on cuttings transport in horizontal well and affecting parameters.
b) Application for access into University Technology of PETRONAS laboratory for understanding of the available CFD softwares.
c) Familiarization with ANSYS CFX 14 software under guidance of Final Year Project Supervisor, Dr. Reza Ettehadi Osgouei, guiding mentor and self trial and error.
d) Modeling of the horizontal well geometry and input of required parameters such as drilling fluid rheological properties, eccentricity, cuttings particles size, rate of penetration and etc.
e) Running of the simulations and variation of mud flow rate, rate of penetration and pipe rotation.
f) Data recording.
g) Data analysis and consultation. Repeat the set up and/ or simulations from step (d) to step (g) if necessary.
h) Validation of collected data with experimental data.
i) Report compilation.
j) Sharing of findings.
k) End

3.2 Simulation Setup

The horizontal eccentric wellbore model is developed conforming to the test parameters published in Ettehadi Osgouei (2010). Table 3.0 shows the parameters used in this project.

Table 3.0: Parameters Used In The Simulation

Parameters	Value
Well Bore Length	2 ft
Well Bore Diameter	2.91 in
Drill Pipe Diameter	1.85 in
Eccentricity	0.623
Cuttings Material	Gravel
Cuttings Diameter	0.079 in
Cuttings Density	23.050 ppg
Rate of Penetration	60 – 80 ft/hr
Annular Water Flow Rate	2 – 9 ft/s
Temperature	25°C
Pressure	16 – 20 psi

3.1.1 Model Setup

This section describes the steps taken to set up the model for simulations. The first step involved in setting up the model is to design the well bore model with eccentricity of 0.623. The hole inner diameter is 2.91 in while the drill pipe outer diameter is 1.85 in. The total length of the model is set to be 2 ft. The geometry is defined in Design Modeller.

Figure 3.1 shows the working panel for Design Modeller.

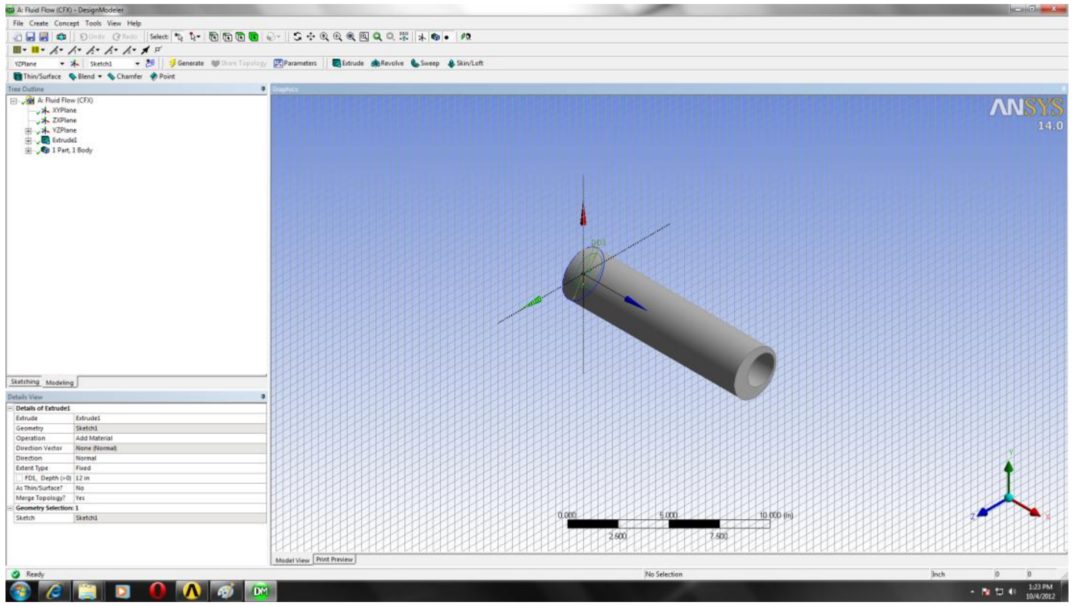


Figure 3.1: Design Modeller

After the geometry is designed, the model is discretized in Meshing. The total numbers of element meshed in this project is 4, 107, 471. Figure 3.2 shows the inlet meshing and Figure 3.3 shows the model meshing.

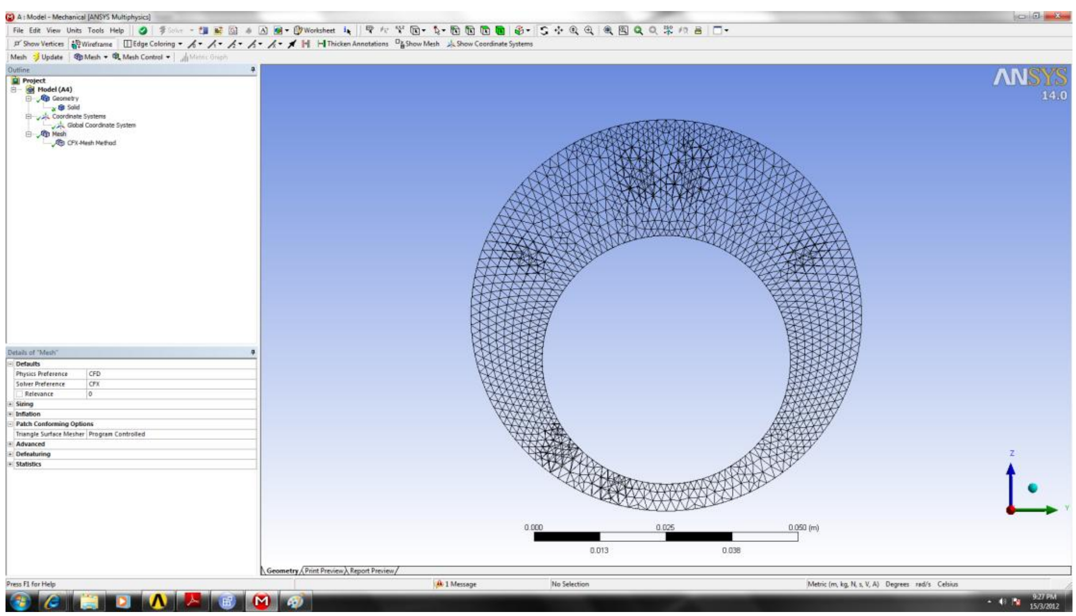


Figure 3.2: Inlet Meshing

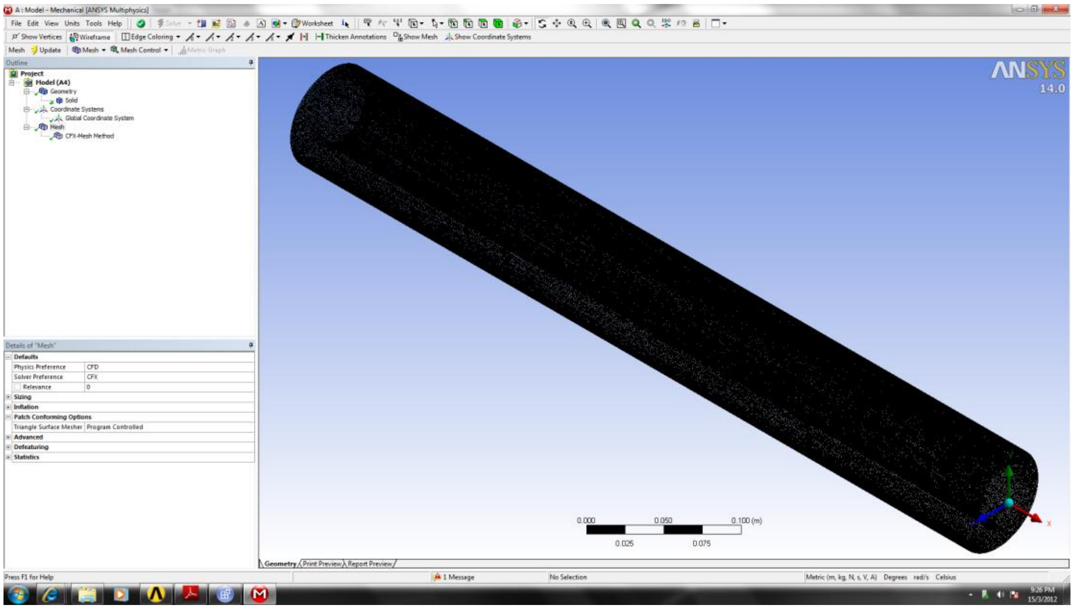


Figure 3.3: Isometric Meshing

Next, the set up of the simulation is defined in CFX Pre. Firstly, the cuttings are defined in the material list. Then, the domain which is the geometry of studied is defined with water flow with cuttings injection. Lastly, the inlet and outlet boundaries conditions are defined. Figure 3.4 shows the working panel of CFX Pre.

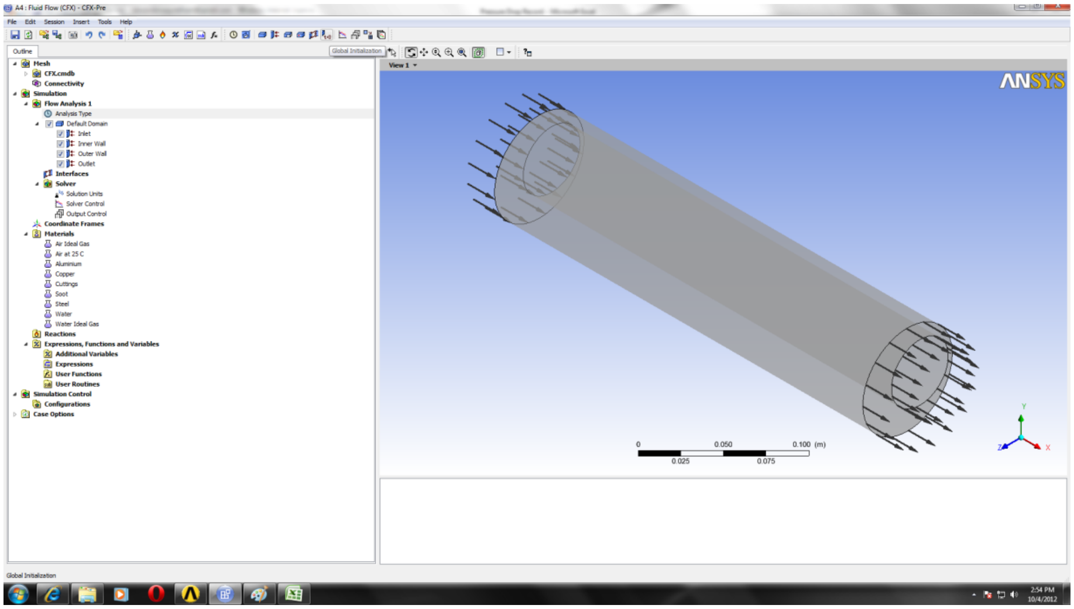


Figure 3.4: CFX Pre

After the set up is complete, the simulation is ready for run. From ANSYS Workbench, the CFX Solver is initiated. Figure 3.5 shows the working panel of CFX Solver when the simulation has completed normally.

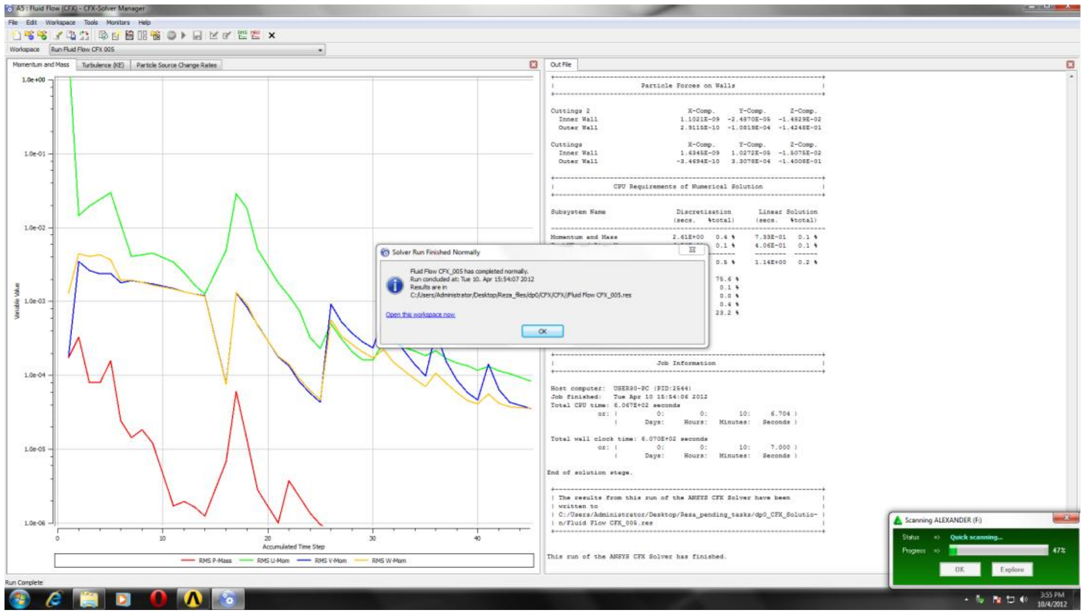


Figure 3.5: CFX Solver

Finally, the results are obtained from CFX Post. Figure 3.6 shows the working panel of CFX Post.

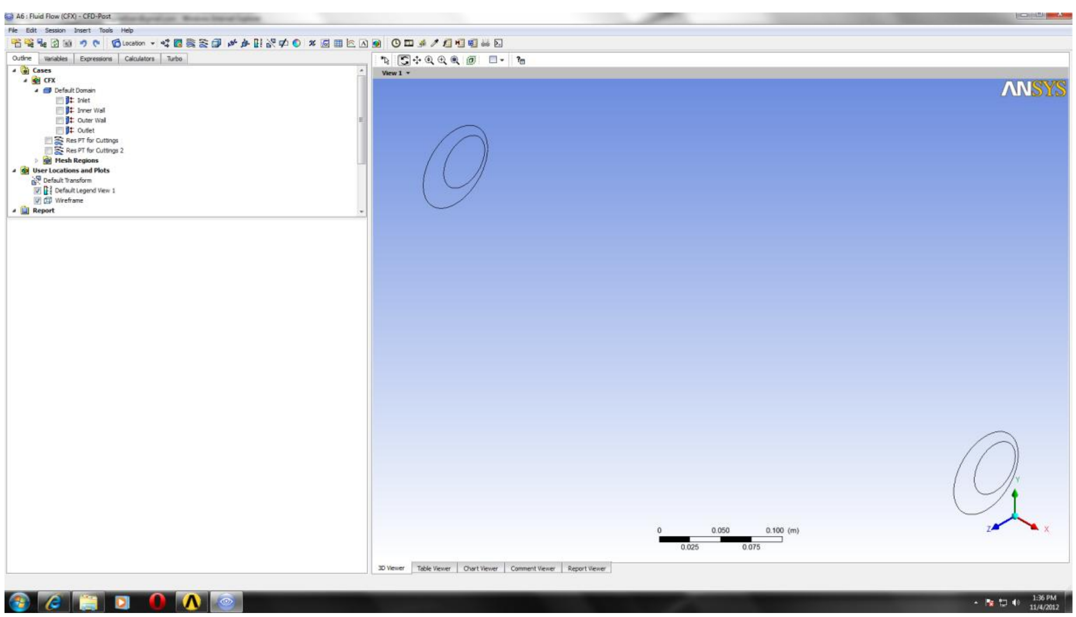


Figure 3.6: CFX Post

Figure 3.7 summarizes the methodologies involved in setting up the model for simulations.

Horizontal eccentric annulus geometry is modeled using Design Modeller. The well bore is modelled after flow loop tests conducted by Dr. Reza Ettehadi Osgouei.

The model is then discretized using Meshing. Refinements are required to produced good meshing. The total elements are 4,107,471.

The set up for the simulations is defined in CFX Pre. Gravel is defined as new properties in the Material. Domain is defined with water as continuous fluid and cuttings as particle transport solid. Next, the velocity of water is defined in inlet and initial pressure is defined in domain initialisation. Lastly, outlet pressure is defined.

The simulation is initiated using CFX Solver and the results are obtained from CFX Post.

Figure 3.7: Steps taken in ANSYS CFX Setup for cuttings transport in horizontal annulus.

ANSYS CFX 14 performance is limited by the host computer memory space. Refined meshing would take up a lot of computing power in solving the iterations to reach convergence. However, rough meshing would yield inaccurate results. Hence, a good juggling between the meshing is required.

Detailed step by step guide of using ANSYS CFX is available in Appendix I.

3.3 Key Milestones

The key milestones of this project are provided themselves in the Final Year Project Guideline (2011). They are summarized in Table 3.1 below.

Table 3.1: Final Year Project Key Milestones

No.	Activities	Date
Final Year Project 1		
1	Proposal Defence Report Submission	03 November 2011
2	Proposal Defence	15 November 2011 - 25 November 2011
3	Interim Draft Report Submission	15 December 2011
4	Interim Report Submission	22 December 2011
Final Year Project 2		
5	Progress Report Submission	16 March 2012
6	Poster Submission	06 April 2012
7	Final Report Submission	16 April 2012
8	Technical Paper Submission	20 April 2012
9	Oral Presentation	30 April 2012
10	Project Dissertation Submission (hard bound)	11 May 2012

3.4 Gantt Chart

Gantt Chart for this project is shown in Table 3.2 and Table 3.3 below. Table 3.2 shows the Gantt Chart for Final Year Project 1.

Table 3.2: Final Year Project 1 Gantt Chart

No.	Detail/ Week	1	2	3	4	5	6	7	MID SEMESTER BREAK	8	9	10	11	12	13	14
1	Selection of Project Topic															
2	Preliminary Research Work															
3	Submission of Extended Proposal Defence															
4	Proposal Defence															
4	Extensive Literature Review on Cuttings Transports in Horizontal Well and the Affecting Parameters															
5	Submission of Interim Draft Report															
6	Submission of Interim Report															

Table 3.3 shows the proposed Gantt Chart for Final Year Project 2.

Table 3.3: Final Year Project 2 Gantt Chart

No.	**Detail/ Week**	**1**	**2**	**3**	**4**	**5**	**6**	**7**		**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	Familiarization of CFD software								**MID SEMESTER BREAK**									
2	Modeling of horizontal well and relevant parameters																	
3	Test running and debug of the model																	
4	Simulation of cuttings transport																	
5	Submission of progress report																	
4	Data recording, analysis and discussion																	
5	Validation with experimental results																	
6	Poster Submission																	
7	Report compilation																	
8	Submission of final report																	
10	Submission of technical paper																	
11	Oral presentation																	
12	Submission of project dissertation (Hard bound)																	

3.5 Tools

The tools used in this project are mainly computer installed with ANSYS CFX 14 software.

