FACTORS AFFECTING PLASTERING EFFECT

IN CASING WHILE DRILINNG

by

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Dissertation submitted in partial fulfillment of

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

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Approved:

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Project Supervisor

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TRONOH, PERAK

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CERTIFICATE 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.

Aidil Aizat Bin Mohamad Farid

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Given this opportunity, I would like to acknowledge those who have been helping me, either directly or indirectly, in continue working on the project – starting from preliminary research, to the development phase and until the completion phase of this Final Year Project in Universiti Teknologi PETRONAS.

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ABSTRACT

Casing while Drilling is simultaneous process of drilling and running casing. One of the benefits using Casing while Drilling technology is plastering effect. Plastering effect or smearing effect is a process where cuttings and drilling mud are plaster to the borehole by force of casing due to small clearance between the annulus. This creates a thin mud cake that is less porous and less permeable, that helping to increase wellbore strength and reduce lost circulation during drilling. However, due to inconsistency of plastering effect during Casing while Drilling operation, it is hard to determine the factors that enhance plastering effect. The objective for this project is to determine the plastering effect factors using parametric studies. This project will focusing on vertical well and five drilling parameters. The parameters are casing size to wellbore size ratio, casing eccentricity, casing rotational speed, annular velocity and cutting volume fraction. For methodology, base case model is selected, such as the wellbore size of 0.4m and length of 4.2m. The simulation will be using two type of drilling fluid which is Newtonian and non-Newtonian fluid. Conclusion from the parametric study, in non-Newtonian fluid, the most contributing factors are cutting volume fraction, casing size to wellbore size ratio and casing rotational speed. While annular velocity and casing eccentricity does not contribute much. For Newtonian fluid, the most contributing factors are cutting volume fraction and casing size to open hole size ratio. While annular velocity, casing rotational speed and casing eccentricity still give lesser contribution in plastering effect. Comparing non-Newtonian and Newtonian fluid based on mud cake thickness and length, plastering effect are easily to produce in Newtonian fluid.

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ABBREVIATIONS AND NOMENCLATURES

Abbreviations

BHA	Bottom Hole Assembly
CFD	Computational Fluid Dynamics
CwD	Casing while Drilling
NPT	Non-productive Time
OBM	Oil Based Mud
ROP	Rate of Penetration
WBM	Water Based Mud

Nomenclatures

D_0	Wellbore Diameter (m)
D_i	Casing Diameter (m)
e	Casing Eccentricity
K	Viscosity Consistency Index (Pa.s)
L	Wellbore Length (m)
n	Power-Law Index
N_{Re}	Reynolds Number
r	Casing Size to Wellbore Size Ratio
R_0	Wellbore Radius (m)
R_1	Casing Radius (m)
V_1	Drilling Fluid Inlet Annular Velocity (m/s)
μ	Dynamic Viscosity (Pa.s)
ρ	Density (kg/m^3)
ω	Casing Rotational Speed (rpm)

CHAPTER 1

INTRODUCTION

This chapter consists of (1) project background, (2) problem statement, (3) objectives, (4) scope of study, and (5) significance of this project.

1.1 Project Background

Exploration and production drilling are facing an ever increase complex environment, requiring to overcome troublesome zones, depleted reservoirs and wells with severe wellbore instability. Casing while Drilling (CwD) have been introduced and becoming a trend in drilling operations replacing conventional drill pipe overcome challenges in drilling operations.

In CwD application, the well is drilled and cased simultaneously where casing are used as drill string replacing conventional drill pipe. CwD reduces and minimize the number of drilling trip and also amount of pipe handling. Using casing as a drill string compare to drill pipe will give different size ratio of drill string to hole size. Large size of casing give bigger ratio size and small annular between casing and hole compared to drill pipe that have small diameter (Karimi et al., 2011).

Using CwD technology give a lot of benefits and advantages in drilling operations. CwD help to reduce the non-productive time (NPT) especially related to well control, stuck pipe and lost circulations. Using casing to drill helps to avoid unexpected, dangerous and potentially costly event such as blowout (Fontenot et al, 2005).

Besides that, plastering effect or smearing effect is a benefits that CwD technology offers in drilling operation. Drilling using casing as drill string that have large diameter size and small wellbore annular size create a mechanical plastering of drill cutting into the surface of the wellbore. This plastering effect builds impermeable filter cake or mud cake to strengthening and mitigate lost circulation problem. There are factors contributing to plastering effect. Therefore, to benefit the plastering effect in drilling operation, this project will focusing on factors affecting plastering effect.

1.2 Problem Statement

From all of the benefits and advantages in CwD application, plastering effect is one of the benefit that CwD technology user looking forward to obtain. This is because in plastering process of cutting onto the wellbore surface it will create less thin and less permeable mud cake to increase wellbore strength and reduce lost circulation during drilling operation (Karimi et al, 2011).

However, due to inconsistency of plastering effect during CwD operation, it is hard to determine the factors that enhance plastering effect. In fact, the effect of plastering effect on the thickness of mud cake cannot be seen or observe during operation. In addition, theoretical studies on plastering effect are limited, and there is no research nor study found in the open literature.

1.3 Objectives

The objectives of this project are:

1. To produce plastering effect using different drilling parameter and condition such as drilling fluid viscosity, eccentricity of the casing, casing rotational speed, drilling fluid flow rate and ratio of casing to open hole size
2. Parametric study on the drilling parameters to determine the factors enhancing plastering effect by analyzing the thickness of mud cake form on the wall of wellbore.

1.4 Scope of Study

This project is research study base on software simulation. The simulation model will focusing on vertical well with five factors drilling fluid viscosity, eccentricity of the casing, casing rotational speed, drilling fluid flow rate and ratio of casing to open hole size.

1.5 Significant of Study

There is no research or studies related to factors affecting plastering effect in CwD. In this study, the factors can be determine through the parametric simulation base on five drilling parameters and condition. By knowing the factors, CwD operation can be optimize to obtain plastering effect that help to mitigate lost circulation and increase wellbore strength.

1.6 Outline of Thesis

Appropriate analysis is required to investigate the factor affecting plastering effect in Casing while Drilling. The contributions of present study for this interim report are presented in four chapters. An overview of each chapter is given below.

Chapter one introduced CwD and plastering effect, problem statement, objectives and scopes of research.

Chapter two presents the review of the available studies and theory related to CwD plastering effect.

Chapter three presents the methodology used for CwD plastering effect simulation. The assumptions, mathematical formulation and boundary conditions are discussed in detail in this chapter.

Chapter four show the expected results for this study. While, chapter five draws conclusion and makes recommendation from the analysis conducted.

CHAPTER 2

LITERATURE REVIEW

The literature review for this project will be in fragmented flow which consists of (1) Casing while drilling, (2) plastering effect, (3) factors affecting plastering effect and (4) concluding remarks.

2.1 Casing while Drilling

Casing while Drilling is a beneficial technology where drilling process and running in casing are done simultaneously. Casing is used replacing conventional drill pipe as drill string (Mohammed et al., 2012). While a top drive mechanism provides the mechanical and hydraulic energy to the casing string and its pilot bit. Drilling fluid is circulated down through the casing string and circulated up through the annulus, which has a smaller annulus compared to conventional drilling (Arlanoglu, 2011).

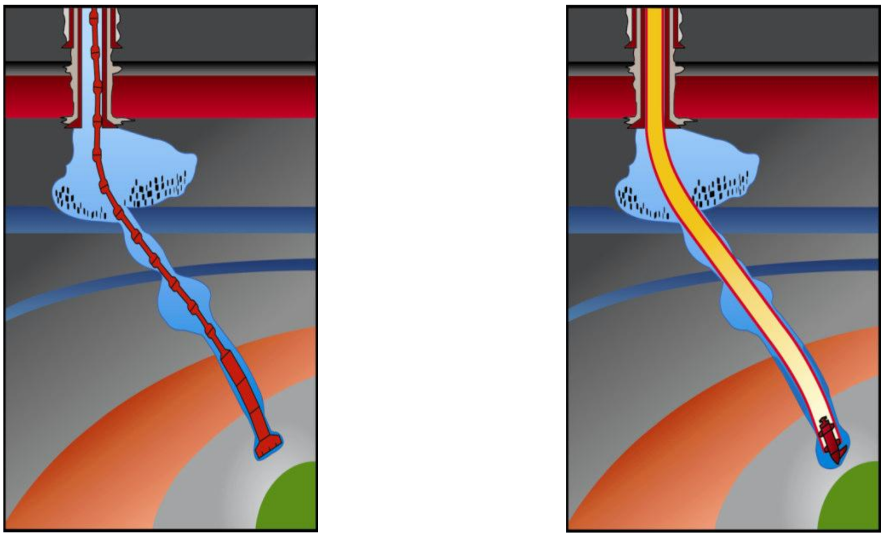


Figure 2.1: Conventional vs CwD (Tessari, 2009)

There are many types of CwD application. According to Fontenot et al. (2005), CwD can be summarized into three main type based on the CwD bottom hole assembly (BHA) configuration. The types of CwD are:

- Non-retrievable Drilling BHA for Casing
- Retrievable Drilling BHA for Casing
- Retrievable BHA for Liner Drilling

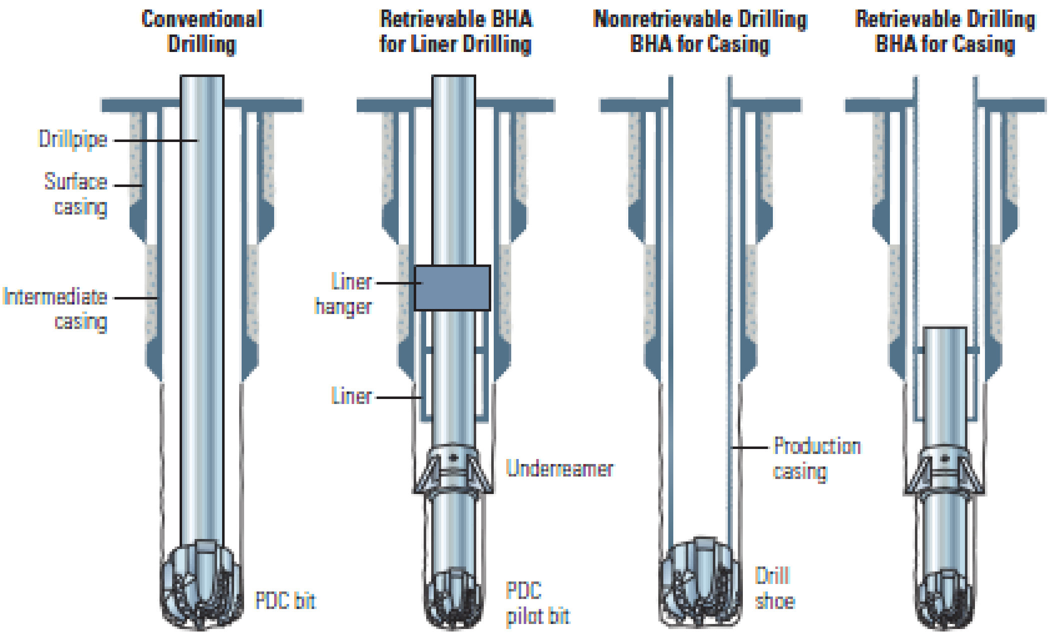


Figure 2.2: Type of CwD BHA Configuration. (Fontenot et al., 2005)