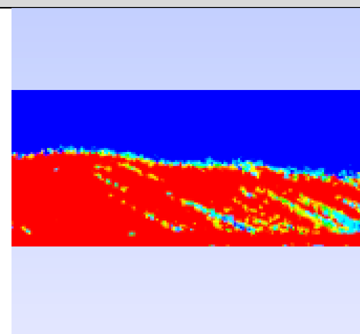
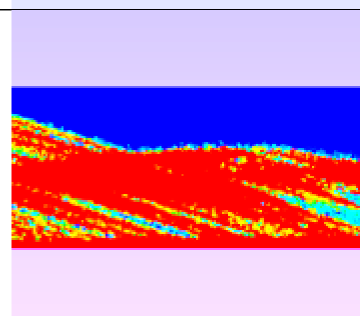
CHAPTER 4

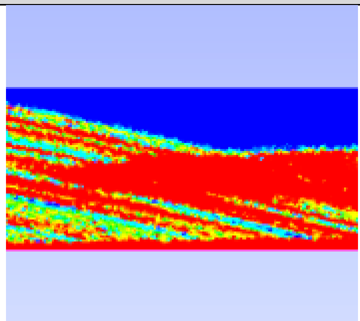
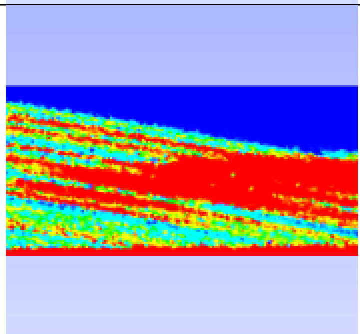
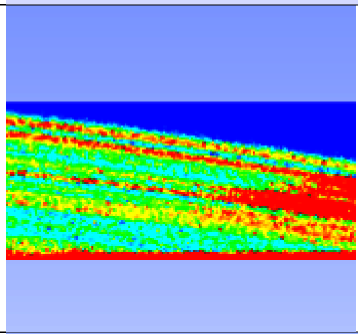
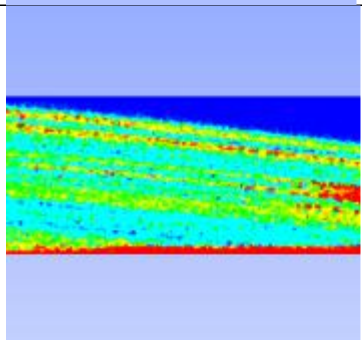
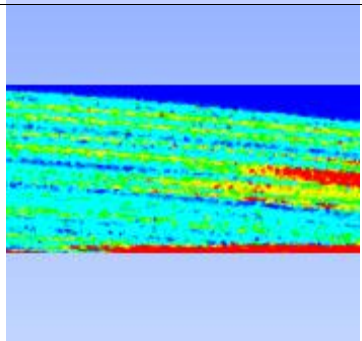
RESULTS AND DISCUSSIONS

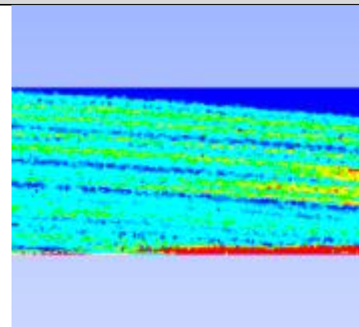
4.1 Flow Pattern Observed

Table 4.1 shows the flow patterns obtained from ANSYS CFX 14 simulations for each drilling fluid velocity with Rate Of Penetration (ROP) of 60 ft/hr. Regions with blue color are water while regions with color other than blue are cuttings particles. The legends by default are in rainbow spectrum. As the color descend from red to blue, the cuttings concentration decreases.

Table 4.1: **Flow Patterns for ROP of 60 ft/hr**

Drilling Fluid Velocity (ft/s)	Flow Pattern
2	
3	

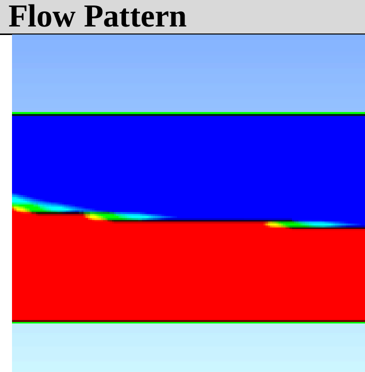
Drilling Fluid Velocity (ft/s)	Flow Pattern
4	
5	
6	
7	
8	

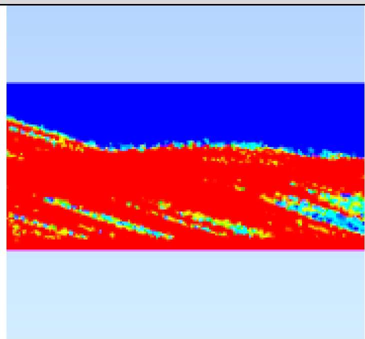
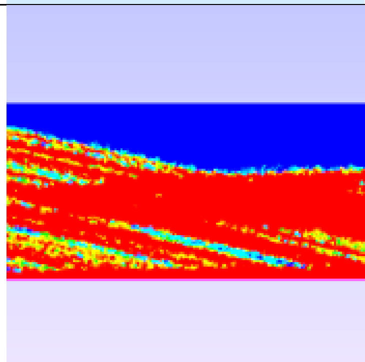
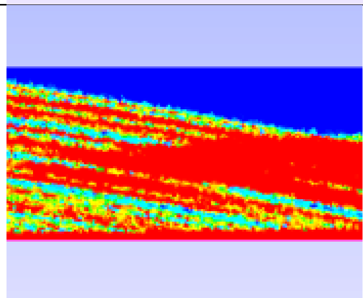
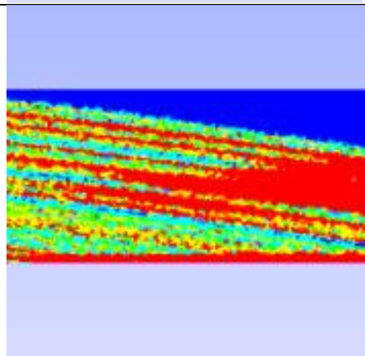
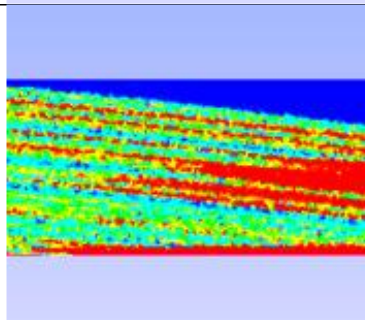
Drilling Fluid Velocity (ft/s)	Flow Pattern
9	

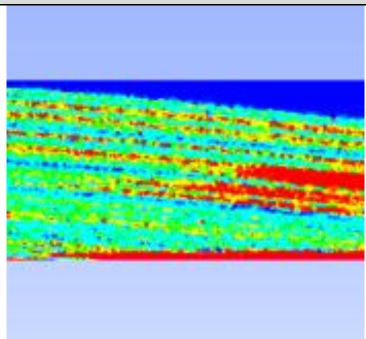
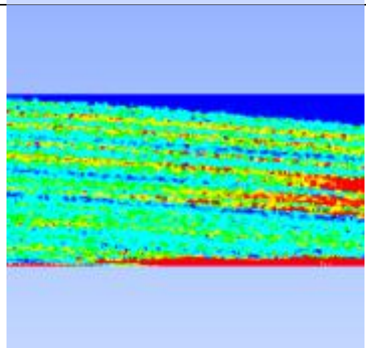
The flow patterns change from stationary bed to dispersed flow as the water velocity increases. There is a stationary bed for water velocity from 2 ft/s to 3 ft/s. From 4 ft/s to 5 ft/s, moving bed is observed. Then, at 6 ft/s dispersed flow (heterogeneous flow) is observed. Finally from 7 ft/s to 9 ft/s, we have dispersed flow (homogeneous flow). Four flow patterns are successfully identified here, which are stationary bed, moving bed and dispersed flow for both heterogeneous and pseudo – homogeneous flow.

Table 4.2 shows the flow patterns resulted from variation in water velocity for 80 ft/hr ROP.

Table 4.2: Flow Patterns for ROP of 80 ft/hr

Drilling Fluid Velocity (ft/s)	Flow Pattern
2	

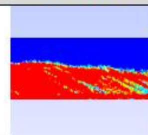
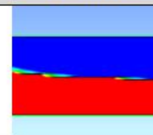
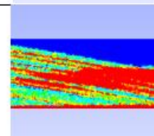
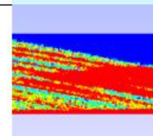
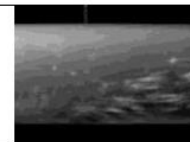
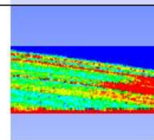
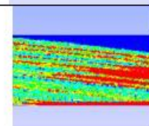
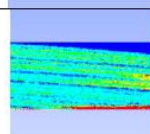
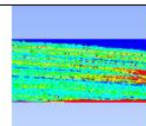
Drilling Fluid Velocity (ft/s)	Flow Pattern
3	
4	
5	
6	
7	

Drilling Fluid Velocity (ft/s)	Flow Pattern
8	
9	

Similar flow patterns are observed from ROP of 80 ft/hr. The flow pattern begins with stationary bed at 2 ft/s. There is a transition from stationary bed to dispersed flow from 4 ft/s onwards. At water velocity of 4 ft/s to 6 ft/s, moving bed is observed. Then, from 7 ft/s to 8 ft/s, dispersed flow (heterogeneous flow) is observed. Finally at 9 ft/s, dispersed flow (pseudo – homogeneous flow) is observed. The cuttings concentration is observed to be higher and the transition of the flow patterns occurs at a higher velocity than 60 ROP. As the penetration rate increased, more cuttings are generated per unit time. Hence, the existing water velocity cannot transport the additional cuttings effectively.

Table 4.3 compares the flow patterns obtained from ANSYS CFX 14 simulations to flow patterns observed in flow loop tests.

Table 4.3: Flow Patterns Classification

Flow Patterns	ROP 60 ft/hr	ROP 80 ft/hr	Flow Loop Tests
Stationary Bed			
Moving Bed			
Dispersed Flow (Heterogeneous Flow)			
Dispersed Flow (Pseudo – Homogeneous Flow)			

4.2 Annular Pressure Drop

The first step involved after the model set up was to validate the model. To perform the verification check, pure water with different velocities were simulated through the model and their annular pressure drops were recorded and validated with the experimental runs. Figure 4.1 shows the comparisons of annular pressure drop between simulations and experiments for water flow without any cuttings injection.

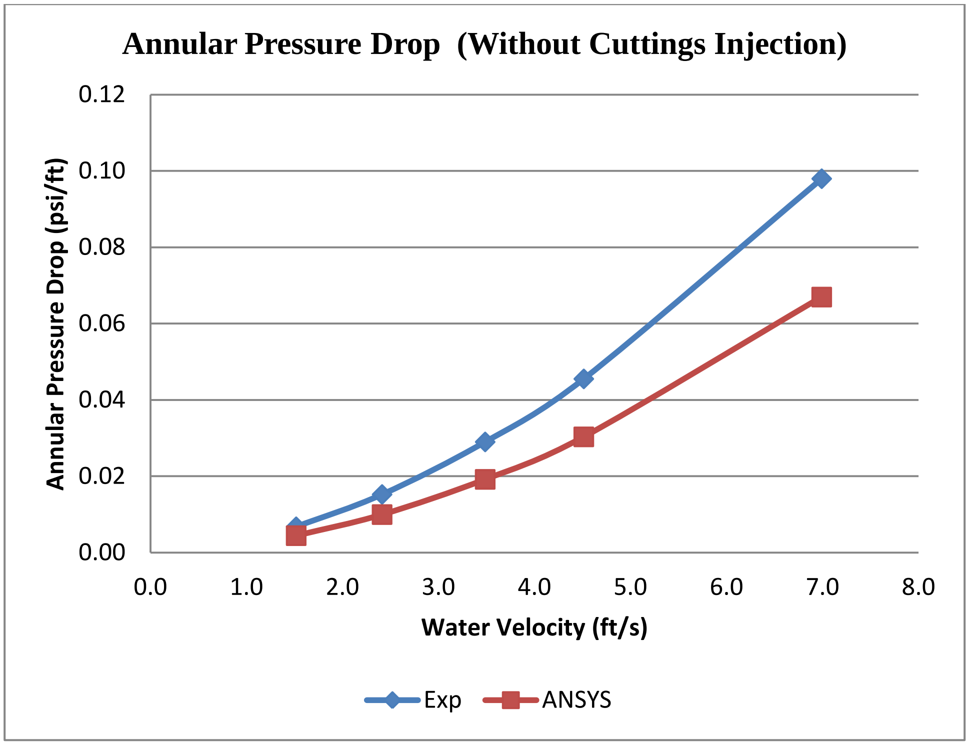


Figure 4.1: Comparisons of Annular Pressure Drop between Simulations and Experiments for Water Flow without Any Cuttings Injection

As the water velocity increases the annular pressure drop is observed to be increasing. According to Bernoulli's Principle, the pressure is inversely proportional to liquid flow velocity. As the flow the faster, the pressure at the outlet is lower. Hence, the pressure drop is higher.

Initially at 1.5 ft/s, the annular pressure drop is in good agreement with the experimental data. As the flow increases in velocities, the results deviated 20 – 30%. This deviation is obtained because the water velocity profile injected is assumed to be uniform. However in reality, water has velocity profile. In addition to that, the meshing is compromised to accommodate the host computer memory allocation. In general, the result is acceptable and cuttings are introduced into the flow to simulate the influx of cuttings into drilling fluid during drilling.

Figure 4.2 compares annular pressure drop for ANSYS CFX 14 simulations with experiment observations for ROP of 60 ft/hr.

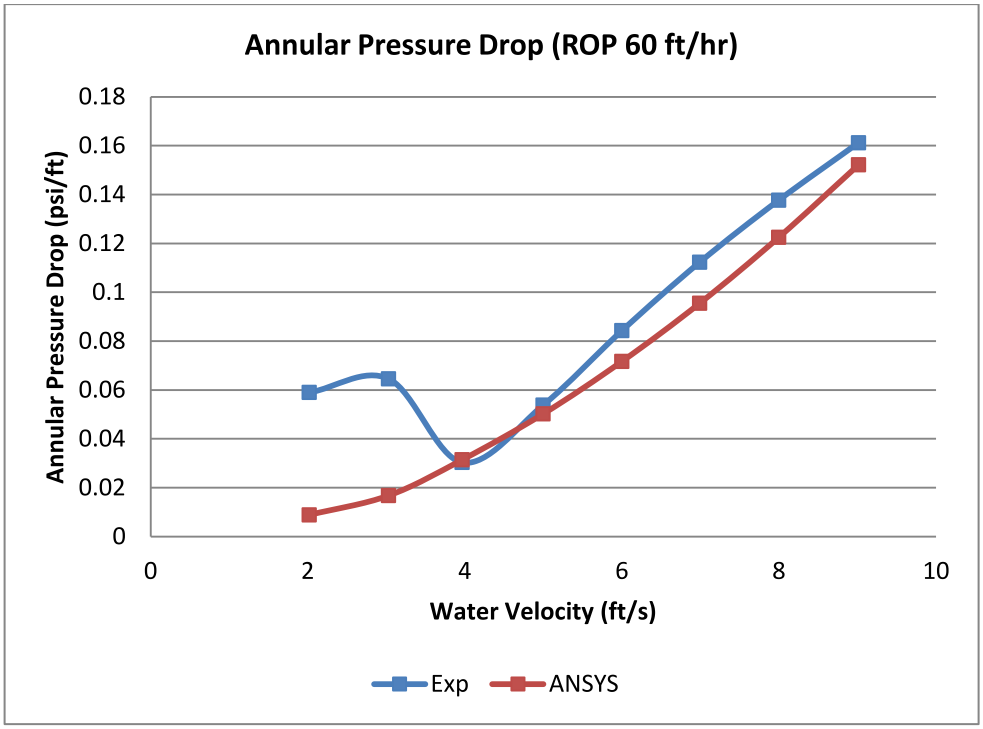


Figure 4.2: Comparisons of Annular Pressure Drop between ANSYS Simulations and Experiments for ROP 60 ft/hr

From Figure 4.2, as the annular flow rate increases, the annular pressure drop recorded increases. It is also observed that the pressure drop of flow with cuttings injection is higher than pressure drop without cuttings injection. This is due to increase in cuttings concentration in the annulus and reduction of flow area in the annulus.

The results obtained from ANSYS CFX 14 simulations show close agreement with the experimental observations with deviation less than 10 %. However, it is observed that from 2 ft/s to 4 ft/s, the pressure drop obtained from the experiments deviated significantly from ANSYS CFX simulations in where it shows a sudden rise in pressure drop and decreases as annular flow rate reaches 3 ft/s. This occurs due to the runs conducted in flow loop tests are continuous. Hence, as the annular velocity increases from 2 ft/s onwards, the accumulated cuttings bed begins its transition to dispersed flow. Therefore, there is a fluctuation in pressure drop.

Figure 4.3 compares annular pressure drop for ANSYS CFX 14 simulations with experiment observations for ROP of 80 ft/hr.

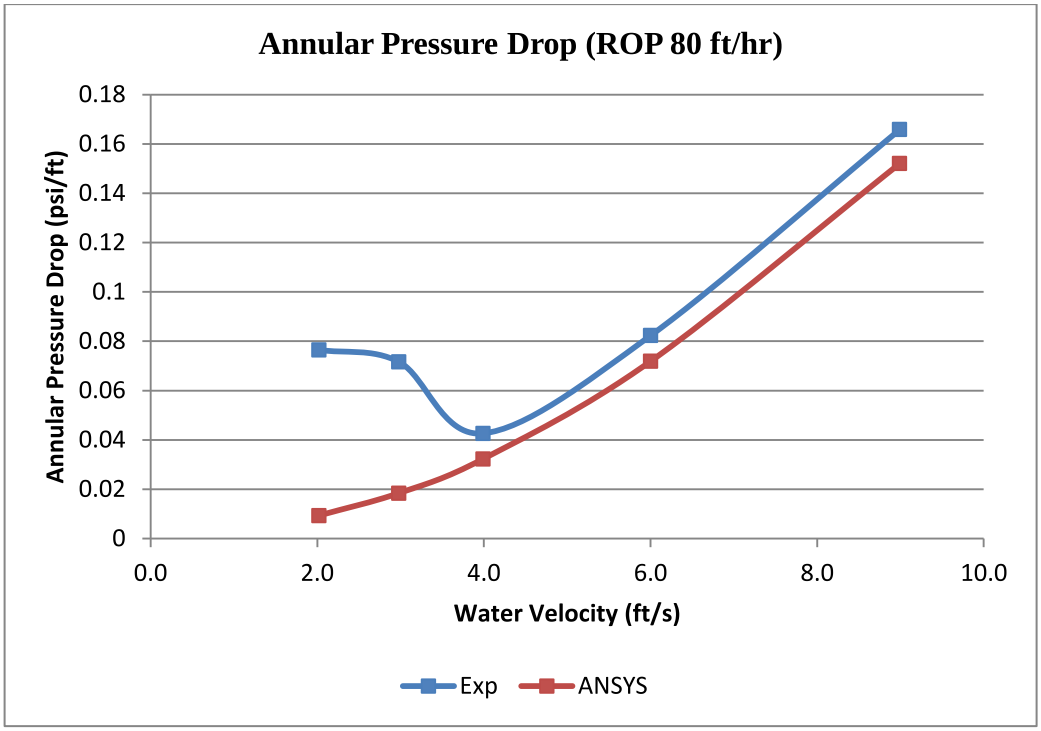


Figure 4.3: Comparisons of Annular Pressure Drop between ANSYS Simulations and Experiments for ROP 80 ft/hr

Annular pressure drop for ROP 80 ft/hr shows the similar trend as ROP 60 ft/hr. The deviation from experimental results is very little which less than 15 %.

Figure 4.4 presents annular pressure drop for ROP 60 ft/hr and ROP 80 ft/hr simulated from ANSYS CFX 14.

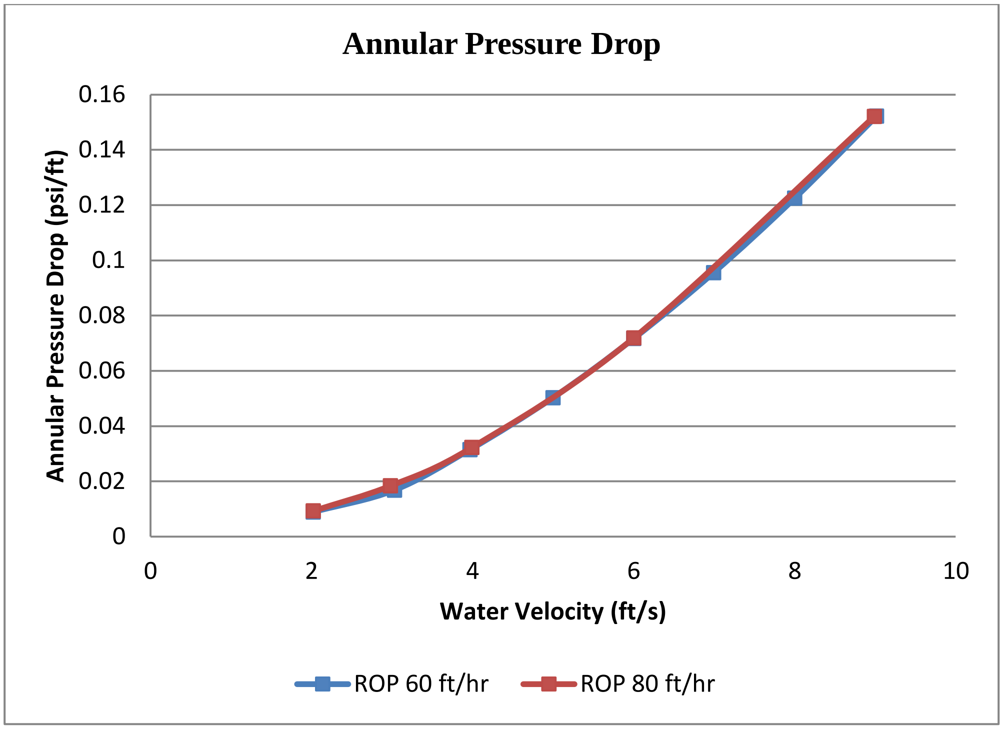


Figure 4.4: Annular Pressure Drop (ROP = 60 ft/hr and ROP = 80 ft/hr**)**

Annular pressure drop is slightly higher for 80 ft/hr penetration rate as compared to 60 ft/hr. This is due to higher cuttings concentration generated from 80 ft/hr ROP inside the well bore.

4.3 Cuttings Concentration

Figure 4.5 presents the validation of cuttings concentration with flow loop tests observed data for ROP of 60 ft/hr.

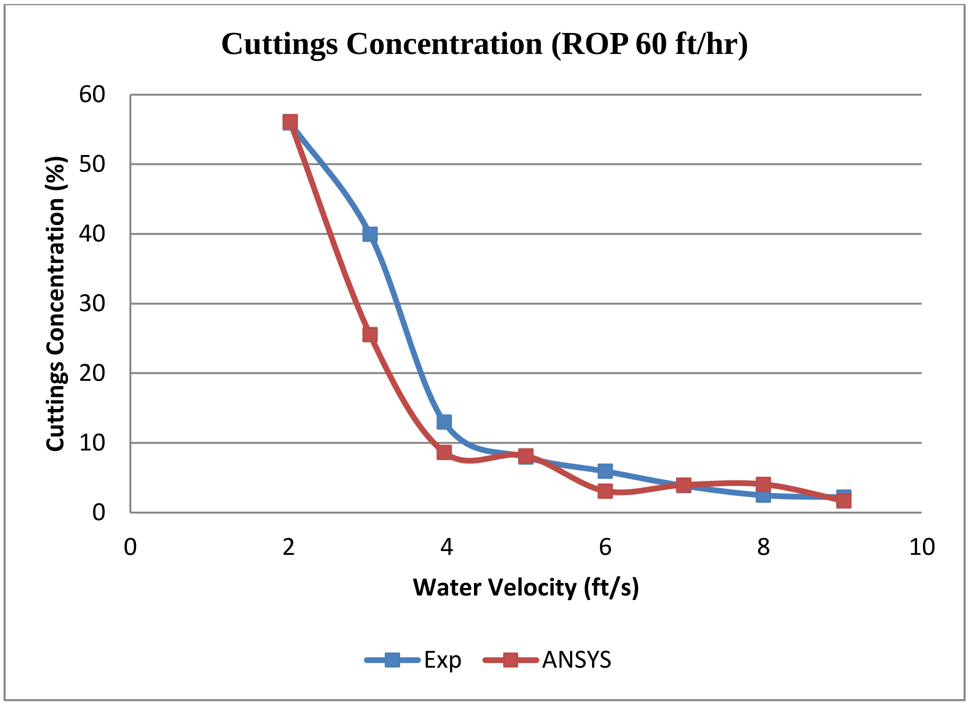


Figure 4.5: Comparisons of Cuttings Concentration between ANSYS Simulations and Experiments for ROP 60 ft/hr

The results obtained from simulations show close agreement with experimental data, especially at flow rate reading 2 ft/s and 9 ft/s.

From Figure 4.5, we can see that the cutting concentration is the highest when the annular velocity is at the lowest. As the water velocity increases, the cuttings concentration decreases significantly. Low water velocity is unable to prevent the cuttings from slipping downward as their slip velocity is higher. In brief, the water velocity has not reached the required Minimum Transport Velocity. As a result, cuttings particles settled at the bottom of the annulus and eventually a continuous stationary cuttings bed is formed. When the flow rate is increased, the transport velocity is higher than the required Minimum Transport Velocity, the cuttings would be carried in two mechanisms, which are rolling and saltating on the bottom wall of the well and dispersed in the water in suspension.

Figure 4.6 presents the validation of cuttings concentration with flow loop tests observed data for ROP of 80 ft/hr.

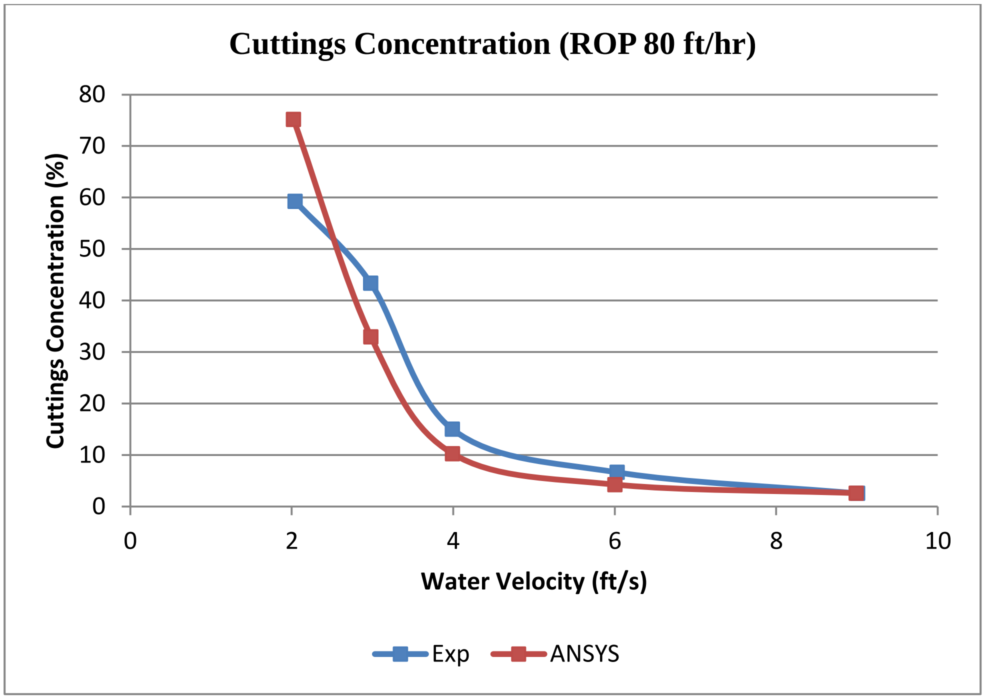


Figure 4.6: Comparisons of Cuttings Concentration between ANSYS Simulations and Experiments for ROP 80 ft/hr

The results obtained are in good agreement with the experimental observations. There is deviation of 20 % in the initial flow rate. However, as the flow rate increases, the readings from both simulations and experiments converged.

The pattern observed is the same as in Figure 4.5. The cuttings concentration decreases tremendously as the flow rate increases.

Figure 4.7 shows the cuttings concentration (%) against water velocity (ft/s) for ROP 60 ft/hr and ROP 80 ft/hr.

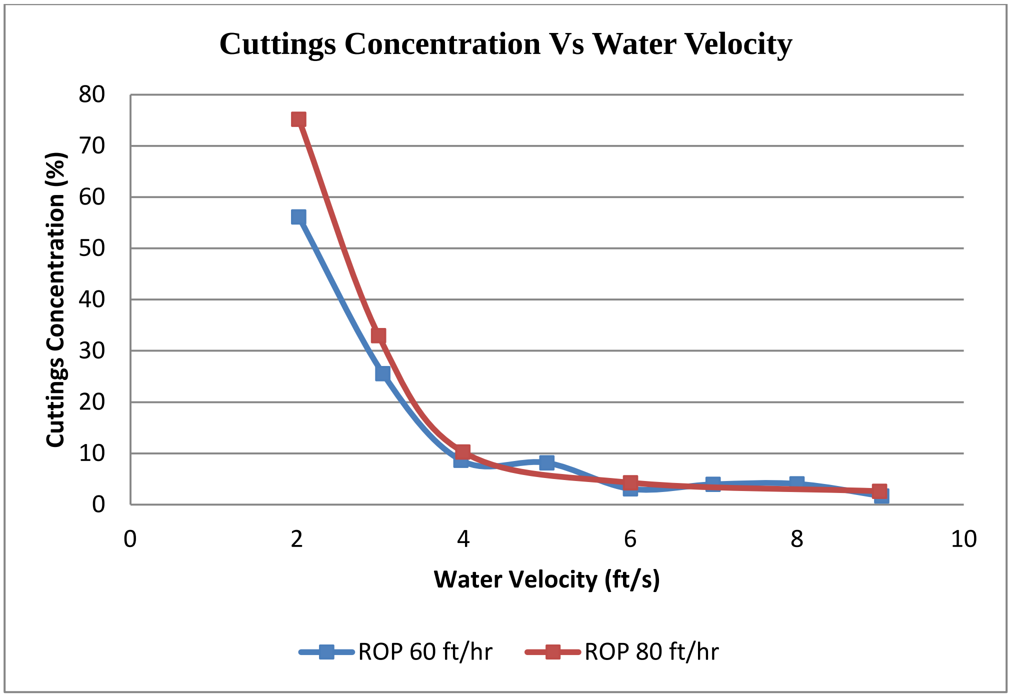


Figure 4.7: Cuttings Concentration Vs Water Velocity for ROP 60 ft/hr and ROP 80 ft/s

We can see that the cuttings concentration generated from 80 ft/hr ROP is in general higher than 60 ft/hr. This occurs due to higher influx of cuttings into the annulus. The same annular flow rate could not accommodate the addition of cuttings.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This project aims to study cuttings – water two phase flow in horizontal eccentric annulus in ANSYS CFX 14 CFD software program. The effects of annular flow rate and penetration rate are the main focus of this study. Based on the results collected, the following conclusions can be made:

(a) ANSYS CFX 14 has successfully modeled cuttings – water flow in horizontal eccentric annulus.
(b) Annular flow rate and rate of penetration play a major role in hole cleaning in horizontal eccentric well.
(c) As annular flow rate increases, the cuttings transport increases.
(d) As rate of penetration increases, the cuttings transport decreases.
(e) The flow patterns in horizontal eccentric well have been identified as stationary bed, moving bed and dispersed flow (pseudo - homogeneous and heterogeneous).

The author has identified several improvements to be recommended in cuttings transport study. The recommendations are as follow:

(a) For ANSYS CFX 14 simulations:
    i. Introduction of water inlet velocity profile would yield more accurate results.
    ii. Since the software operability is dependent on the host computer memory allocation, the cuttings particle can be modeled as dispersed solids instead of particle transport solids.

iii. Since the model is exhibits symmetry about XZ axis, the model geometry can be split into half and simulations to be run on only one half, reducing the computing memories and resources.

(b) For further studies:

i. This study only focused on Newtonian liquid. Further studies can be conducted on Non – Newtonian liquid.

ii. Further studies can be conducted on the effect of well inclination from vertical axis.

iii. Develop Graphical User Interface (GUI) of the model that simplifies the commands, inputs required and made user friendly for suitability of the operation purposes.

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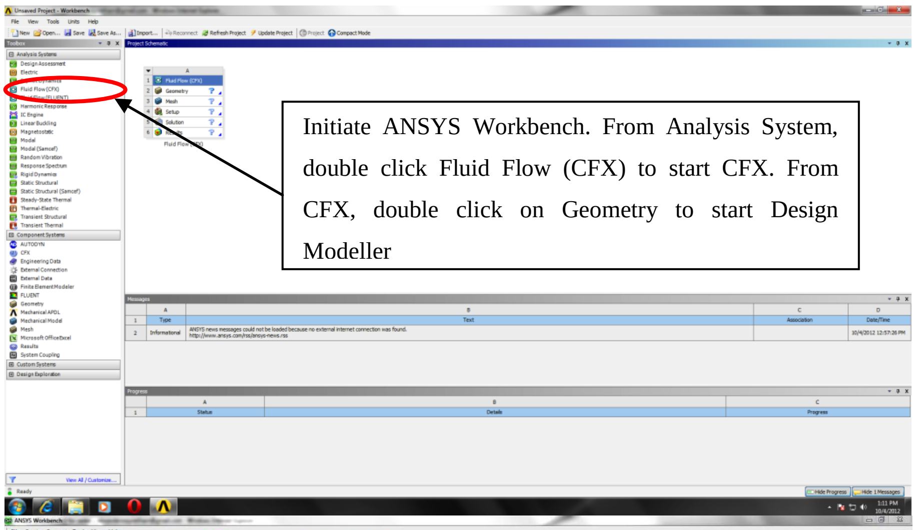
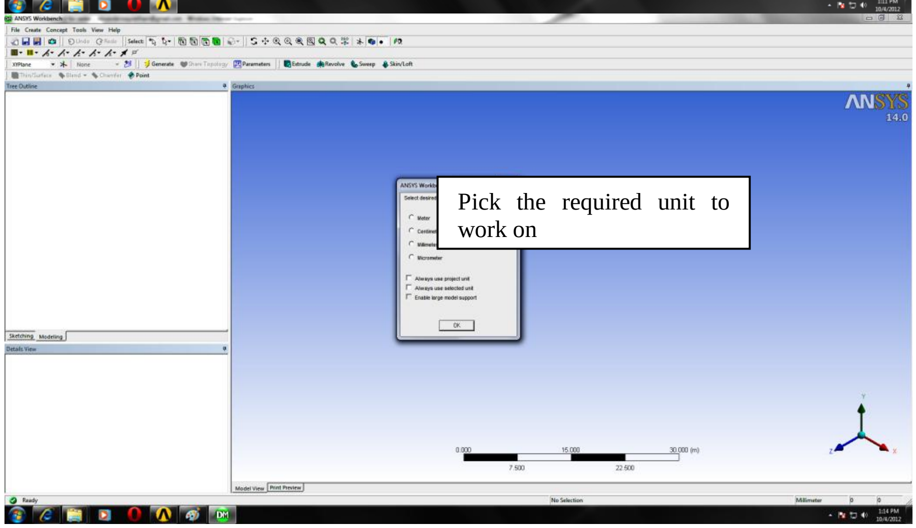
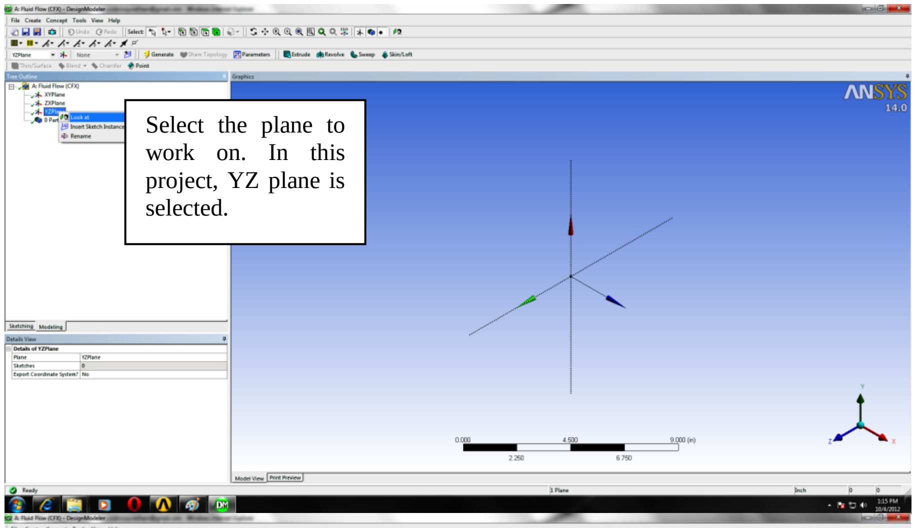
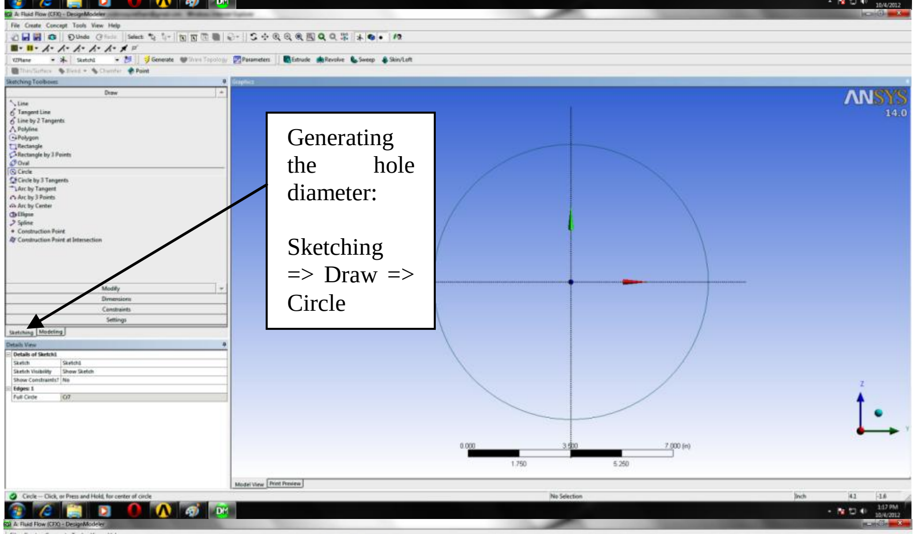
APPENDICES