Nowadays, Casing drilling have been a popular choice against conventional drilling, because casing drilling offers several benefits that helpful to mitigate wellbore stability issues and lost circulation problems. Studies from Moellendick and Karimi (2011) and Erivwo et al. (2012) state several benefits of Casing while drilling;

- No Tripping
- Gauged Well
- Less Drilling Time
- Efficient Borehole Cleaning
- Superior Hydraulic
- **Plastering Effects**

2.2 Plastering Effects

In casing drilling, the main advantages using this technology and wanted to be utilize by everyone is plastering effect. Plastering effect or smearing effect is a process of mud fluid and cuttings were embedded to the borehole by force of casing due to small clearance between the annulus (Arlanoglu, 2011). Moellendick and Karimi (2011) believe that plastering effect is a smearing process of casing and filter cake or mud cake to the wall creating thin and less permeable and less porous of mud cake compare to conventional drilling.

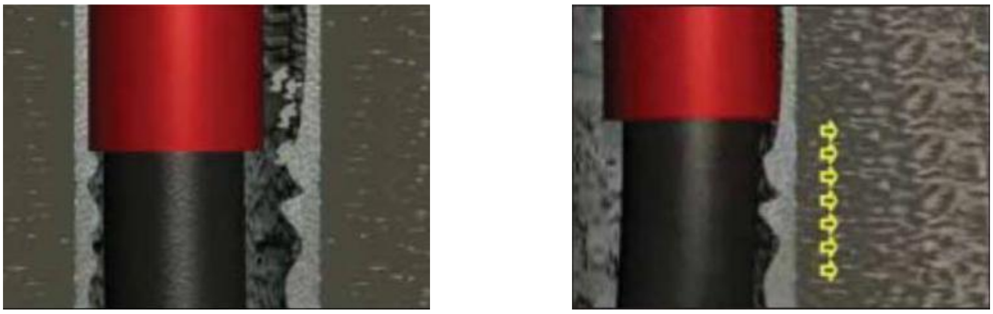


Figure 2.3: Casing is force against bore wall, smearing mud cake and sealing porous formations by producing thinner mud cake. (Moellendick & Karimi, 2011)

Mokhtari et al. (2012) stated that plastering effect theory backed by smaller cuttings at the shale shaker. The size of cuttings using CwD is finer than conventional drilling. In addition, to support plastering effect, the amount of cuttings also 10% to 20% less at the shaker (Tessari, 2009).

Figure 2.4: Fine Cuttings at Shaker in CwD Application
(Tessari, 2009)

Watts et al. (2010) and Samuel and Kumar (2013) relate plastering effect to the idea of stress caging that benefit to the industry. While drilling process occur, crack form at the wellbore due to low fracture gradient. Therefore, in plastering effect, when cuttings and mud particles were smear by force into the gap or crack formed, it create a bridge or wedge between the cracks that increase the hoop stress around the wellbore, simultaneously raise the fracture gradient of the wellbore and helps in wellbore strengthening. In this case Arlanoglu (2011), report that well can be drill by using higher equivalent circulating density (ECD). This phenomena is corresponds to Alberty and McLean (2004) stress caging idea.

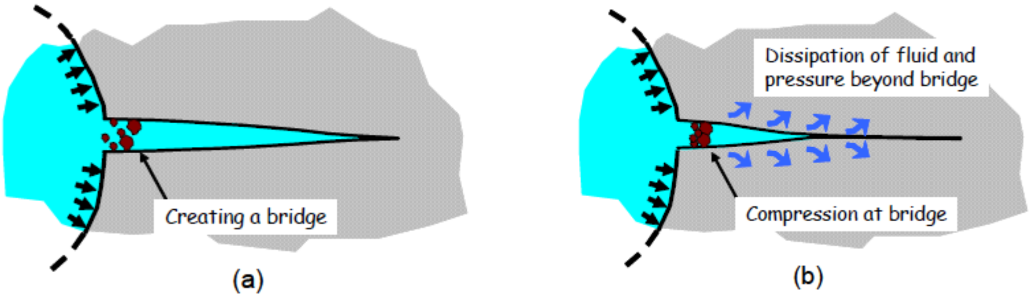


Figure 2.5 : Stress Caging Idea. (Alberty & McLean, 2004)

Beside increase wellbore strength and stability, plastering effect offers reduction of fluid/mud loss. Plastering effect producing a thin mud cake, which is less porous and less permeable due to smashing between casing and mud cake to the wall of borehole. Less porous and less permeable mud cake will prevent the mud passing through it to enter the formations (Karimi et al., 2011).

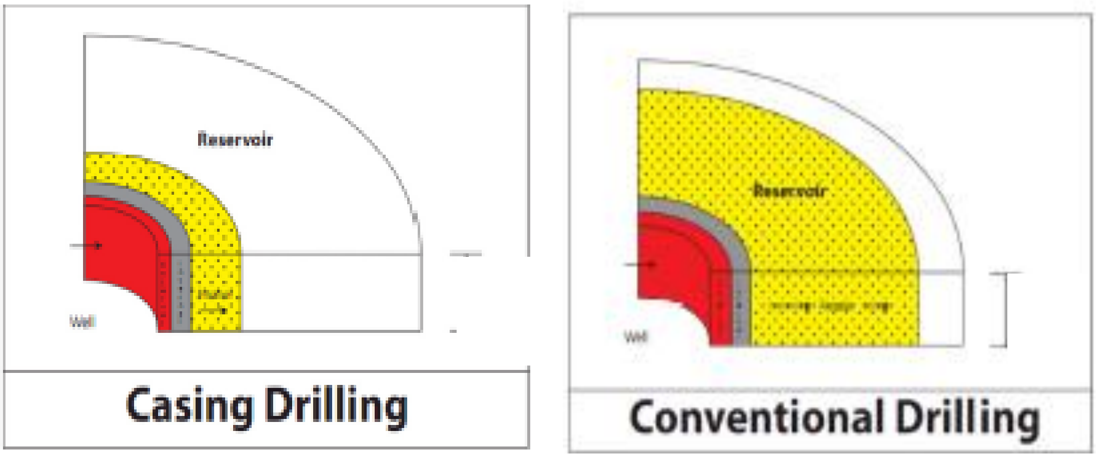


Figure 2.6: Comparison of mud cake thickness between CwD and Conventional Drilling. (Karimi et al., 2011)

2.3 Factors of Plastering Effect

Observation and experience during casing drilling operations, theories have been made to predict all the possible factors of plastering effect. From different drilling parameter, formation type and different configurations, researchers have made some conclusion on the factors.

2.3.1 Particle Size of Cutting

From case study reported by Watts et al. (2010), he proved that particle size of cutting can affect the plastering effect by observing the wellbore strength through Leak-Off Test (LOT). Watts et al. (2010), observing CwD operations using different particle size distribution by adding particle to the mud such as calcium carbonate. In Alaska test, at Kuparuk and Tarn field, Watt et al. conclude that "Wellbore strengthening with CwD has been achieved by filling in the particle size distribution from 100 microns to 2000 microns. Other CwD application may require a different particle size distribution."

2.3.2 Ratio of Casing to Open Hole Size

Karimi et al. (2011) state that to create the benefits attribute to the plastering effect, necessary pipe size relative to hole diameter is a key element. Comparing to the convention drilling, pipe size is smaller, therefore less interaction between the pipe and the formation. In addition, if drill pipe contacts the wellbore, this erratic motion can cause damage to the mud cake rather than healing or improving it. Casing Outer Diameter (OD)/Hole size ratio is the main criterion to evaluate the annulus geometry.

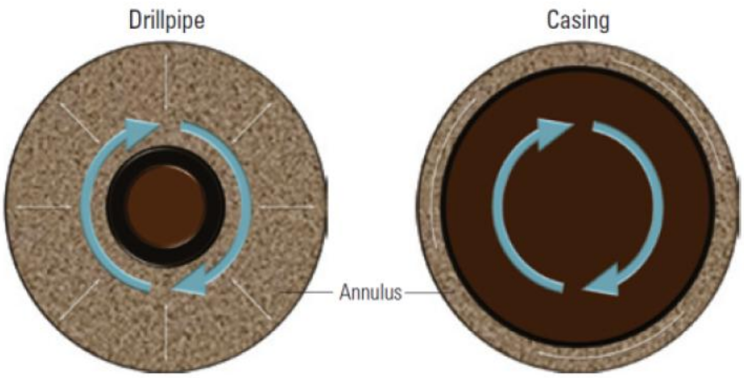


Figure 2.7: CwD Annulus comparison with conventional drilling.

(Karimi, Moellendick, et al., 2011)

Table 2.1 below shows the summary of the casing OD and hole size prepared by Karimi et al. (2011).

Table 2.1: Summary of Casing OD to Holes Size ratio

Casing size, inch	Hole diameter, inch	Ratio
7	8 7/8	0.79
7	8 3/4	0.80
13 3/8	17 1/2	0.76
20	24	0.83
9 5/8	12 1/4	0.79
18 5/8	22	0.85
13 3/8	17 1/2	0.76
9 5/8	12 1/4	0.79
7 5/8	9 7/8	0.77
7	8 1/2	0.82
7 5/8	8 7/8	0.86
13 3/8	17 1/2	0.76
18 5/8	22	0.85
8 1/2	7	0.82
8 1/2	7	0.82
12 1/4	9 5/8	0.79
10 5/8	9 5/8	0.91

From geometrical study from Karimi et al. (2011) authors conclude that plastering effect has been most effective when the ratio is between the range of 0.75 and 0.9. The reasonable number to be consider when choosing the ratio for well planning is 0.8.