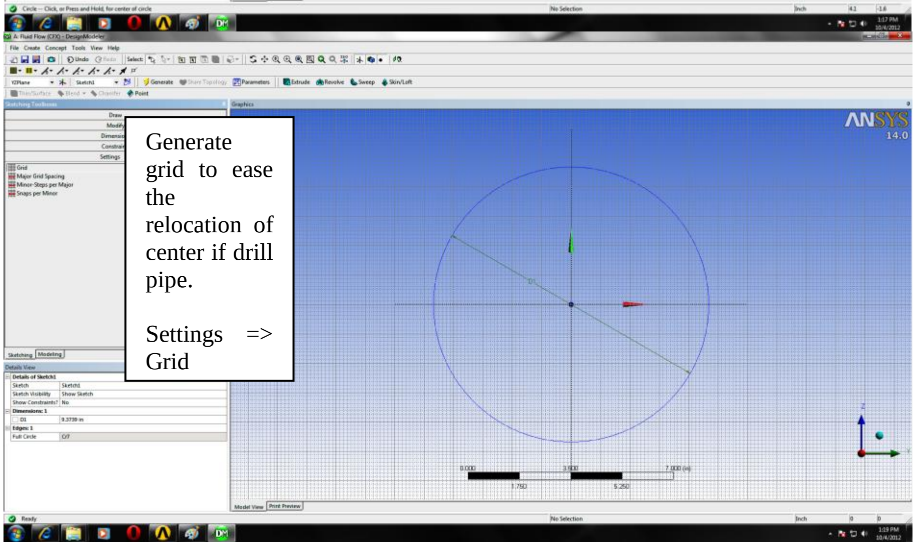
Appendix 1 - ANSYS CFX 14 Simulation Set Up Steps

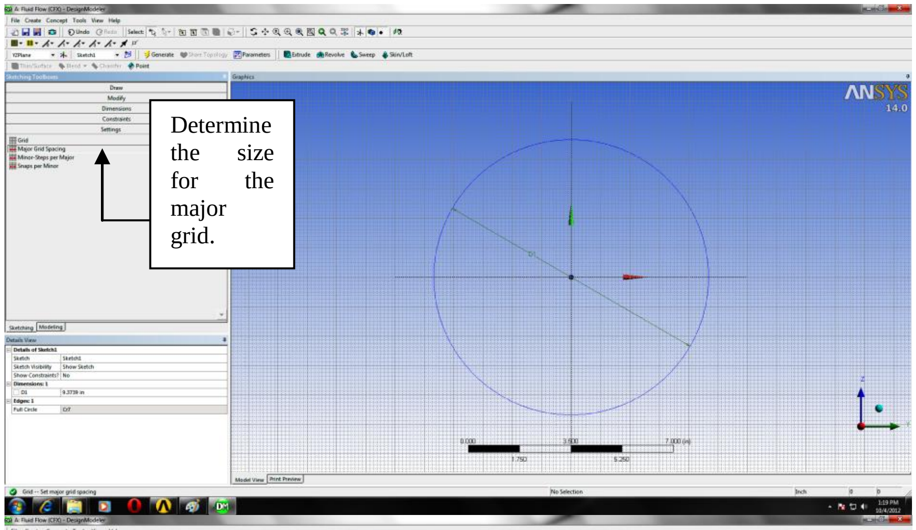


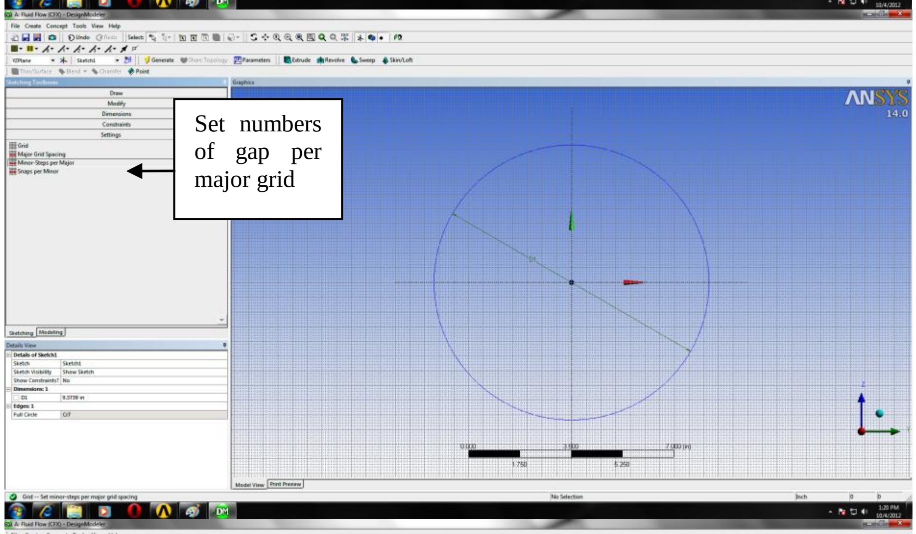


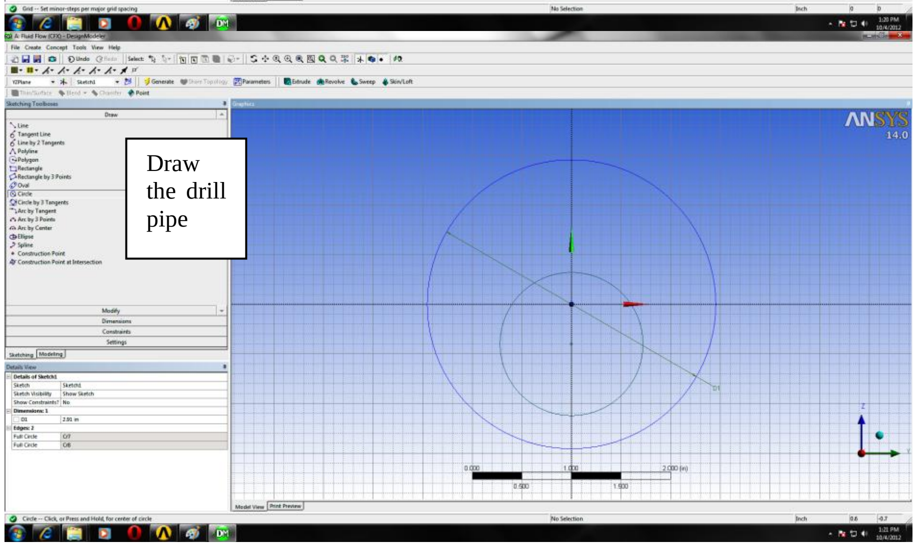

ANSYS
14.0
Select the plane to work on. In this project, YZ plane is selected.

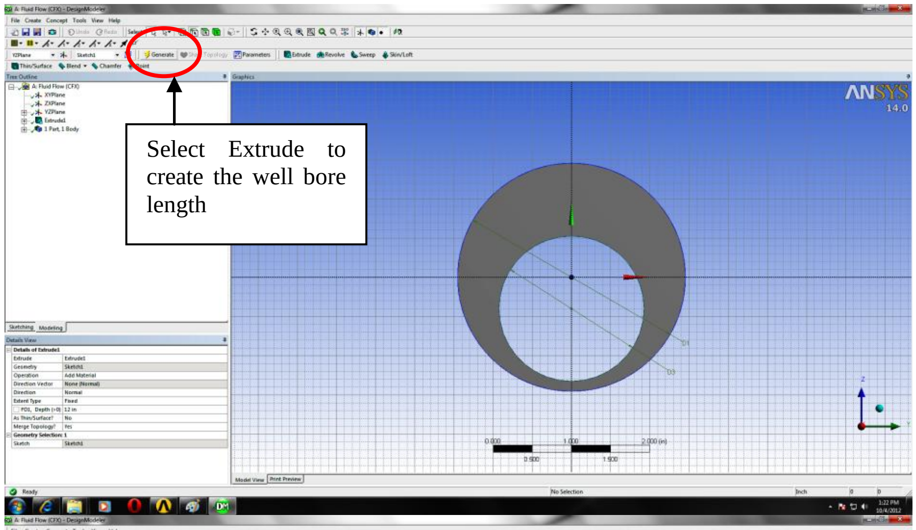

ANSYS
14.0
Generating the hole diameter:
Sketching => Draw => Circle

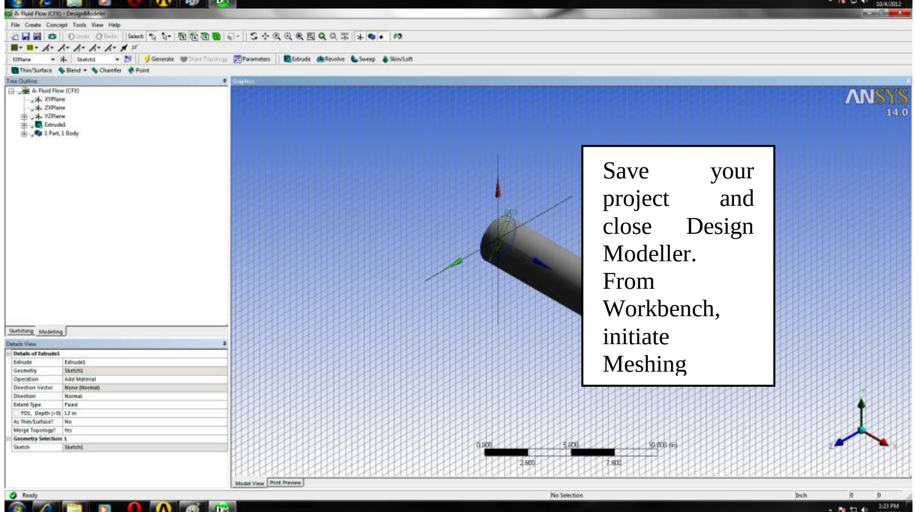

ANSYS
14.0
Generate grid to ease the relocation of center if drill pipe.
Settings => Grid

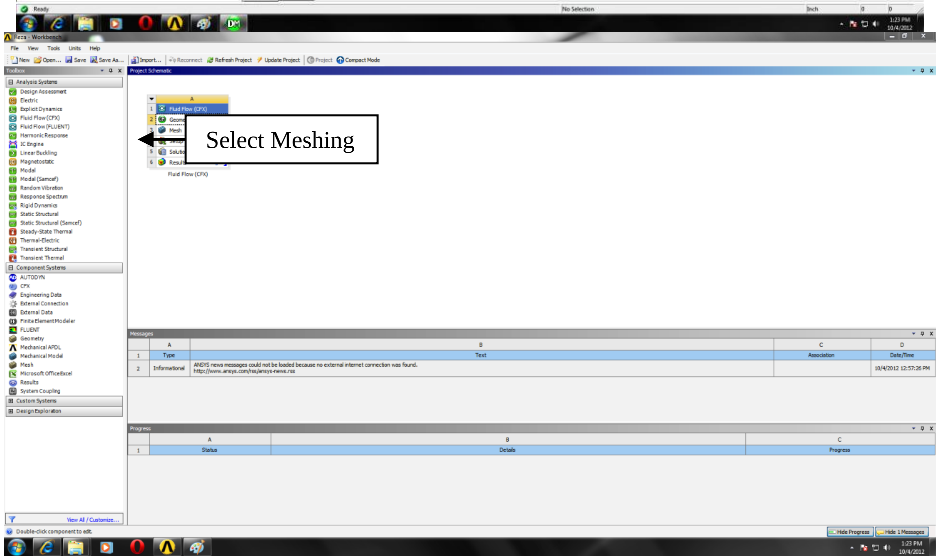

Determine the size for the major grid.

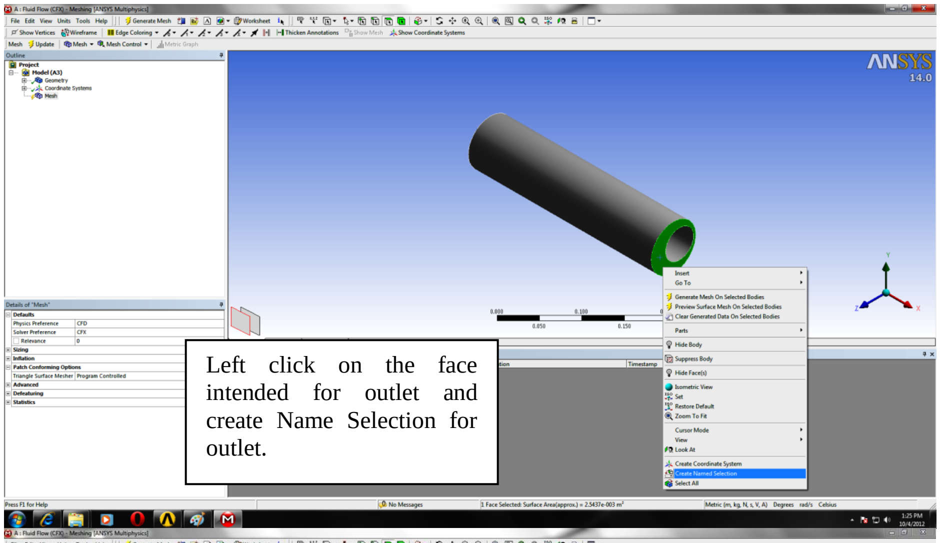

Set numbers of gap per major grid


Draw the drill pipe

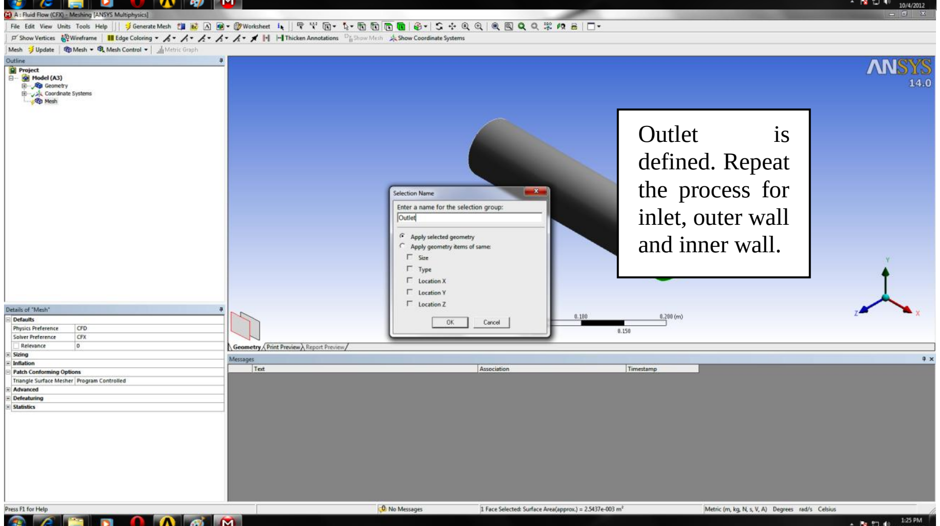

Select Extrude to create the well bore length


Save your project and close Design Modeller. From Workbench, initiate Meshing

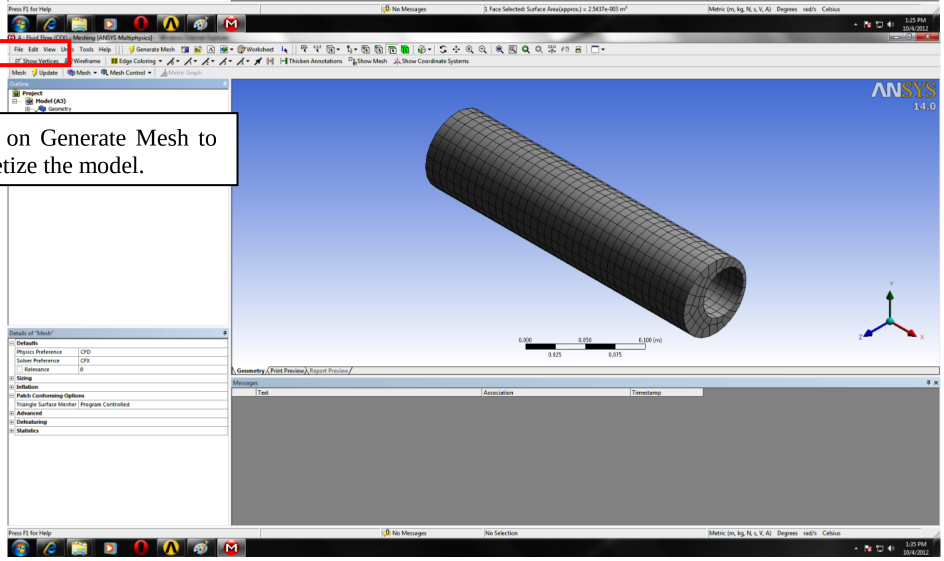

Select Meshing



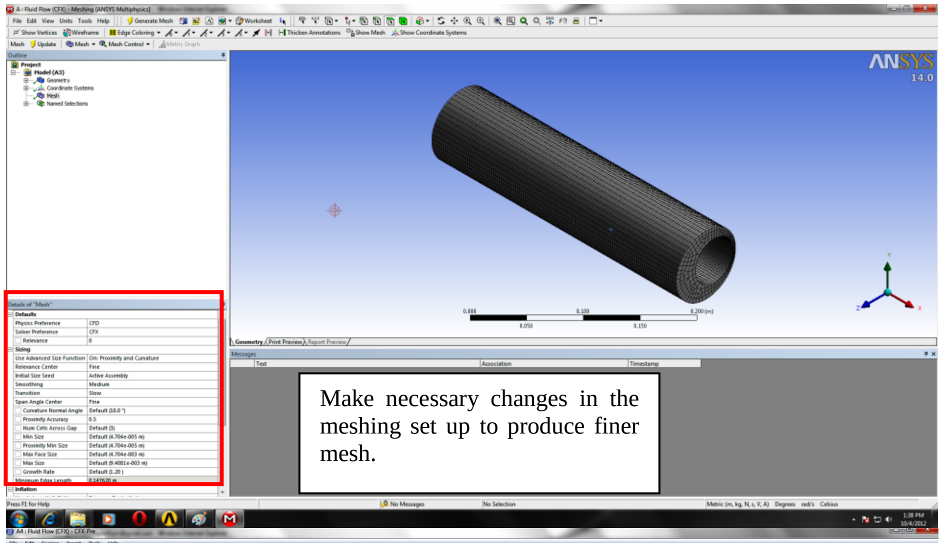
Left click on the face intended for outlet and create Name Selection for outlet.

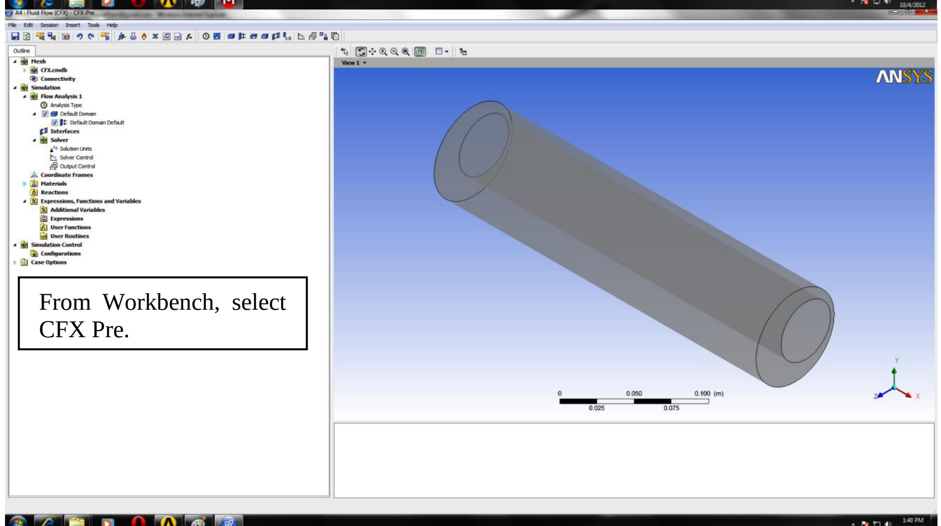


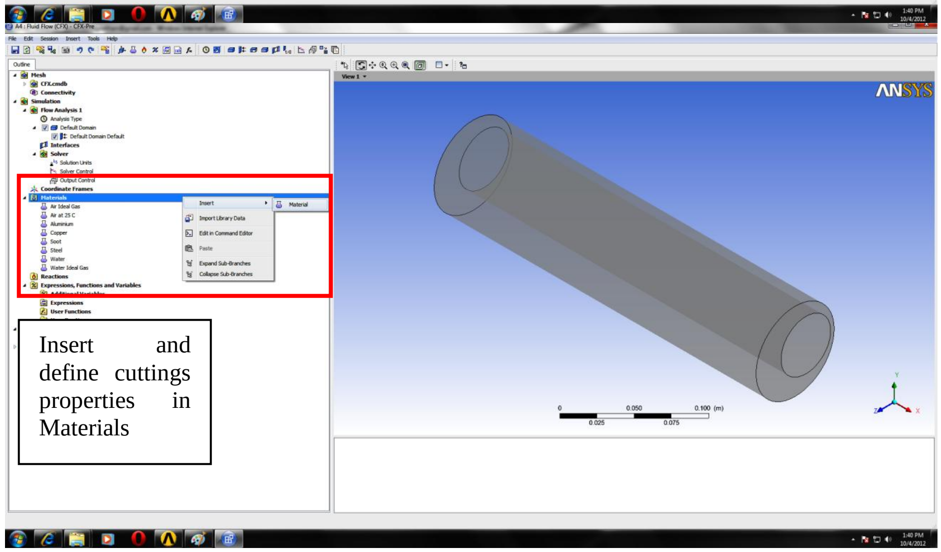
Outlet is defined. Repeat the process for inlet, outer wall and inner wall.

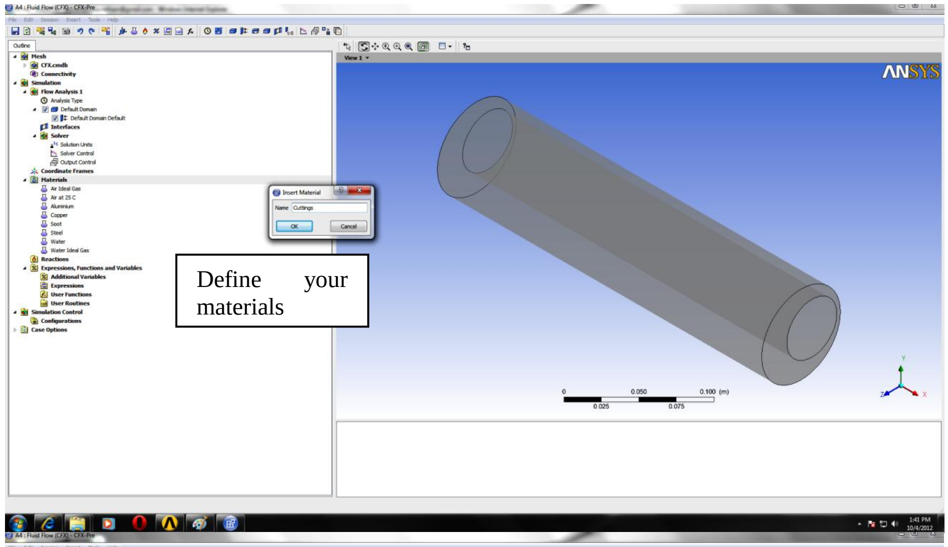


Click on Generate Mesh to discretize the model.

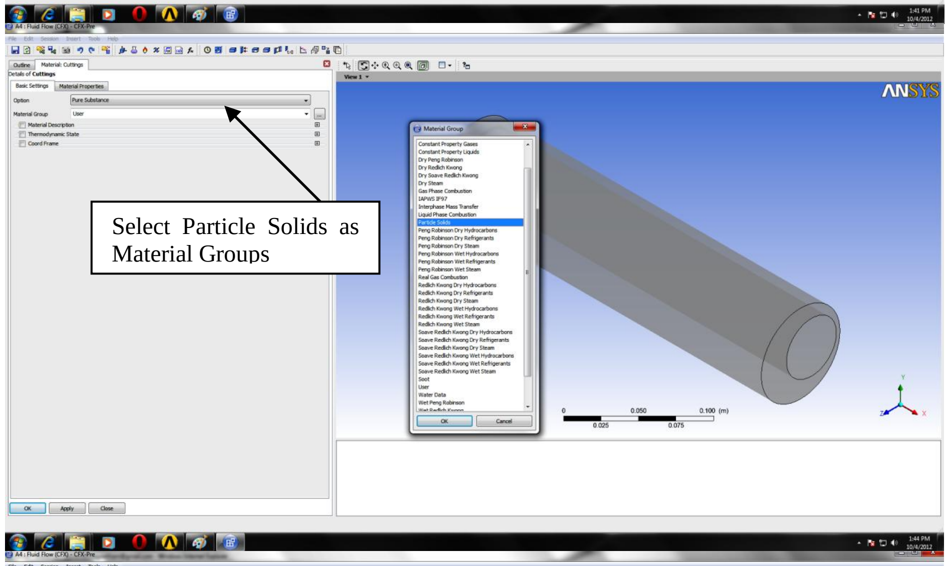

Make necessary changes in the meshing set up to produce finer mesh.


From Workbench, select CFX Pre.

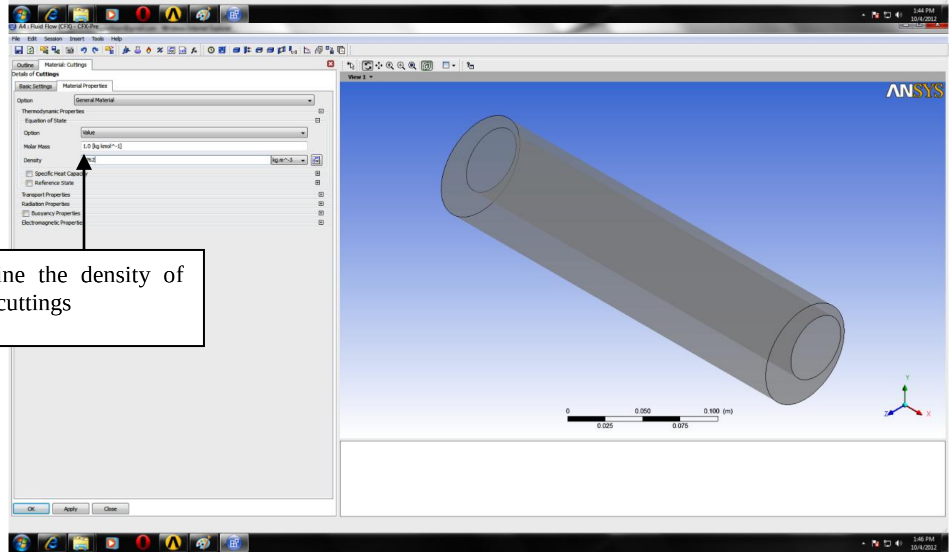

Insert and define cuttings properties in Materials



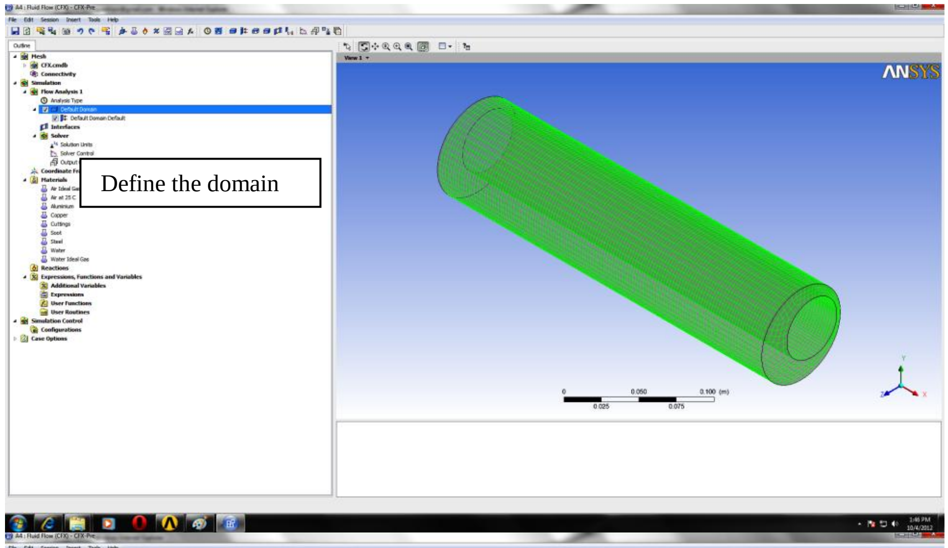
Define your materials

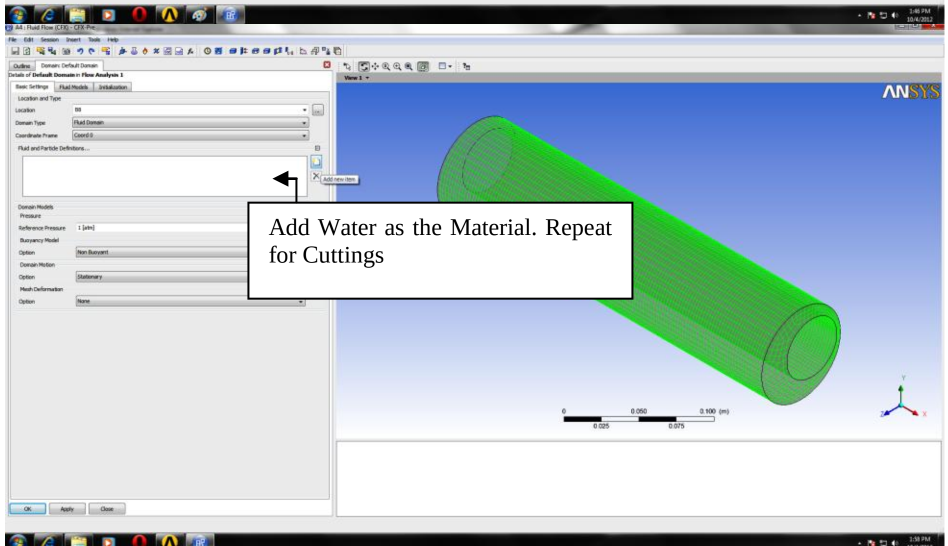


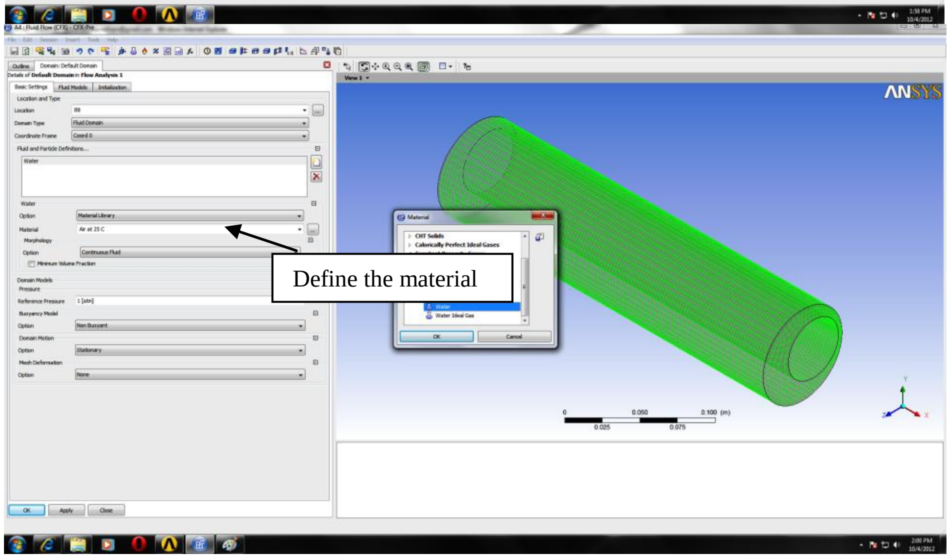
Select Particle Solids as Material Groups