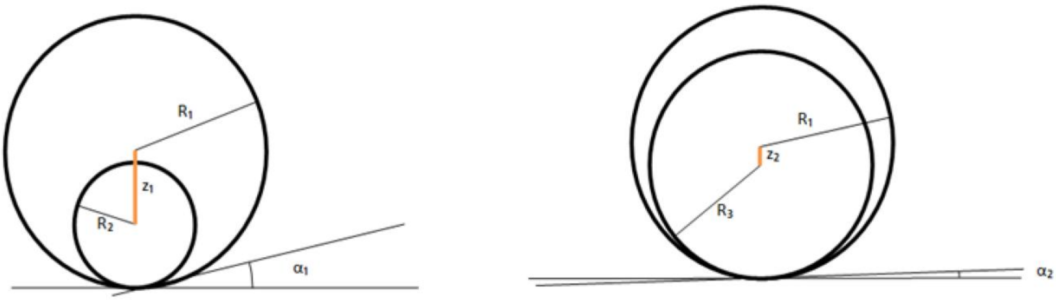


Figure 2.8: Casing Drilling & conventional drilling pipe geometry
(Karimi et al., 2011)

2.3.3 Casing Eccentricity

In conventional drilling, drill pipe eccentricity usually has a tendency in deviated and horizontal wells. However, in casing drilling, due to small annulus clearance, eccentricity is easier to occur(Mokhtari et al., 2012).Casing eccentricity is important where it reduce the velocity at the narrow section of eccentric annulus helps in mud cake build up. Fisher et al., (2000), studies on mud cake build up on eccentric drill pipe model. The study outcome is almost the same to Mokhtari et al. (2012) where mud cake build up dominant at region where drill pipe close to the wall of bore hole.

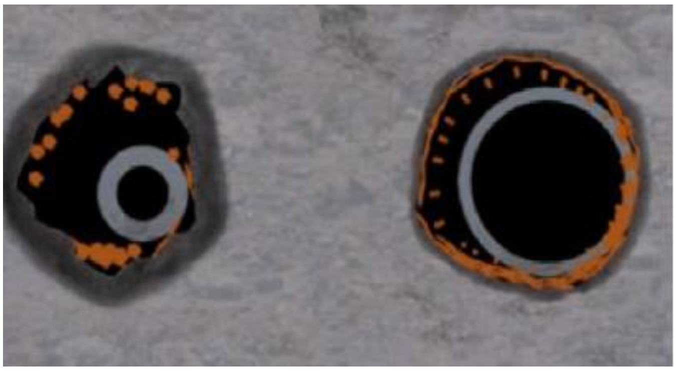


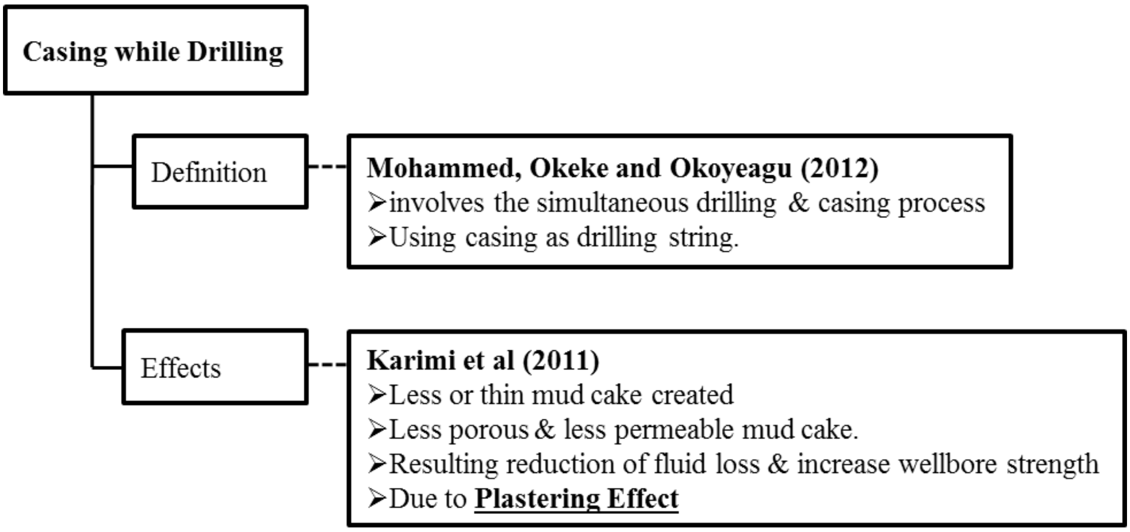
Figure 2.9: Eccentricity of CwD and conventional drilling.
(Moellendick & Karimi, 2011)

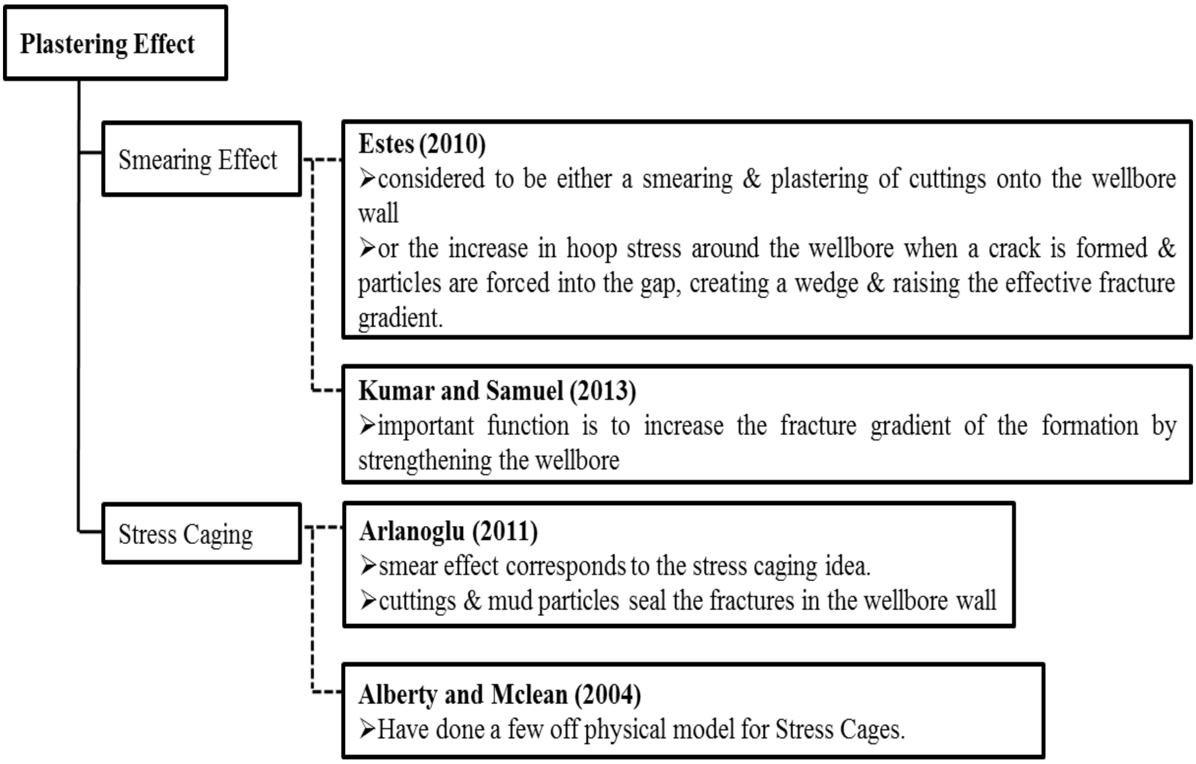
2.3.4 Casing Rotational Speed & Fluid Flow Rate

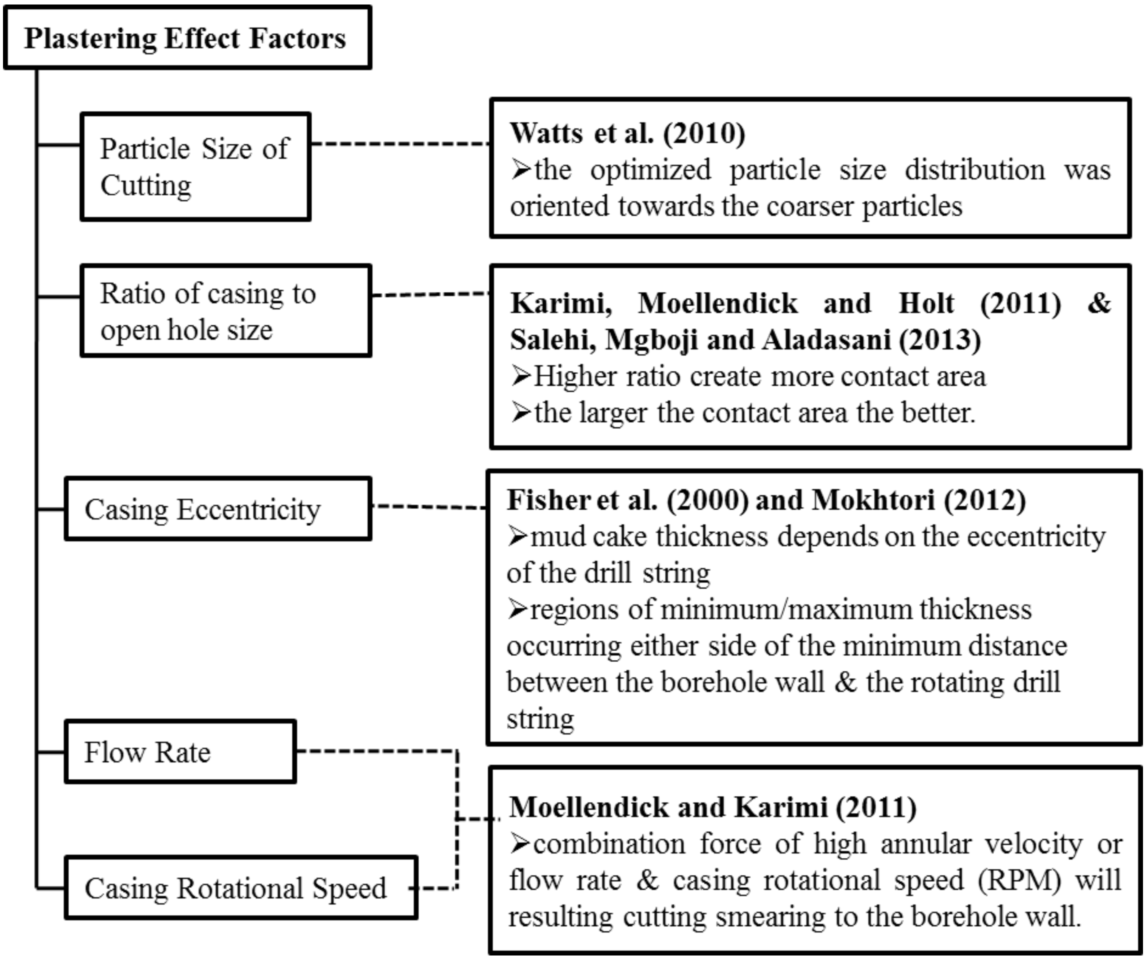
In casing drilling, velocity in annulus is much higher compare to conventional drilling if using the same flow rate. Mokhtari et al. (2012) recommended lower flow rate for casing drilling because low flow rate in casing drilling will still produce high velocity in annulus. With combination of eccentricity flow rate can be 50% higher in narrow section.