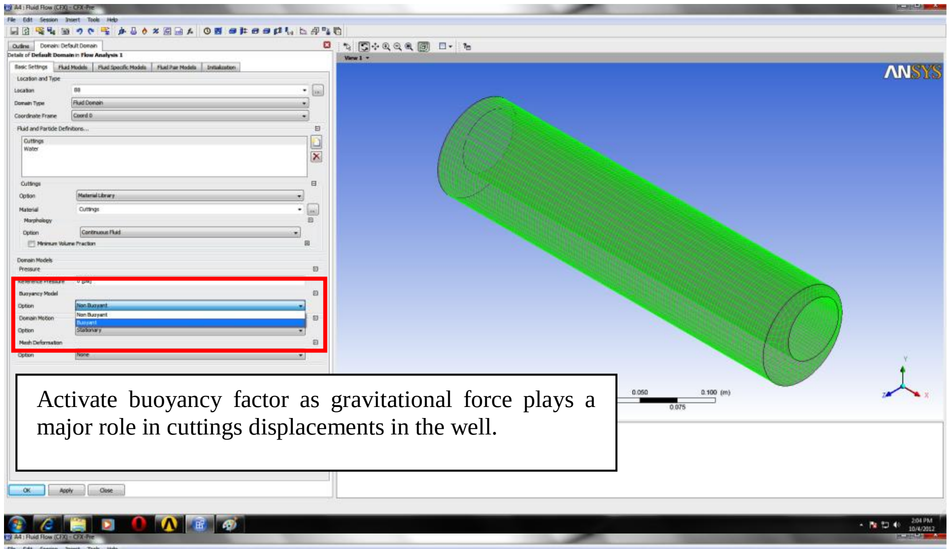


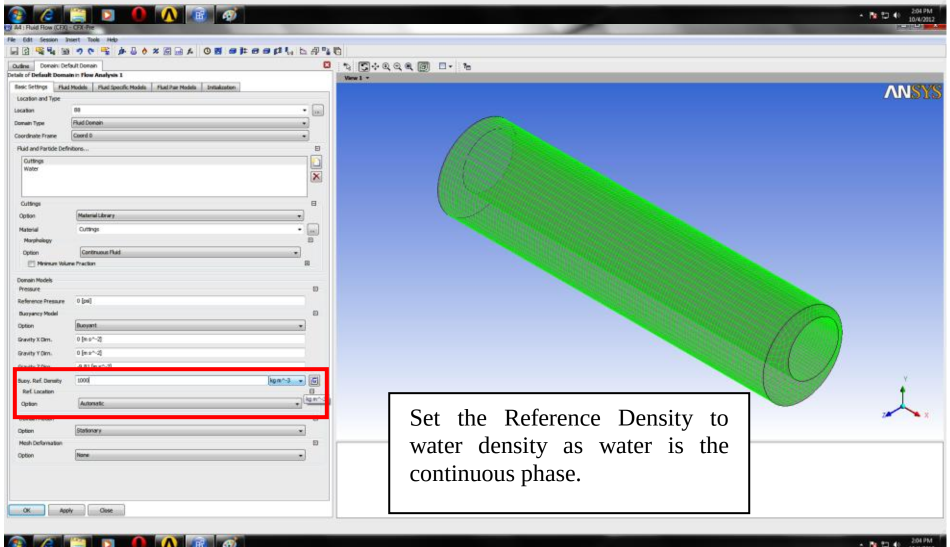
Define the density of the cuttings

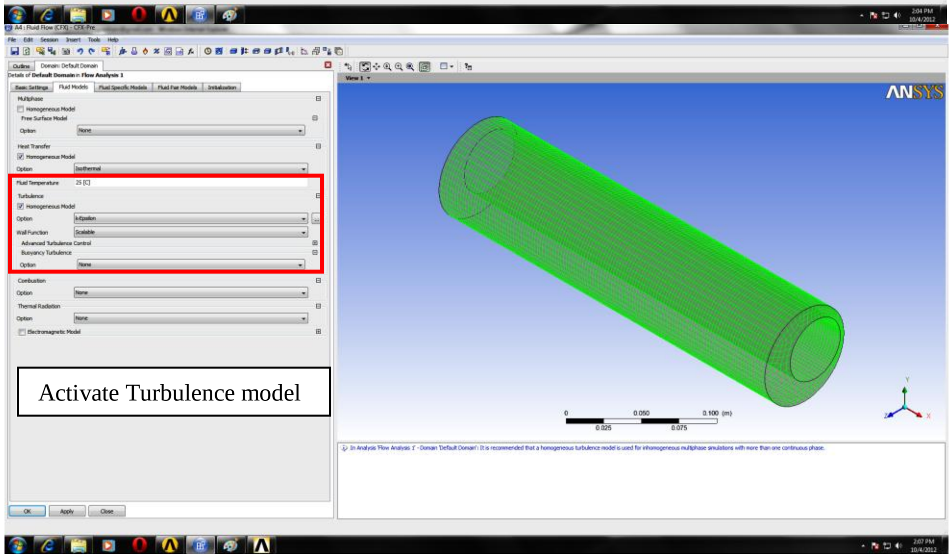

Define the domain

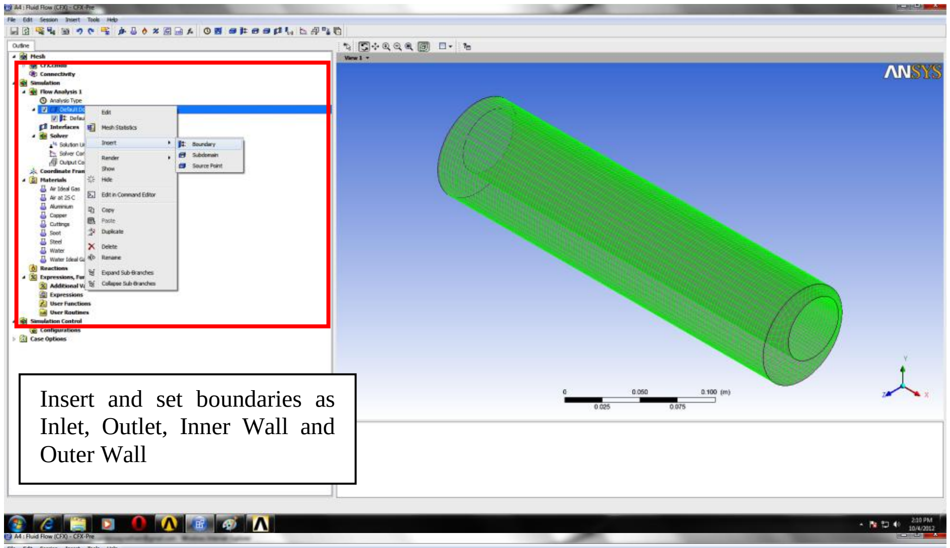

Add Water as the Material. Repeat for Cuttings

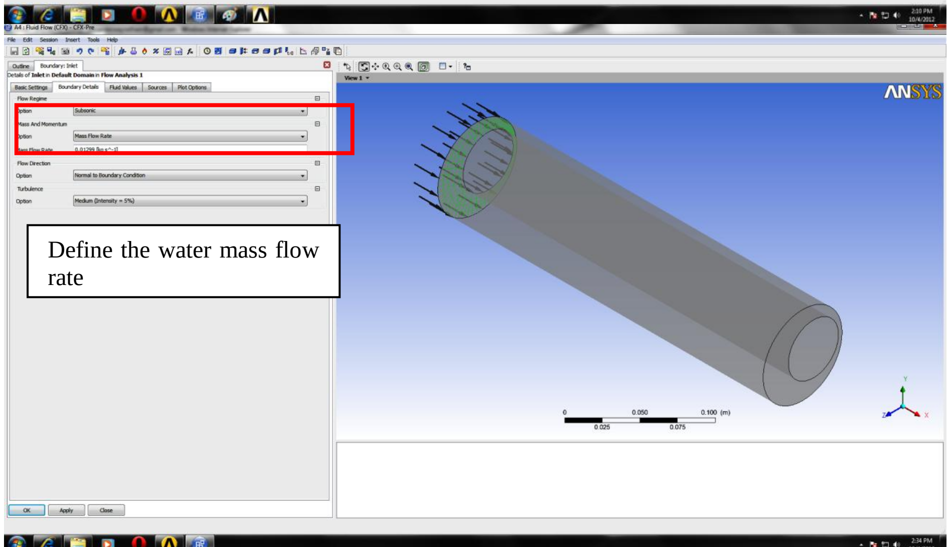

Define the material

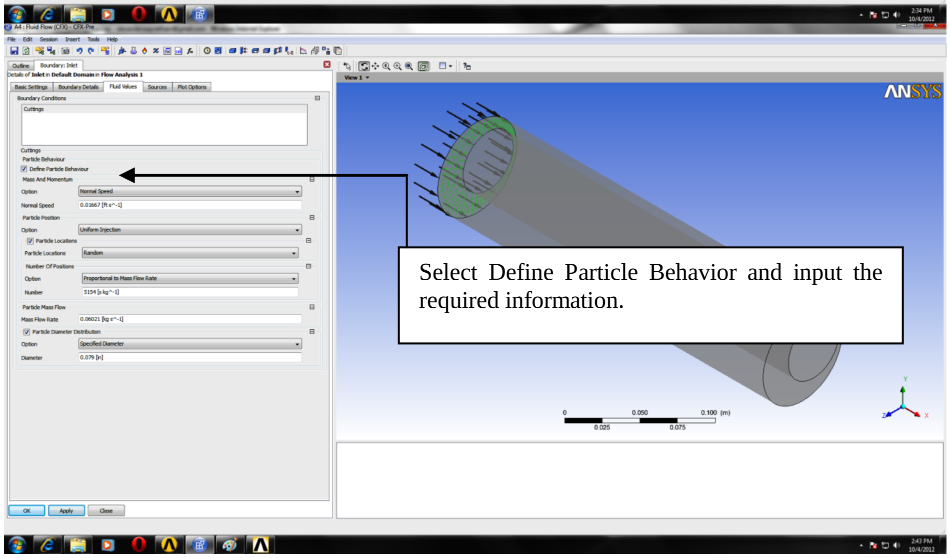

Activate buoyancy factor as gravitational force plays a major role in cuttings displacements in the well.

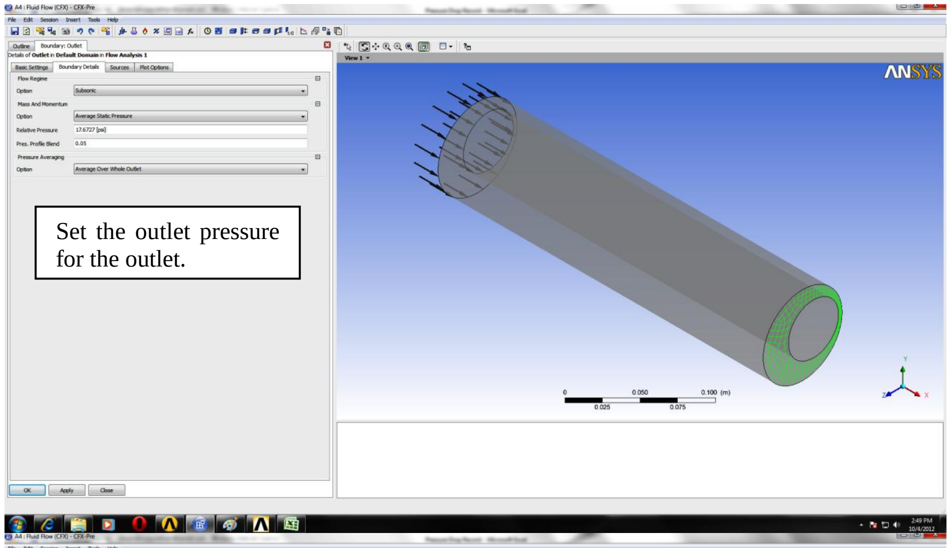

Set the Reference Density to water density as water is the continuous phase.

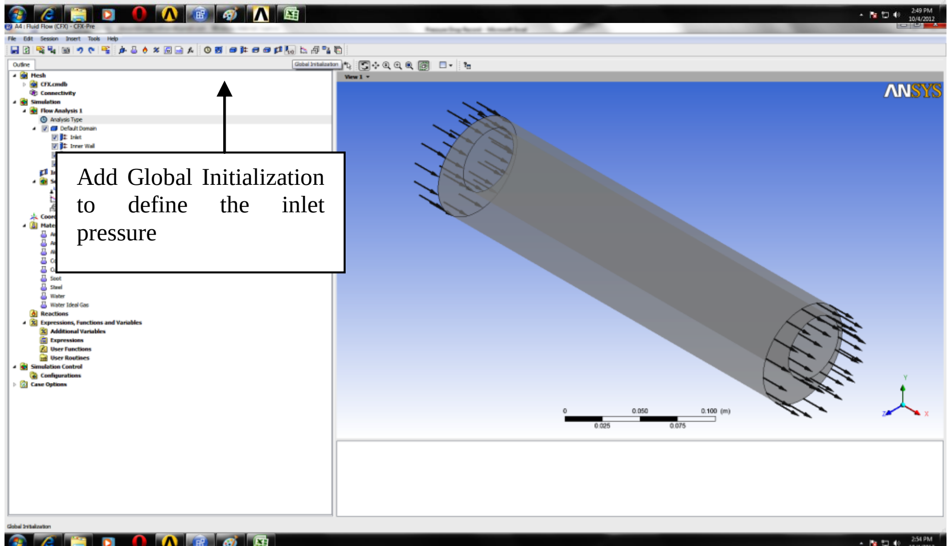

Activate Turbulence model

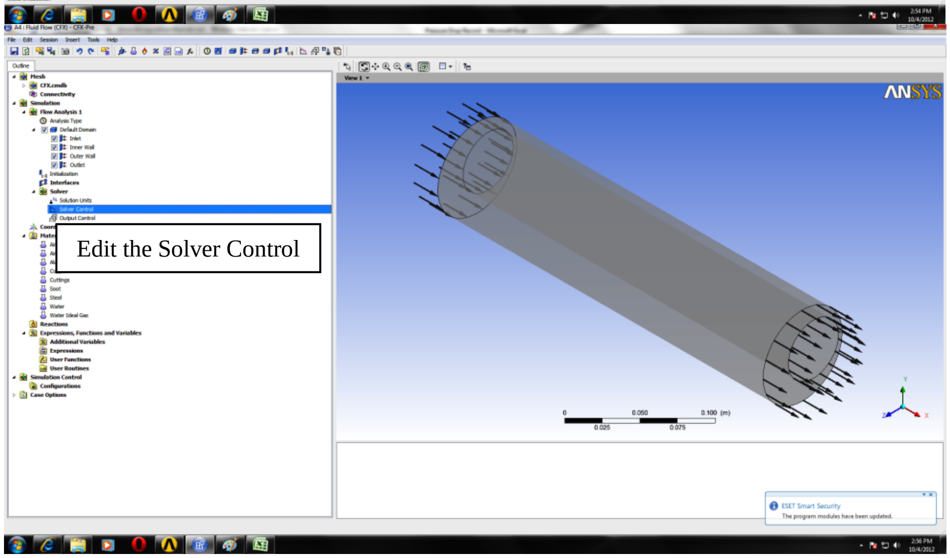

Insert and set boundaries as Inlet, Outlet, Inner Wall and Outer Wall

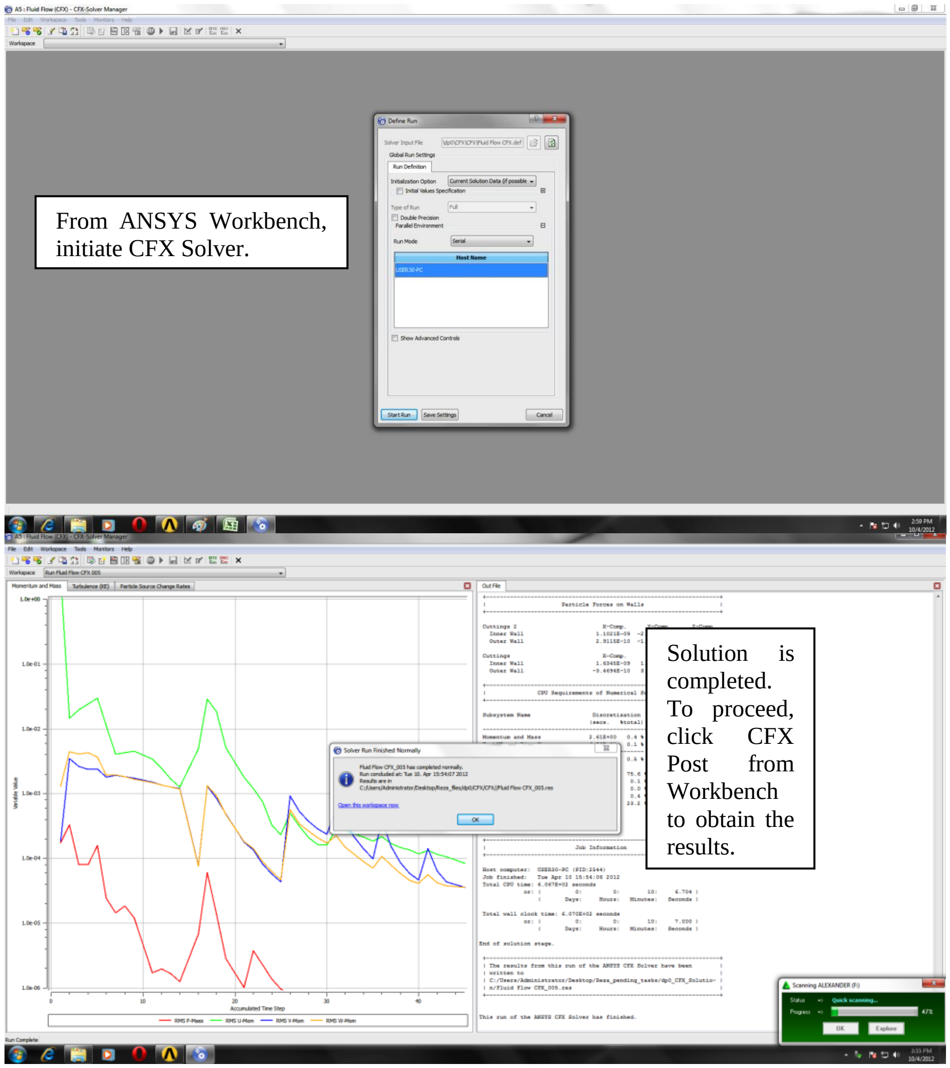

Define the water mass flow rate


Select Define Particle Behavior and input the required information.


Set the outlet pressure for the outlet.


Add Global Initialization to define the inlet pressure


Edit the Solver Control


From ANSYS Workbench, initiate CFX Solver.
Solution is completed. To proceed, click CFX Post from Workbench to obtain the results.

Appendix 2 - Annular Pressure Drop

ROP = 60 ft/ hr

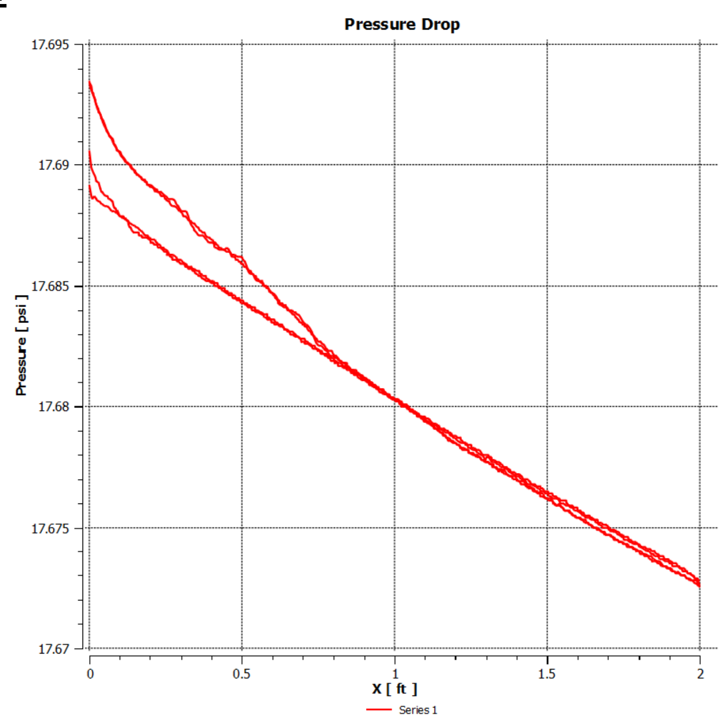


Figure 5.0: Annular Pressure Drop for Water Velocity 2 ft/s

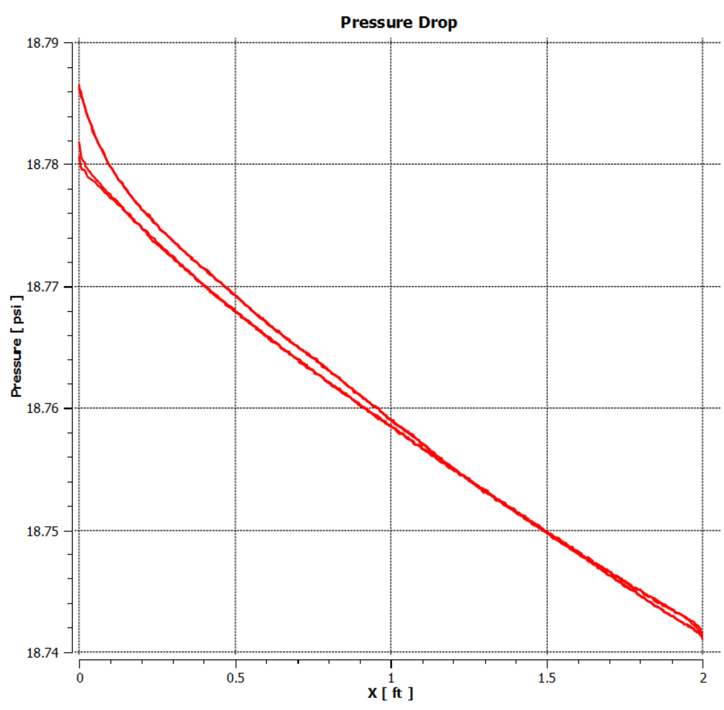


Figure 5.1: Annular Pressure Drop for Water Velocity 3 ft/s

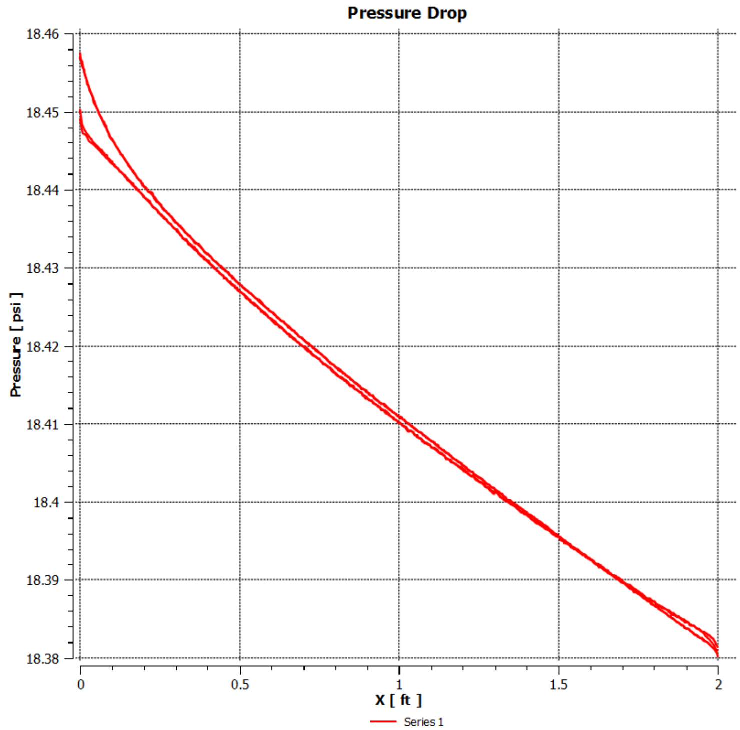


Figure 5.2: Annular Pressure Drop for Water Velocity 4 ft/s

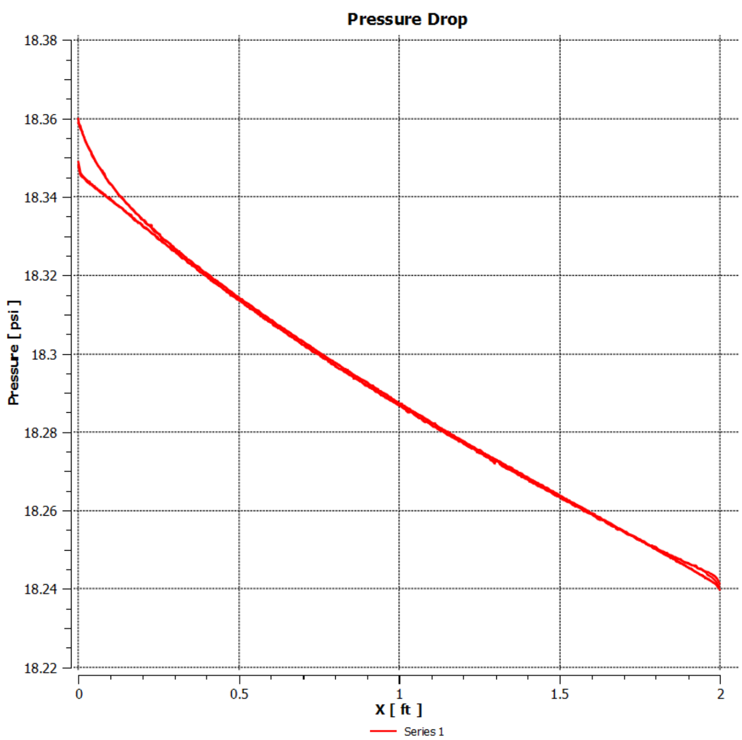


Figure 5.3: Annular Pressure Drop for Water Velocity 5 ft/s

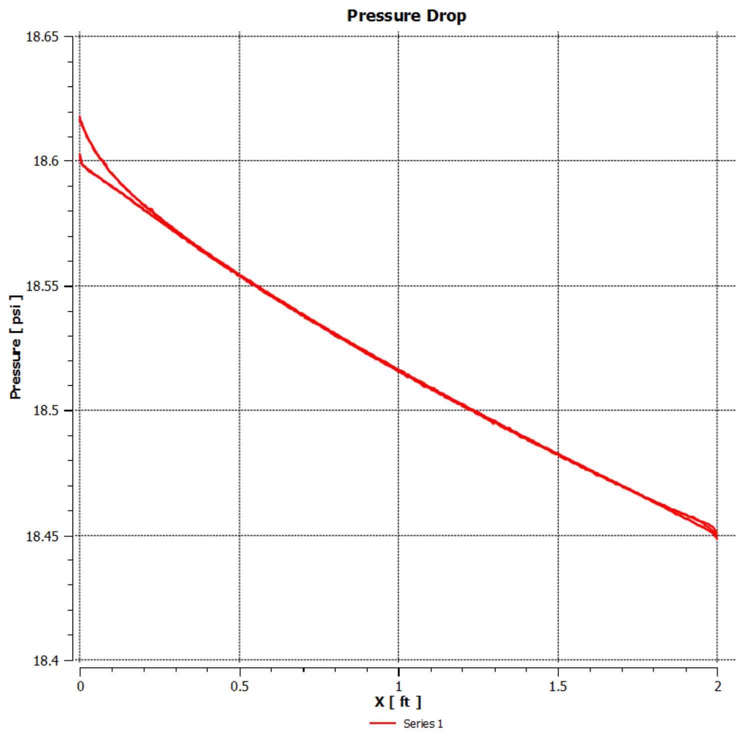


Figure 5.4: Annular Pressure Drop for Water Velocity 6 ft/s

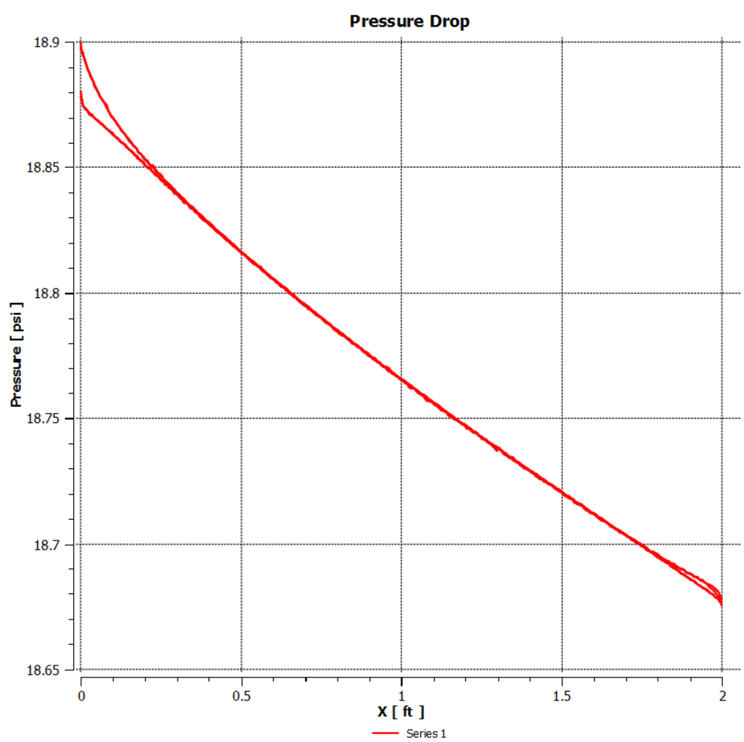


Figure 5.5: Annular Pressure Drop for Water Velocity 7 ft/s

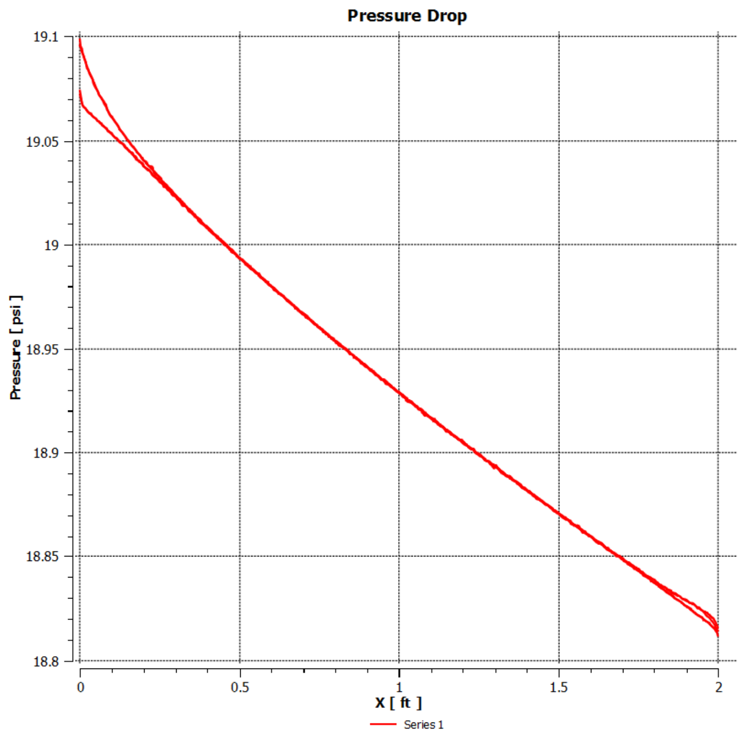


Figure 5.6: Annular Pressure Drop for Water Velocity 8 ft/s

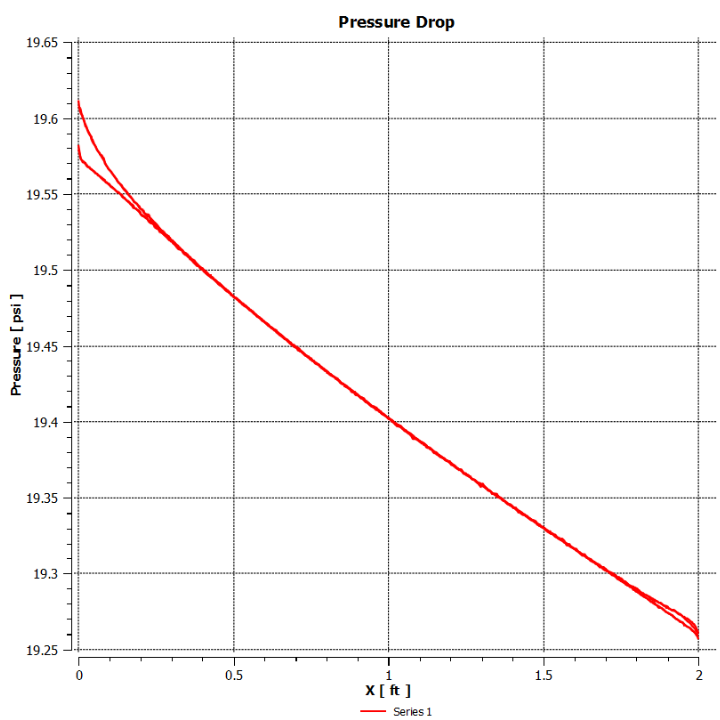


Figure 5.7: Annular Pressure Drop for Water Velocity 9 ft/s

ROP = 80 ft/hr

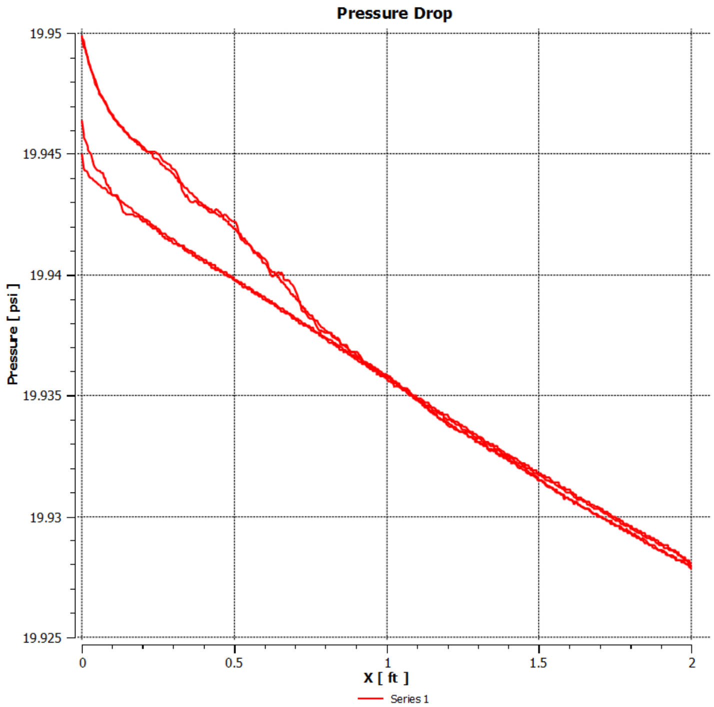


Figure 5.8: Annular Pressure Drop for Water Velocity 2 ft/s

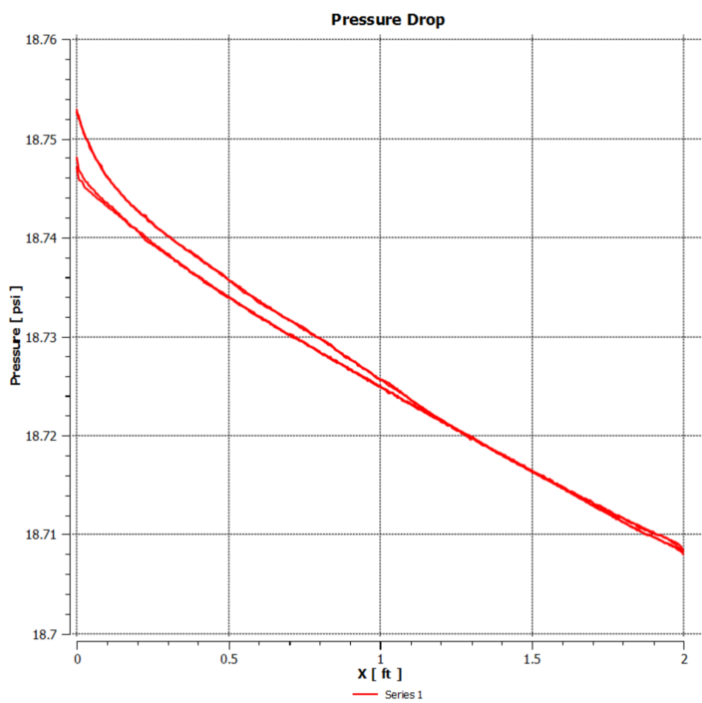


Figure 5.8: Annular Pressure Drop for Water Velocity 3 ft/s

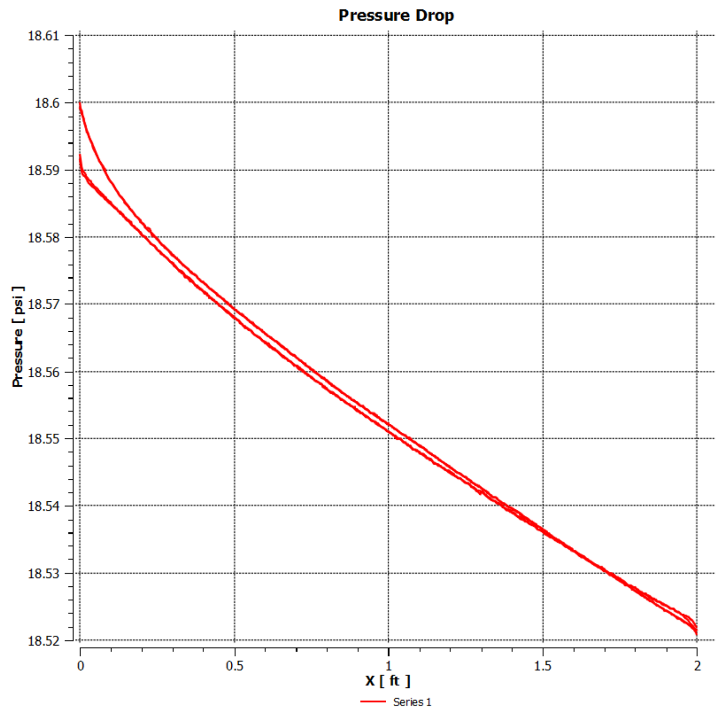


Figure 5.9: Annular Pressure Drop for Water Velocity 4 ft/s

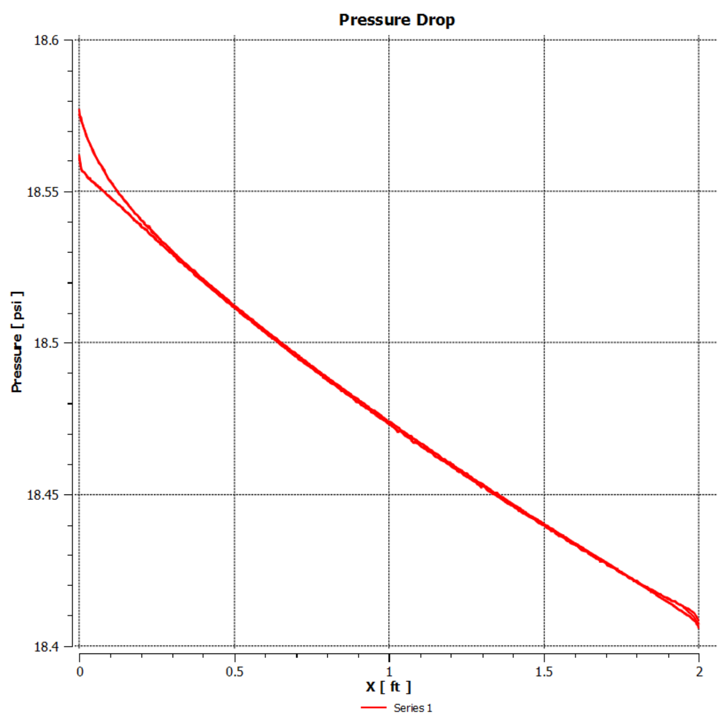


Figure 5.10: Annular Pressure Drop for Water Velocity 6 ft/s