2.4 Concluding Remarks

The literature review can be summarize as below:






Plastering Effect Factors
Particle Size of Cutting
Ratio of casing to open hole size
Casing Eccentricity
Flow Rate
Casing Rotational Speed
Watts et al. (2010)
➢the optimized particle size distribution was oriented towards the coarser particles
Karimi, Moellendick and Holt (2011) & Salehi, Mgboji and Aladasani (2013)
➢Higher ratio create more contact area
➢the larger the contact area the better.
Fisher et al. (2000) and Mokhtori (2012)
➢mud cake thickness depends on the eccentricity of the drill string
➢regions of minimum/maximum thickness occurring either side of the minimum distance between the borehole wall & the rotating drill string
Moellendick and Karimi (2011)
➢combination force of high annular velocity or flow rate & casing rotational speed (RPM) will resulting cutting smearing to the borehole wall.

CHAPTER 3

METHODOLOGY

This chapter consists of (1) research methodology, (2) development of model simulation, (3) model meshing, (4) mesh dependency check analysis, (5) model simulation (6) Gantt chart and key milestone, and (7) tools and equipment.

3.1 Research Methodology

Figure 3.1 illustrate the project methodology for this project. For the first step in this project, preliminary studies on plastering effect have been done to determine the possible variables that can be consider in this project. From this preliminary studies, base case for this project have been determine, where this simulation will focusing on vertical well. All the information obtained in this step will be used in development of model.

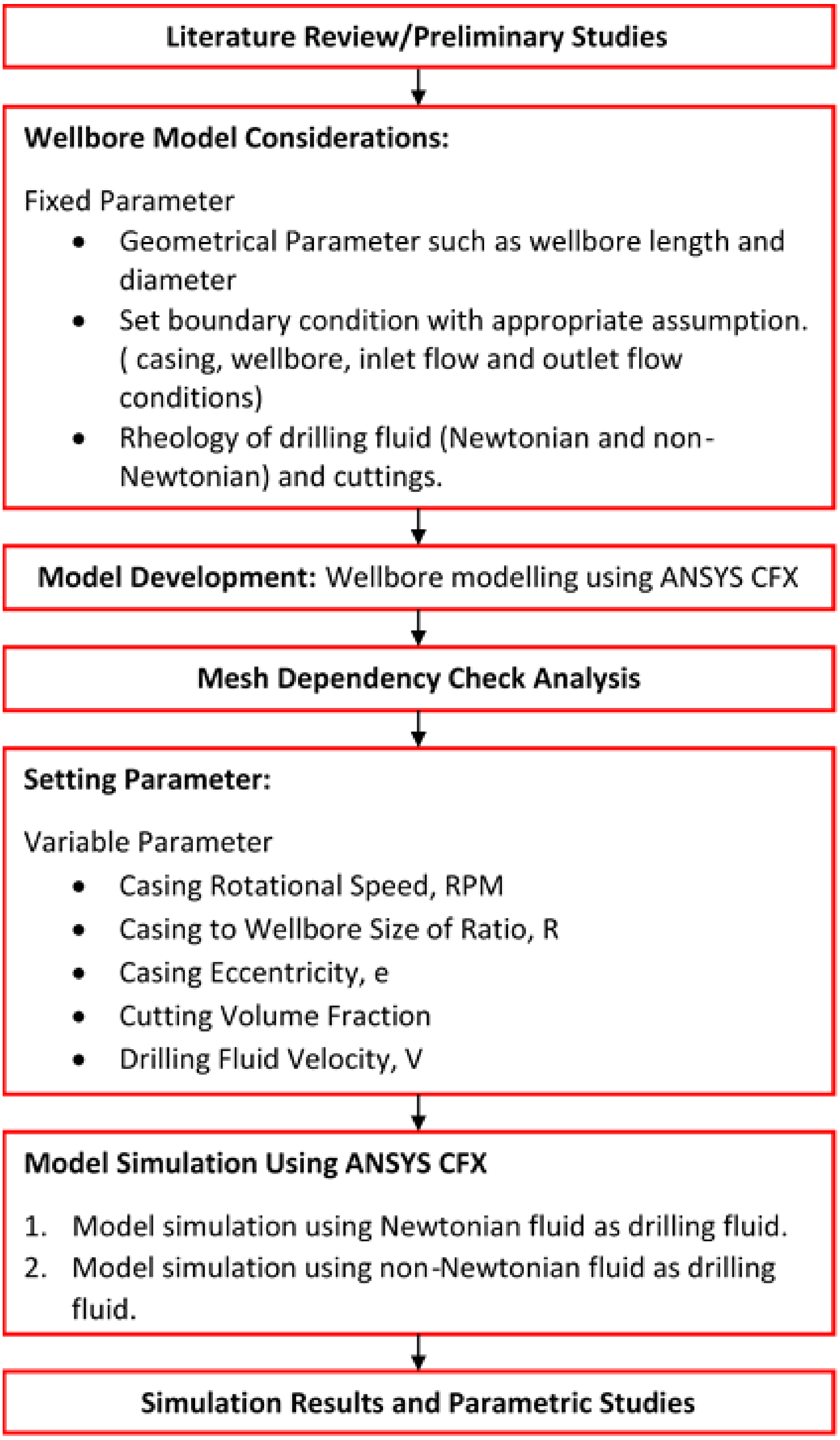


Figure 3.1: Project Methodology

3.2 Development of Model Simulation

The development of model simulation of wellbore for plastering effect in CwD is based on the schematic wellbore with casing in Figure 3.2 where it consists of the inlet flow (1), outlet flow (2), wellbore surface (3) and casing (4) . Fine mesh is applied to the model and then followed by simulation using the CFD program solver (ANSYS CFX). In this ANSYS CFX simulation, drilling fluid and cuttings applied the Eulerian multiphase model.

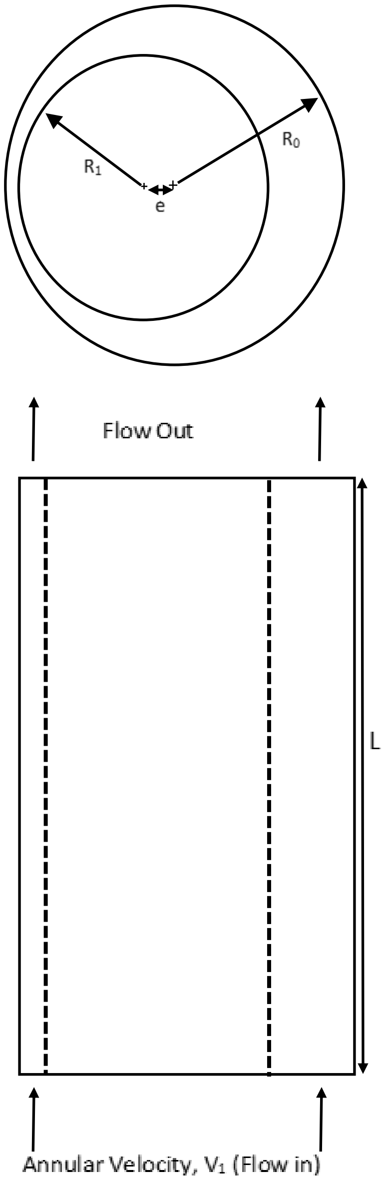


Figure 3.2: Schematic Diagram of Wellbore design

The casing and wellbore wall condition set in the simulation is no slip wall with smooth wall roughness.

Table 3.1 illustrates the comparison parameters betweenEscudier, Oliveira, and Pinho (2002)simulation data and recent study.Escudier et al. (2002) simulation is a study on non-Newtonian flow in an eccentric annuli using CFD. In this case, the study is similar to plastering effect in term of model build up. The lowest and highest limit range for parametric studies have been set and listed in Table 3.1 too in order to have clearer view on how the parameters above affect the plastering effect.

Table 3.1: Input parameters for validations and parametric studies

Input Parameters	**(Escudier et al., 2002)**	**Base Case**
Wellbore Radius, R_0(m)	0.254	0.2
Casing size to Hole Size Ratio, r	0.2, 0.5, 0.8	0.7 to 0.9
Casing Eccentricity, e	0, 0.7	0 to 0.9
Wellbore Length, L (m)	-	4.2
Fluid Annular Velocity, V_1 (m/s)	0.13	0.5 to 1
Casing Rotational Speed, ω (RPM)	9.4	200 to 400

3.3 Model Meshing

After finish model build up, the model is mesh before run the simulation. Fine mesh is essential to gain more accuracy in simulation result. For CwD plastering effect study, the model is mesh using mesh size of9.5 mm^2 of tetrahedrons cells with 10 layer of inflation on the casing and wellbore surface. Figure 3.3 shows the meshing result of base case for present study.

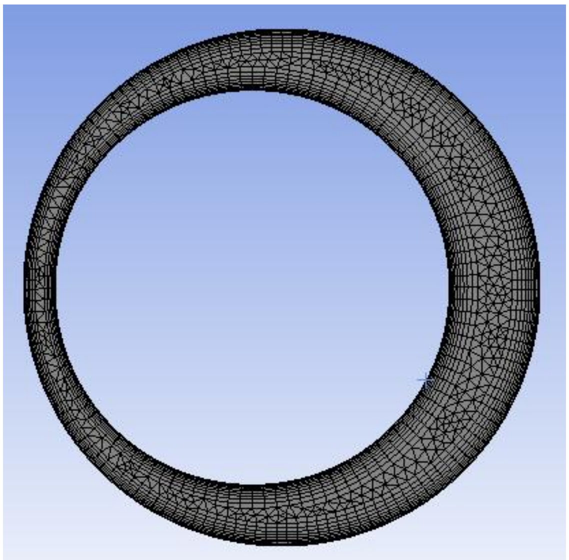


Figure 3.3: Model Meshing Result

3.4 Mesh dependency check analysis

This analysis is used to study the mesh dependent convergence behaviour. In order to study the convergence behaviour, several runs of simulation had been performed with varying size of tetrahedral cells. The pressure drop per unit length in the wellbore annulus is the criteria selected to check on the convergence behaviour. Figure 3.4 shown is the computational mesh of two different wellbore annulus with different size of tetrahedral cells.