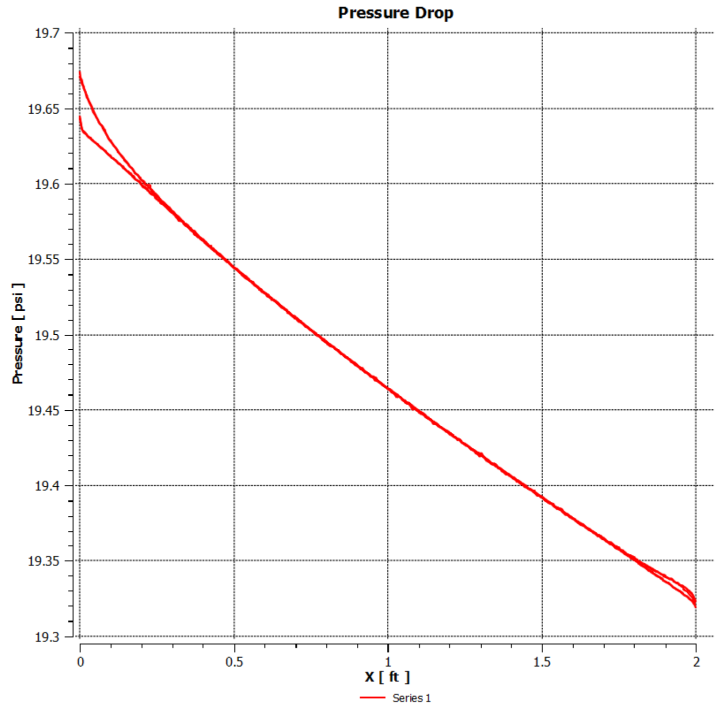


Figure 5.11: Annular Pressure Drop for Water Velocity 9 ft/s

Appendix 3 – Cuttings Concentration

ROP = 60 ft/hr

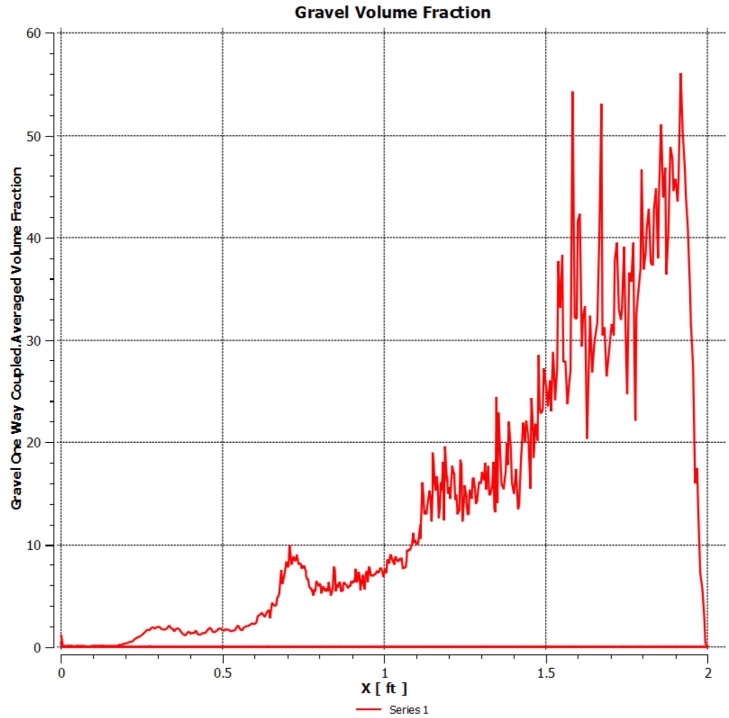


Figure 6.0: Cuttings Concentration for 2ft/s

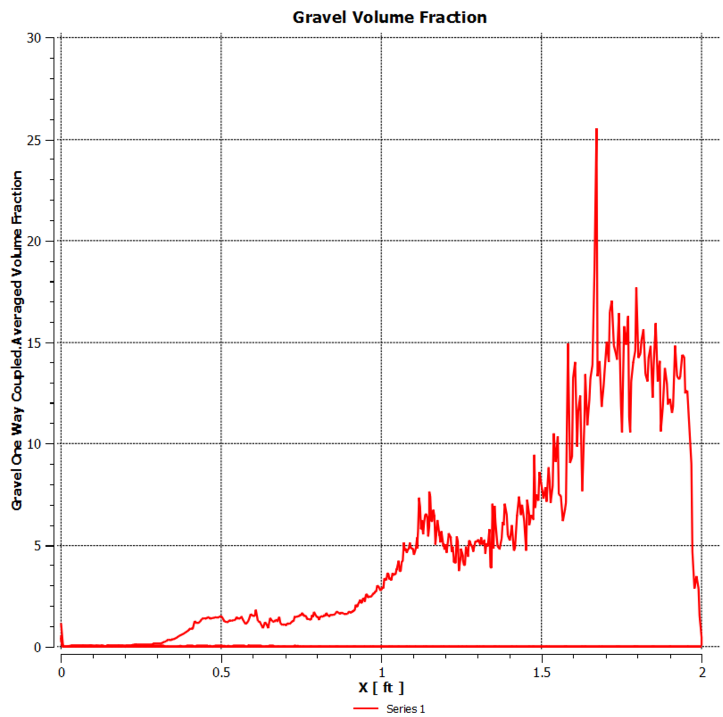


Figure 6.1: Cuttings Concentration for 3 ft/s

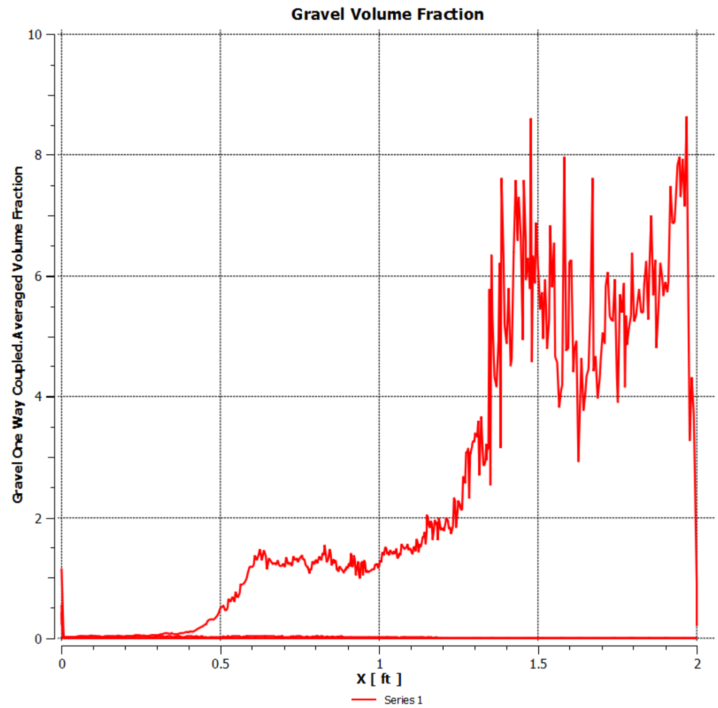


Figure 6.2: Cuttings Concentration for 4 ft/s

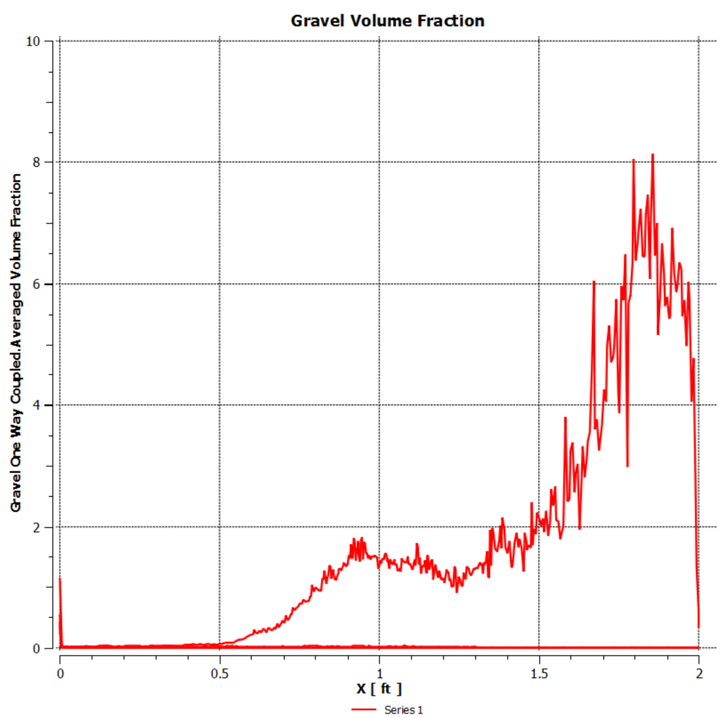


Figure 6.3: Cuttings Concentration for 5 ft/s

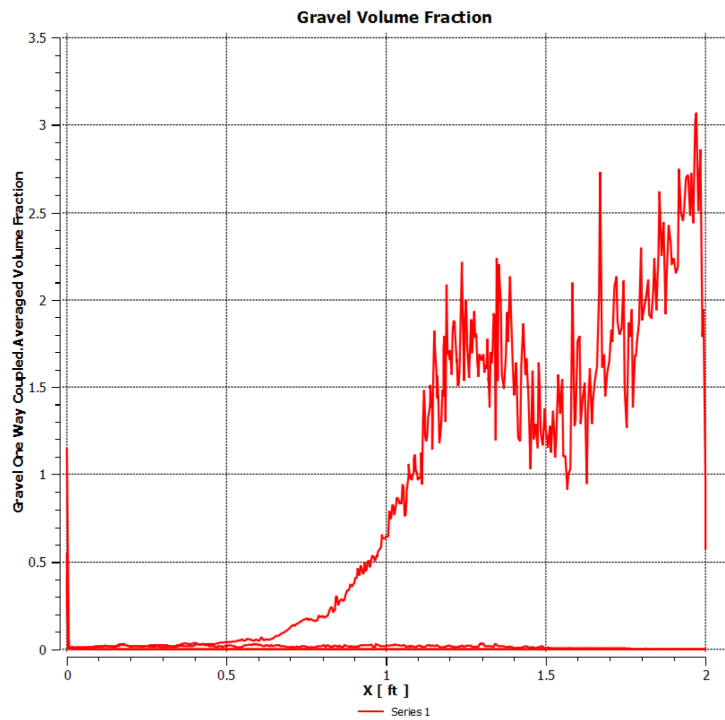


Figure 6.4: Cuttings Concentration for 6 ft/s

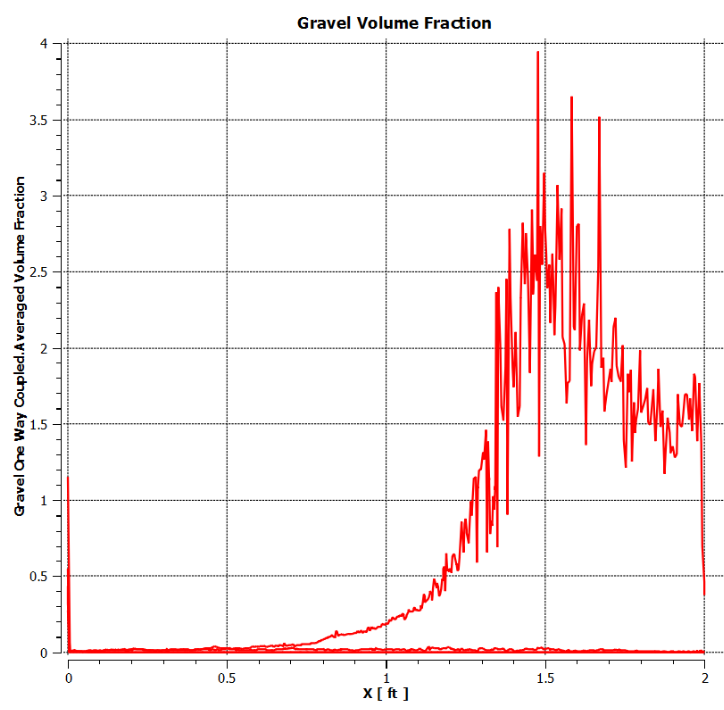


Figure 6.5: Cuttings Concentration for 7 ft/s

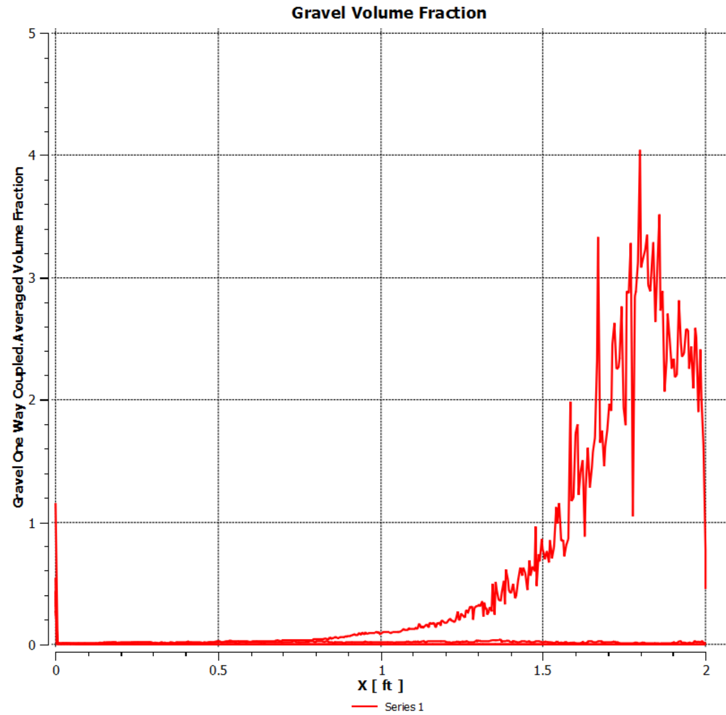


Figure 6.6: Cuttings Concentration for 8 ft/s

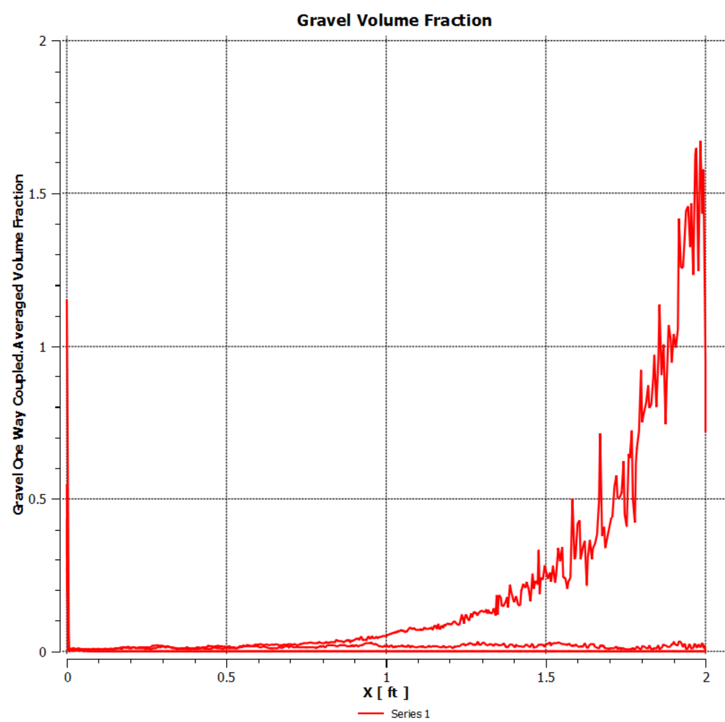


Figure 6.7: Cuttings Concentration for 9 ft/s

ROP = 80 ft/hr

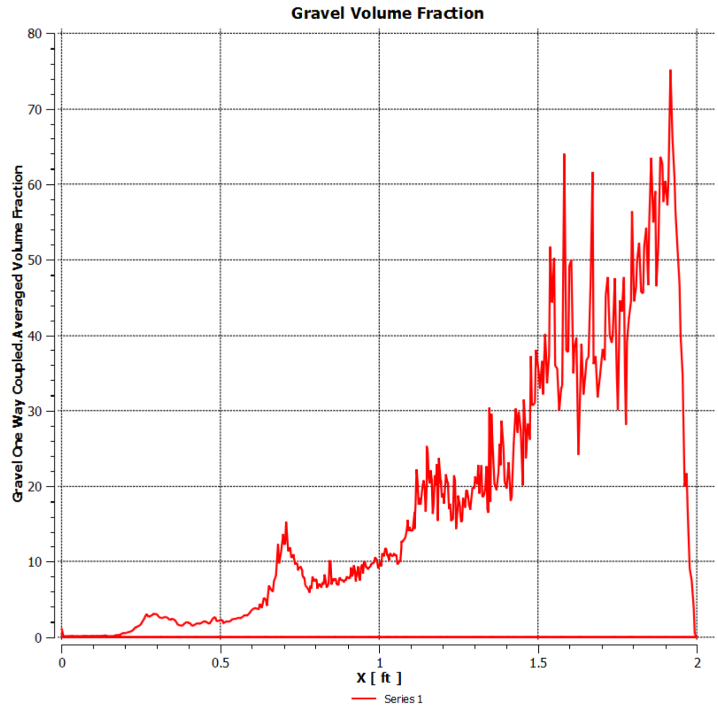


Figure 6.8: Cuttings Concentration for 2 ft/s

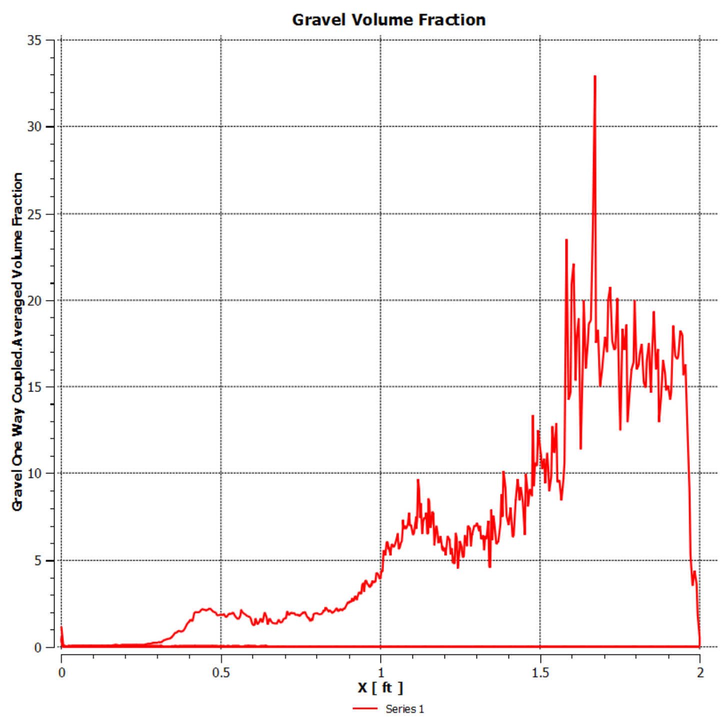


Figure 6.9: Cuttings Concentration for 3 ft/s

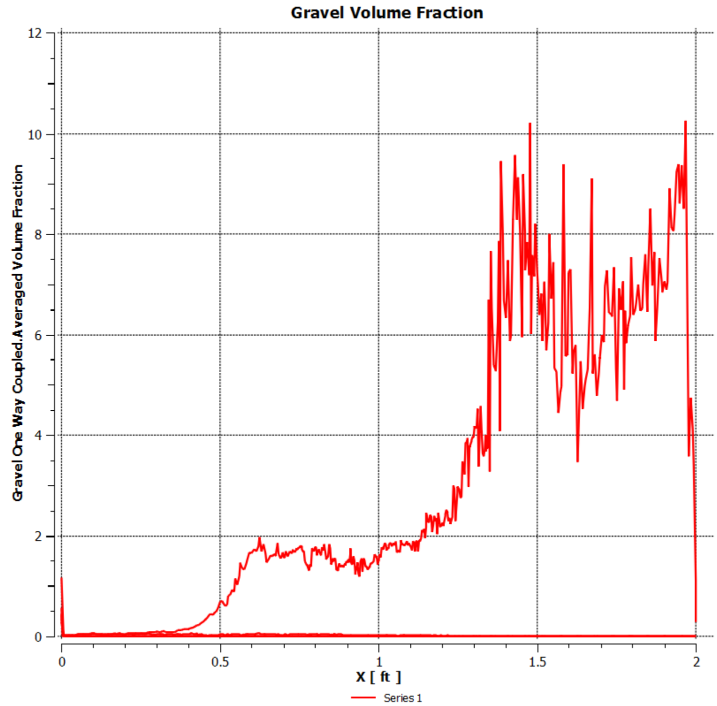


Figure 6.10: Cuttings Concentration for 4 ft/s

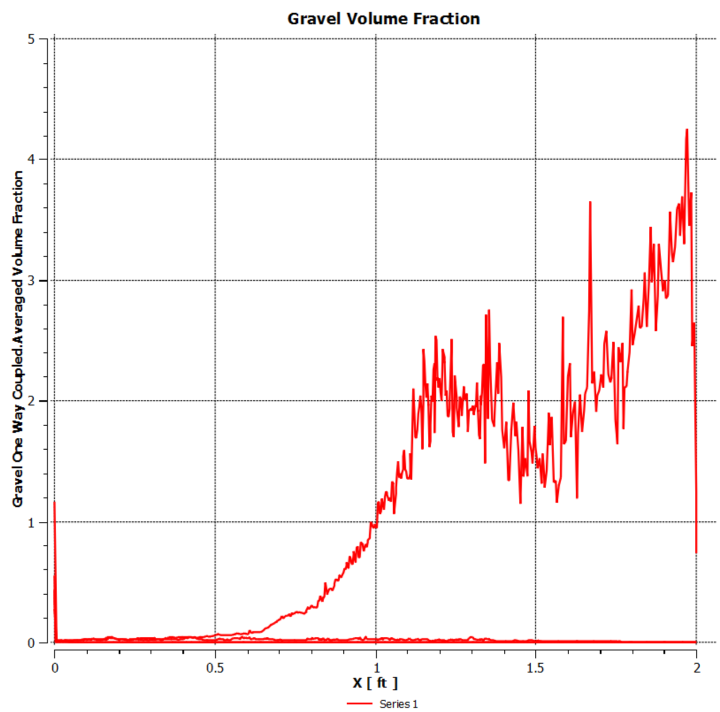


Figure 6.11: Cuttings Concentration for 6 ft/s

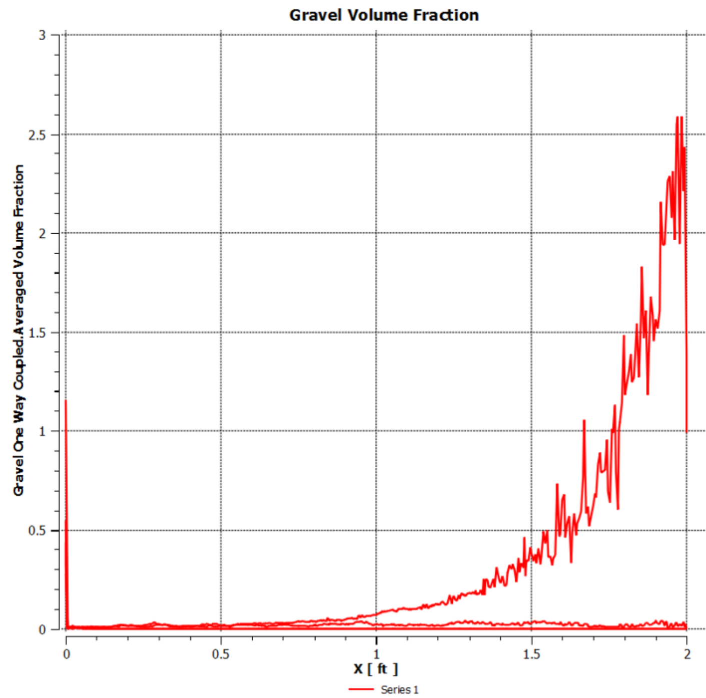


Figure 6.12: Cuttings Concentration for 9 ft/s