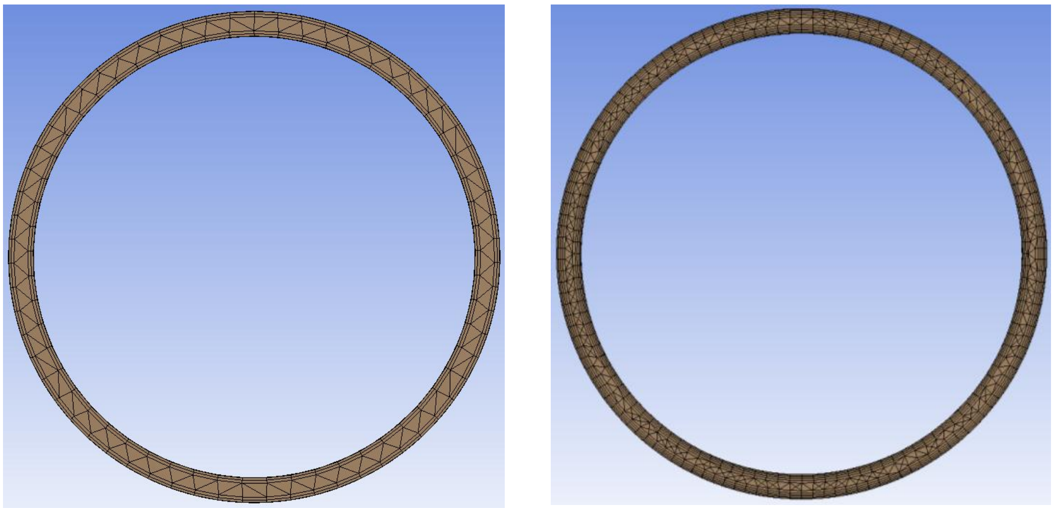


Figure 3.4: Comparison between large and small size of computational mesh of wellbore annulus

While Figure 3.5 illustrates the convergence behaviour of different mesh size based on the pressure drop per unit length obtained in the annulus. For the coarser meshes or smaller mesh size, the pressure drop per unit length values are varying between 7.8 kPa/m to 8.2 kPa/m. In other words, the error on the coarser mesh is high and it is mainly influenced by the mesh size. The curve converges when mesh is refined to smaller than $10mm^2$ and it provides much better resolution compared to a bigger size mesh.

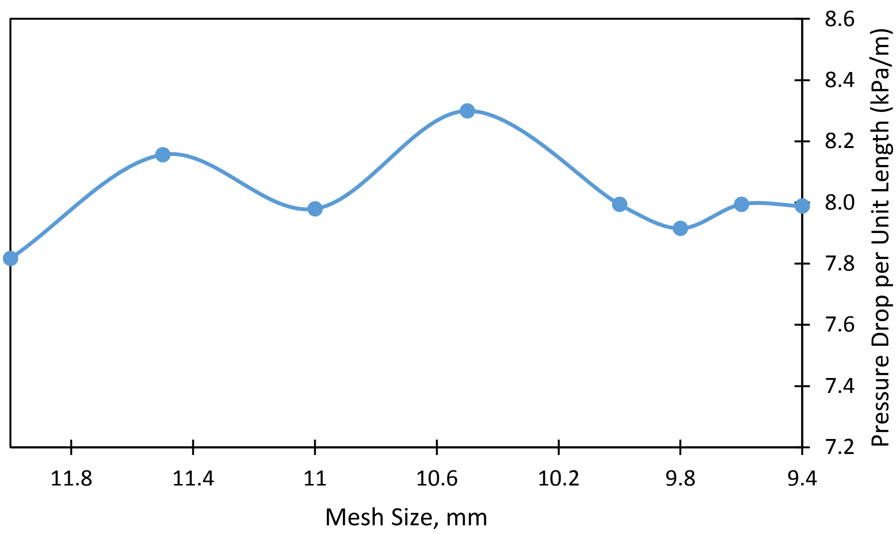
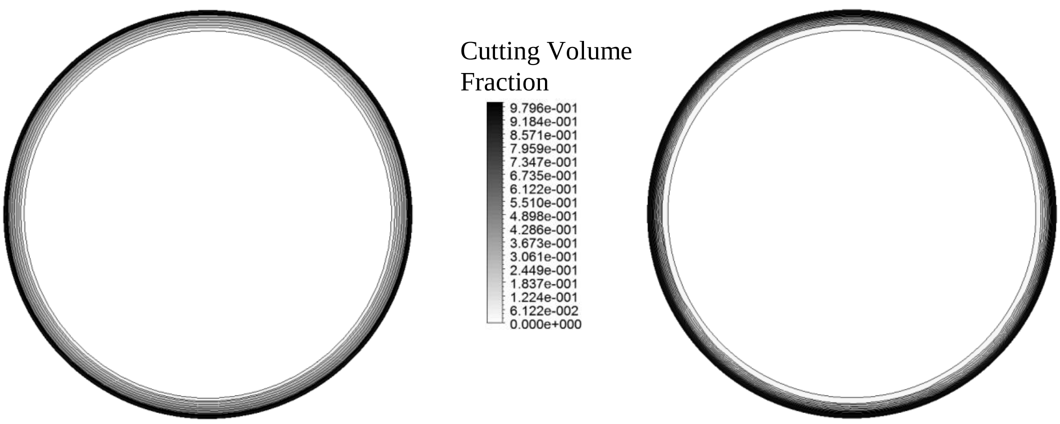


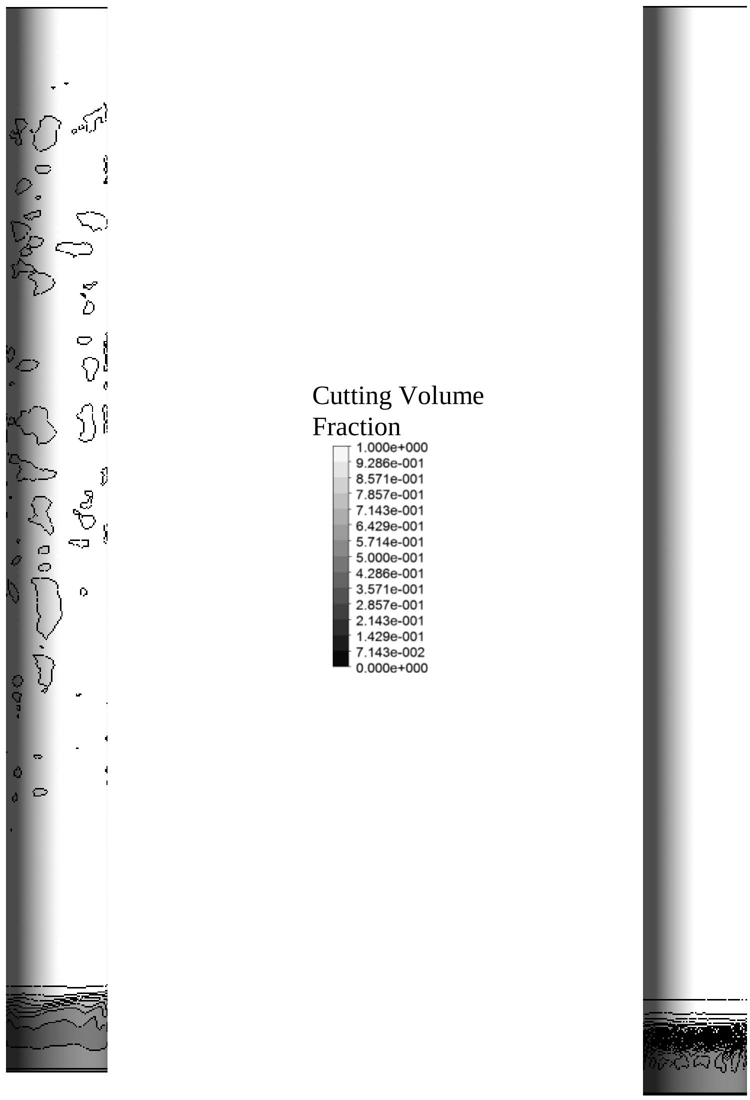
Figure 3.5:Pressure drop per unit length convergence versus mesh size

All the figures below illustrate the contours of the cuttings in wellbore annulus. Basically, the comparisons are made between the coarsest mesh and the finest mesh which have size of 12mm^2 and 9.4mm^2 tetrahedral cells respectively. It is shown that the contours differ from the coarsest and the finest meshes. Smaller mesh size of mesh show more accurate and precise contours compared to lager mesh size.



(a) 12 mm^{2}size mesh at outlet flow

(b) 9.4 mm^2 size mesh at outlet flow



(c) 12 mm^2 size mesh at wellbore surface

(d) 9.4 mm^2 size mesh at wellbore surface

Figure 3.6: Cutting volume fraction contours at outlet flow and wellbore surface for 12 mm^2 and 9.4 mm^2 size mesh

3.5 Model Simulation

Simulation for CwD plastering effect will be separate into two parts according to type of drilling fluid used. The drilling fluids are water and non-Newtonian fluid. For water, the rheology is standard at normal temperature of 27°C with density of 1000 kg/m^3 and shear rate of 0.001 kg/m.s. While for non-Newtonian fluid, the density is same with water but the shear rate is based on power law viscosity model. The value of viscosity consistency index, K = 0.46 and power-law index, n = 0.6 has been chosen. For cuttings, the base case properties are shown in Table 3.2.

Table 3.2: Cutting Properties

Cuttings Properties	Values
Density, (kg/m^3)	2300
Shear Rate, (kg/m.s)	0.001
Mean Diameter, (mm)	2

The variable parameter that adopted in this simulation are casing size to wellbore size ratio, casing eccentricity, drilling fluid annular velocity, casing rotational speed and cuttings volume fraction. The value for each parameter is shown in Table 3.3.

Table 3.3: Simulation Variable Parameter Values

Variable Parameter	Values
Casing Size to Wellbore Size Ratio Size, r	0.7 to 0.9
Casing Eccentricity, e	0 to 0.9
Casing Rotational Speed, ω (RPM)	200 to 400
Drilling Fluid Annular Velocity, V_1(m/s)	0.5 to 1.0
Cutting Volume Fraction	0.2 to 0.4

3.6 Project Gantt Chart

Table 3.4: Gantt Chart for FYP 1 and FYP 2

Research Activities	Week	FYP 1															FYP 2													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	Semester Break	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	Topic Selection	■	■																											
2	Preliminary Research Work			■	■																									
3	Literature Review on CwD Plastering Effect				■	■	■	■	■																					
4	Exploring and familiarization of ANSYS CFX software								■	■	■																			
5	Submission of Extended Proposal								★																					
5	Determine Fixed and variables parameters required									■	■	■	■	■																
6	Submission of Interim Report														★															
6	Model Development using CFX												■	■	■		■													
7	Model Simulation																													
8	Simulation Result Analysis																■	■	■	■	■	■								
9	Parametric Study																						■	■	■					
10	Result and Discussion																									■	■	■	■	
11	Final Report Submission																													★

★ **KeyMilestone**

3.7 Tools Required

ANSYS CFX software is commonly employed for computational fluid dynamic (CFD) simulations in complex geometries. It is ideally suited for both Newtonian and non-Newtonian fluid-flow simulations. This software is also able to provide complete mesh flexibility including the ability to solve flow problems. ANSYS CFX software is required in this project to develop the CwD plastering effect model. The simulation result from this software will be used to analyze the factors affecting plastering effect in CwD.

CHAPTER 4

RESULTS and DISCUSSION

By using the simulation model that has been developed, five factors are examined which are predicted to be affecting plastering effect. These variables are casing rotational speed, casing size to wellbore size ratio, annular velocity of drilling fluids, casing eccentricity and cuttings volume fraction. Detailed parameters of simulation model are summarized in Table 3.3. With the listed parameters range, three outcomes which are mud cake thickness at outer flow, mud cake length on the wellbore and pressure drop per unit length will be analyze to study plastering effect in CwD. Parametric studies will be divided into two parts based on the drilling fluids rheology used which are Newtonian fluid and non-Newtonian fluid.

4.1 Result visualization for non-Newtonian fluid

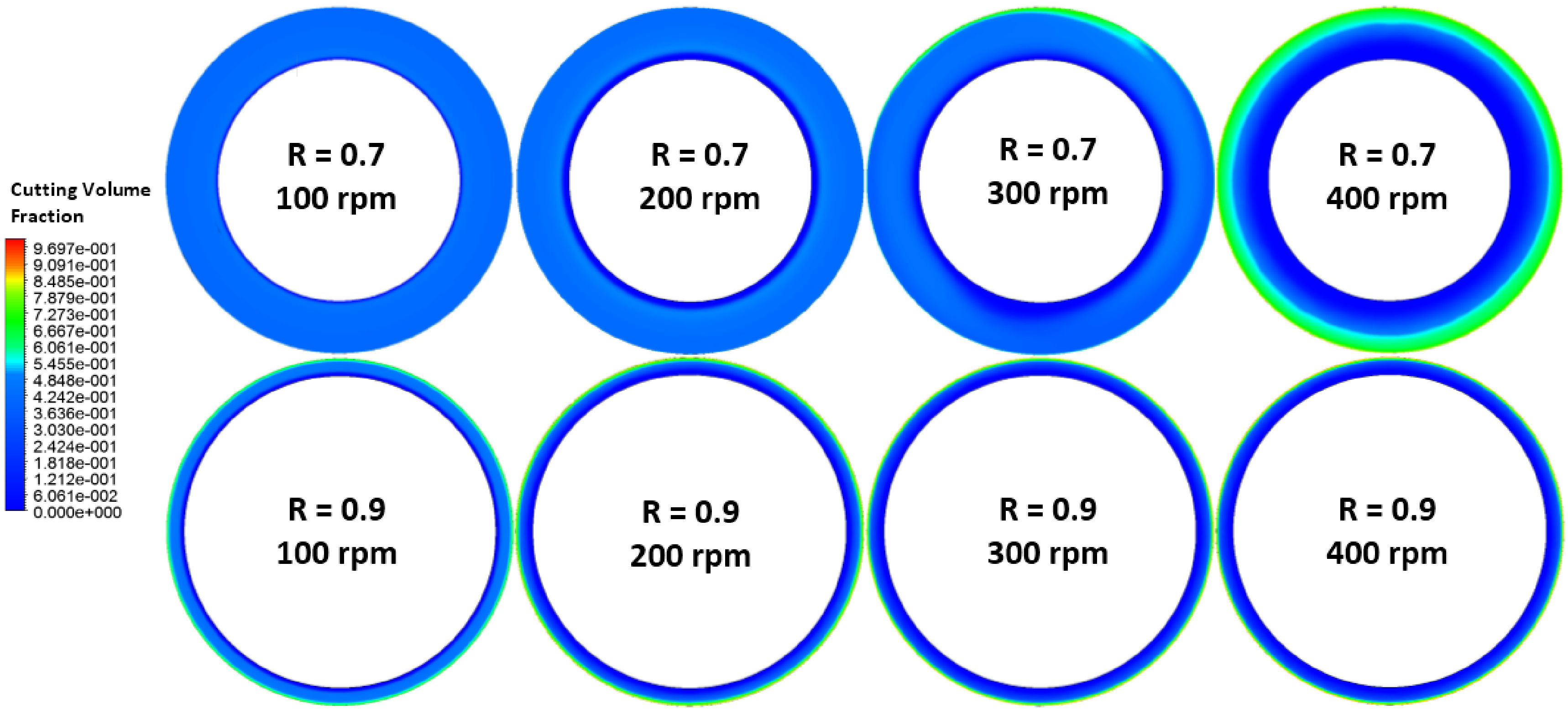
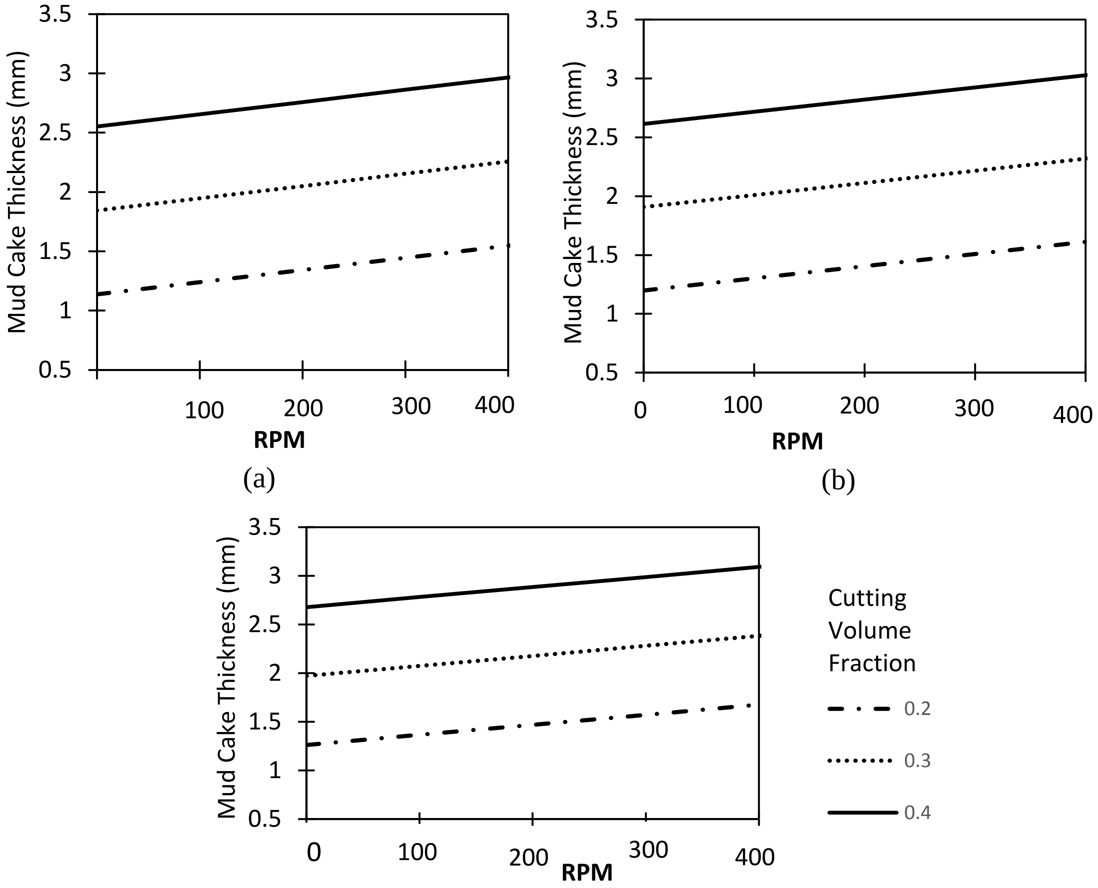


Figure 4.1: Results for non-Newtonian fluid with varying casing rotational speed (RPM) & different casing to open hole size ratio (R). Eccentricity = 0, Annular Velocity = 0.5 m/s and Cutting Volume Fraction = 0.4

4.2 Parametric studies on non-Newtonian fluid

Parametric studies for non-Newtonian fluid will be based on three results which are (1) mud cake thickness on outer flow, (2) mud cake length on wellbore surface, and (3) pressure drop per unit length at the annular of the wellbore.

4.2.1 Mud Cake Thickness



(c)

Figure 4.2: Mud cake thickness based on casing RPM with various cutting volume fraction and annular velocity (a) 0.5 m/s, (b) 0.75 m/s and (c) 1.0 m/s with casing to wellbore size ratio = 0.8 and eccentricity = 0.45

Figures 4.2 (a), (b) and (c), showed the effect of casing rotational speed in RPM, annular velocity and cuttings volume fractions on mud cake thickness for plastering effect in CwD. In Figure 4.2(a), the mud cake becomes thicker when the casing rotational speed value is increasing. While increases in cutting volume fraction will increase the mud cake thickness. Comparing Figure 4.2(a), (b) and (c), increase value of annular velocity resulted in a thicker mud cake.

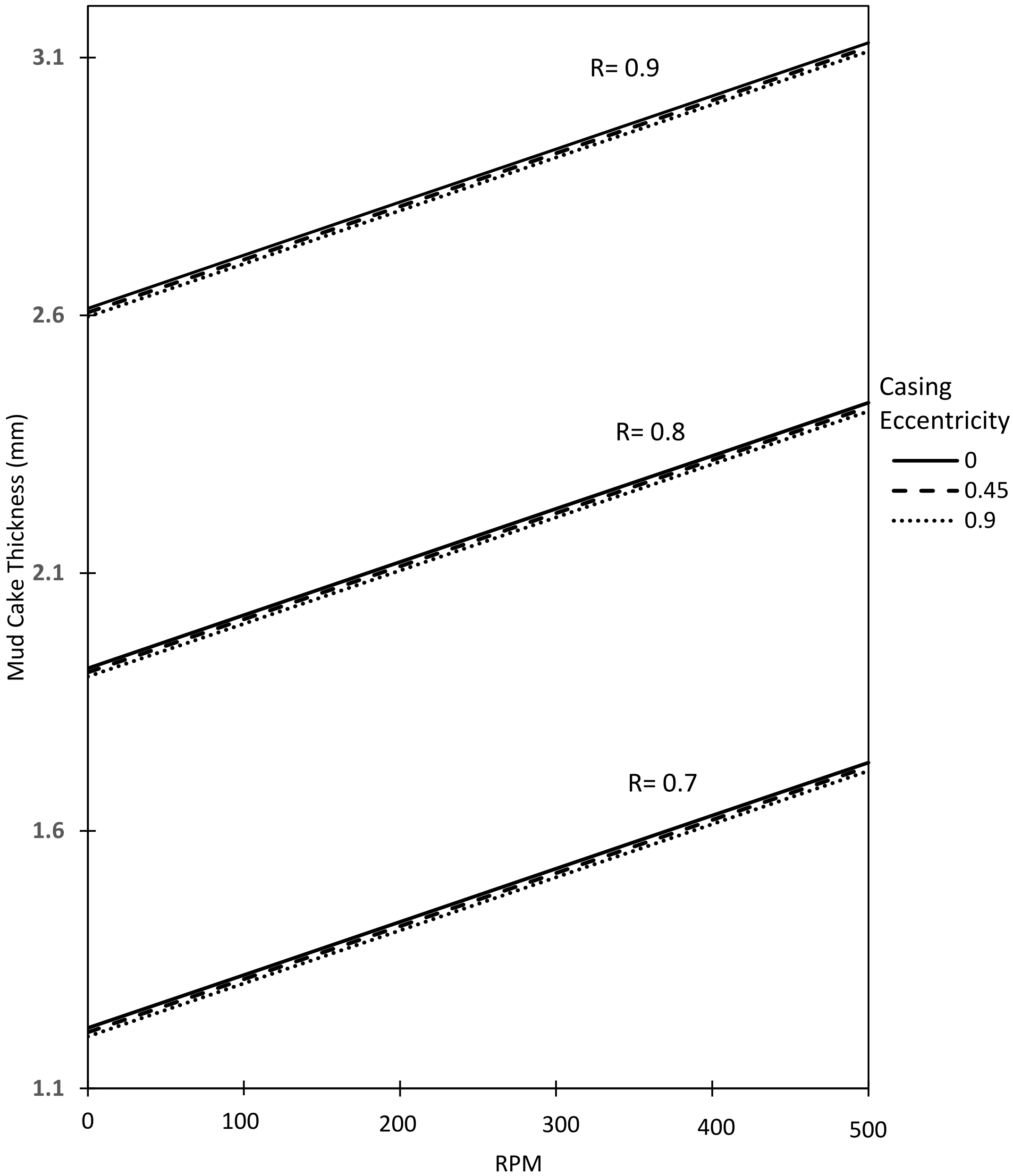


Figure 4.3: Mud cake thickness based on casing RPM with various eccentricity and casing ratio with annular velocity = 0.75 and cutting volume fraction = 0.3

Figure 4.3 showed the effect of mud cake thickness plotted against casing rotational speed in RPM, with various casing eccentricity and casing to wellbore ratio. Figure 4.3 illustrated that higher casing to wellbore ratio resulted in higher mud cake deposition. However, the mud cake will be thinner if the eccentricity is decreased. Therefore, concentric casing will produce the thickest mud cake compare to eccentric casing.

Figure 4.4 summarizes the influence of five parameters in percentage upon mud cake thickness. It illustrates that cutting volume fraction has the most impact on the plastering effect, followed by casing to wellbore ratio, casing rotational speed, and annular velocity respectively. Casing eccentricity has the least impact or does not contribute in plastering effect at all compared to the rest of the parameters investigated.

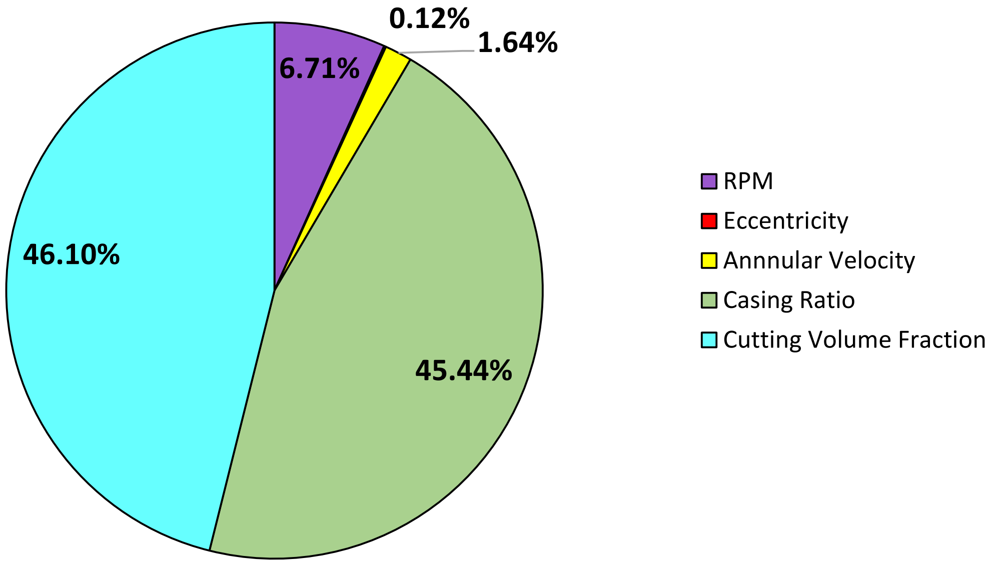


Figure 4.4: Parameter Weighting Factors based on mud cake thickness for non-Newtonian fluid

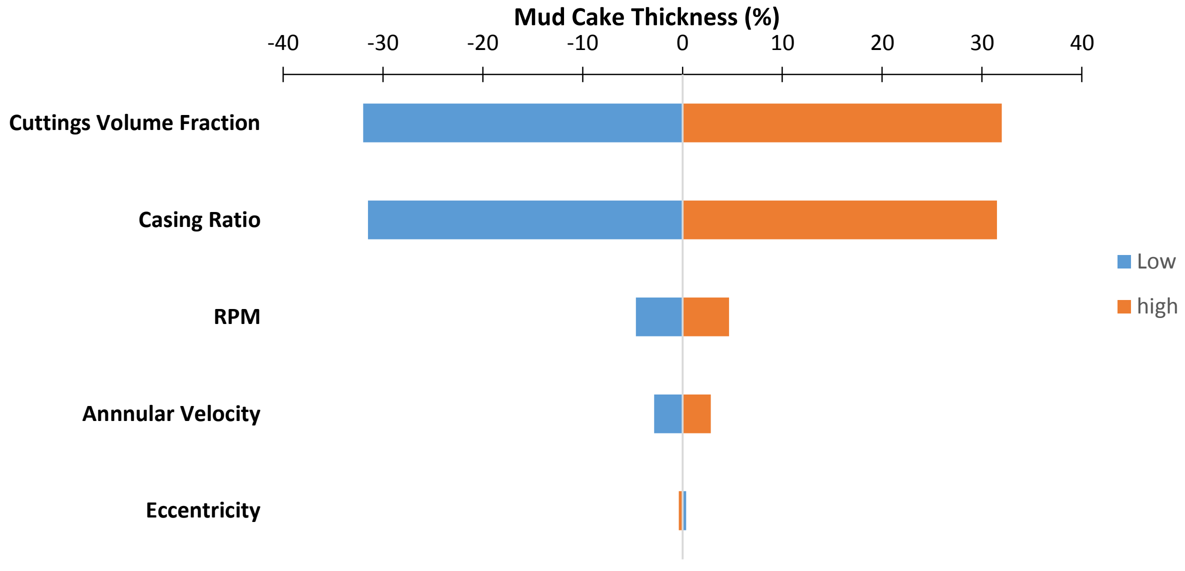
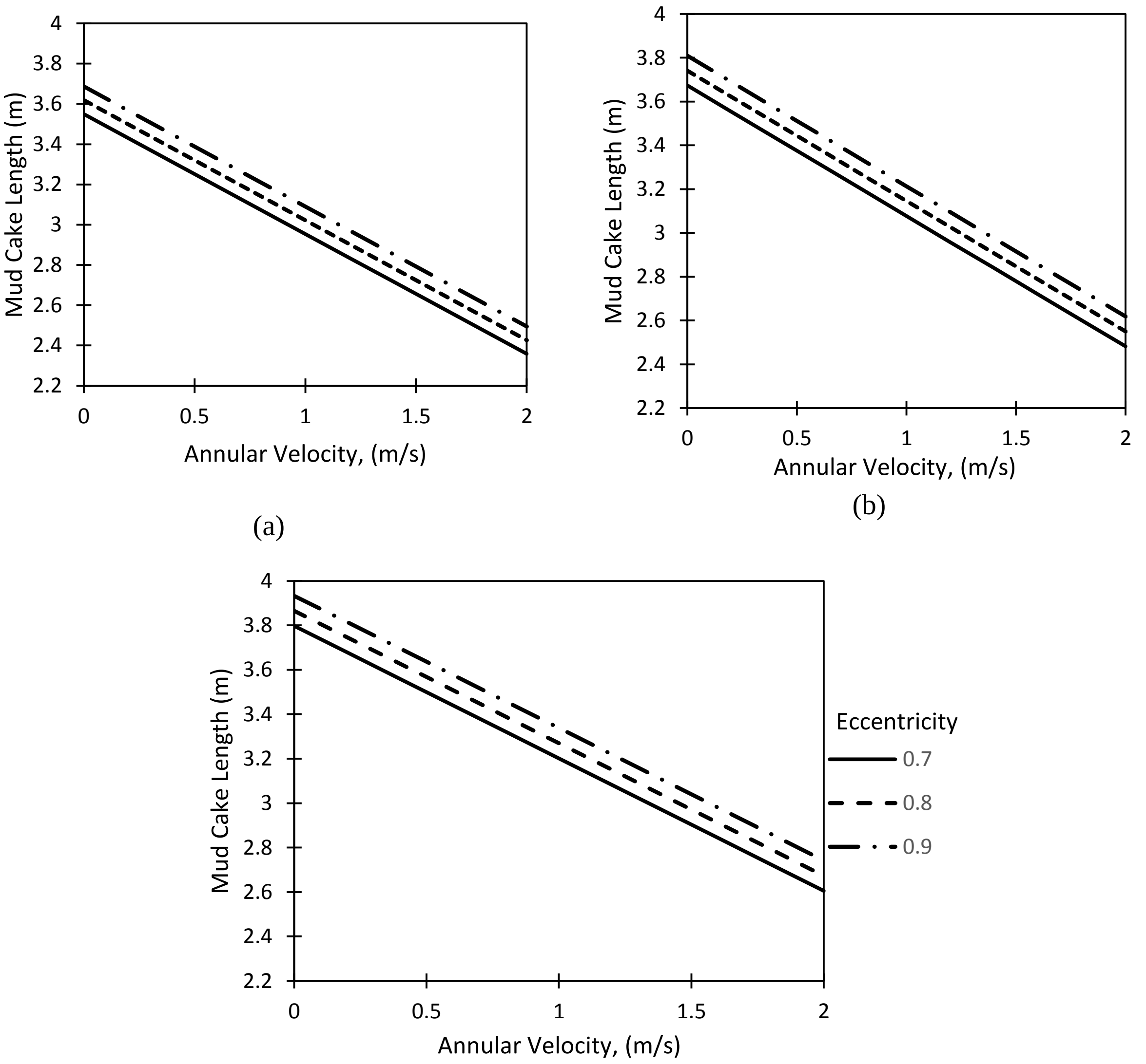


Figure 4.5:Parameters' sensitivity to mud cake thickness for non-Newtonian fluid

In order to look at the parameters' sensitivity, tornado chart is constructed as shown in Figure 4.5. This chart clearly illustrates the sensitivity of parameters to the solution. It reveals that the most sensitive parameters are the cutting volume fraction and casing ratio where all of these factors have the affecting percentage more than 30% out of the five parameters. The least sensitive parameters include the casing rotational speed and annular velocity. While casing eccentricity almost has no effect on the mud cake thickness with its sensitivity less than 1%.

4.2.2 Mud Cake Length



(c)

Figure 4.6: Mud cake length based on annular velocity with various eccentricity and cutting volume fraction (a) 0.2, (b) 0.3 and (c) 0.4 with casing RPM = 0.3 and casing ratio = 0.8

Figures 4.6 (a), (b) and (c), analyze the effect of annular velocity, casing eccentricity and cuttings volume fractions on mud cake length for plastering effect in

CwD. Based on the Figure 4.6 (a), the graph shows the mud cake become shorter on wellbore surface when the annular velocity value is increasing. When eccentricity increases, it will increase the mud cake length. Comparing graphs (a), (b) and (c), increase value of cutting volume fraction resulted a longer mud cake on the wellbore surface.

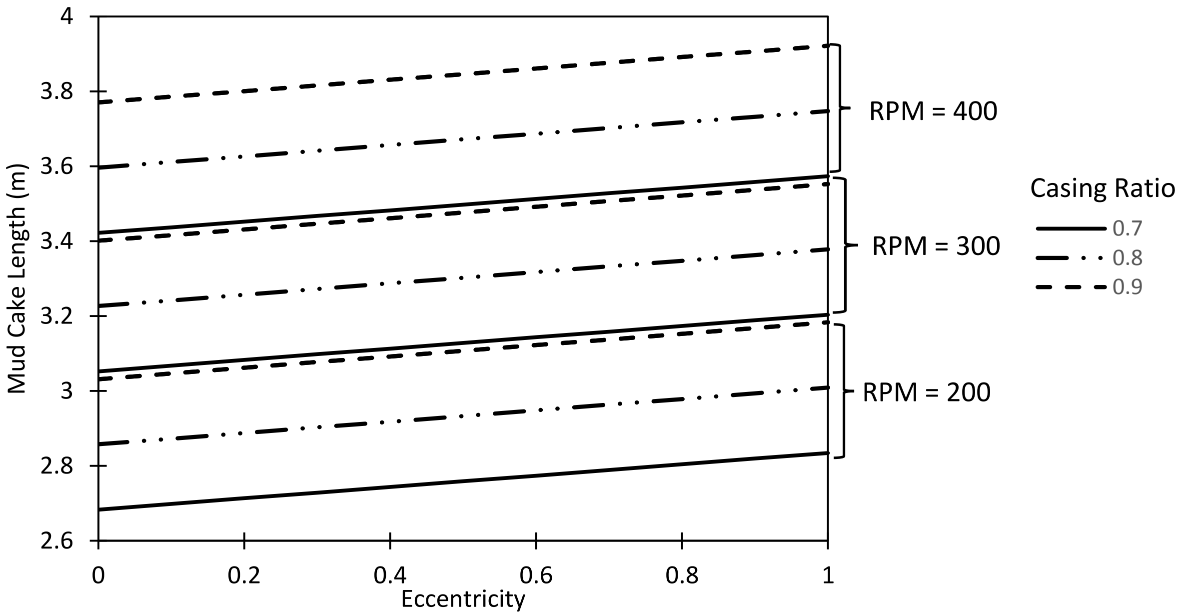


Figure 4.7: Mud cake length based eccentricity with various casing ratio and casing RPM with cutting volume fraction = 0.3 and annular velocity = 0.75

Figure 4.7, analyze the effect of casing eccentricity, casing rotational speed and casing to wellbore size ratio on mud cake length on wellbore surface for plastering effect in CwD. Figure 4.6 explained that when casing eccentricity value increase, it will produce longer mud cake on the wellbore. Besides that, the mud cake will be longer if the casing rotational speed is increase and also the casing ratio increase.

From the parametric studies above for mud cake length, Figure 4.8 summarizes the influence of five parameters in percentage upon mud cake length for plastering effect. It illustrates that casing rotational speed does the most impact on the plastering effect, and then followed by the casing to wellbore size ratio and cutting volume fraction respectively. While, drilling fluid annular velocity and eccentricity have the least impact plastering effect compared to the rest of the parameters.

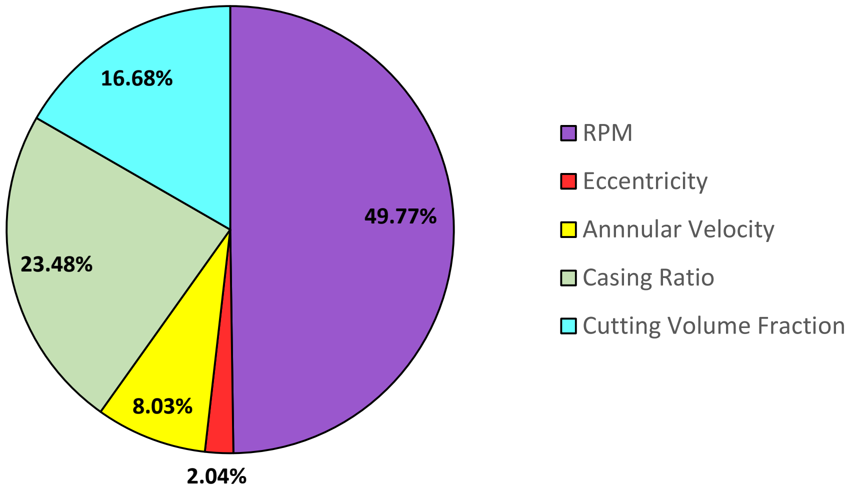


Figure 4.8: Parameter weighting factors based on mud cake thickness for non-Newtonian fluid

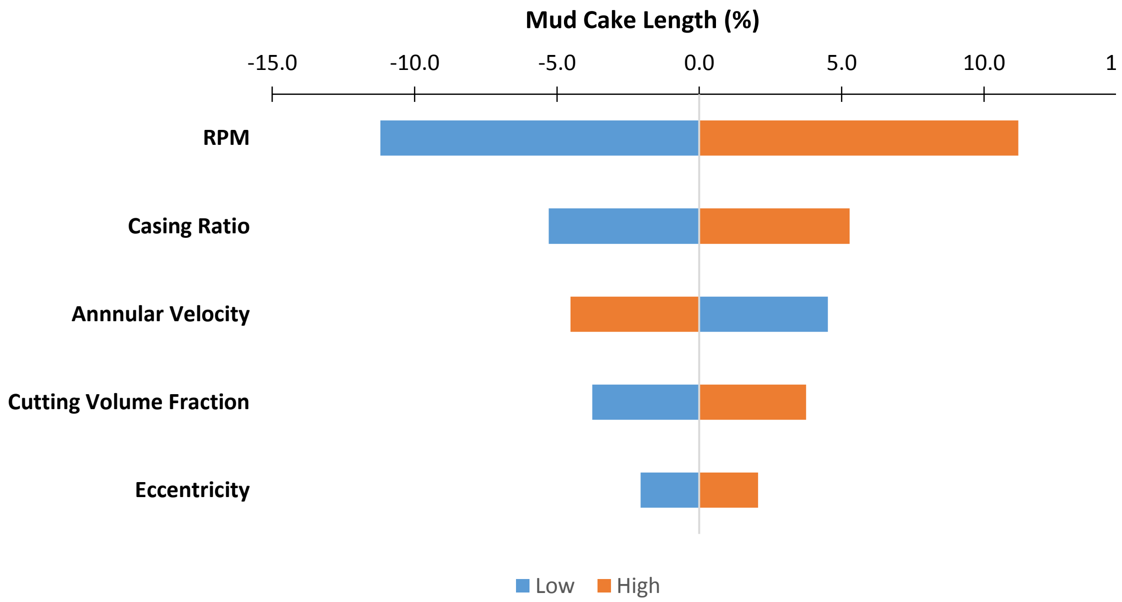


Figure 4.9: Parameters' sensitivity to mud cake length for non-Newtonian fluid

Figure 4.9 is tornado chart to measure parameters' sensitivity to mud cake length. The most sensitive parameter is casing rotational speed where it contributed to more than 10% to the sensitivity of the overall solution. The sensitivity parameters followed by the casing to wellbore size ratio, annular velocity, and cutting volume fraction respectively. The least sensitive is the eccentricity with less than 5% of percentage.

4.2.3 Pressure Drop per Unit Length

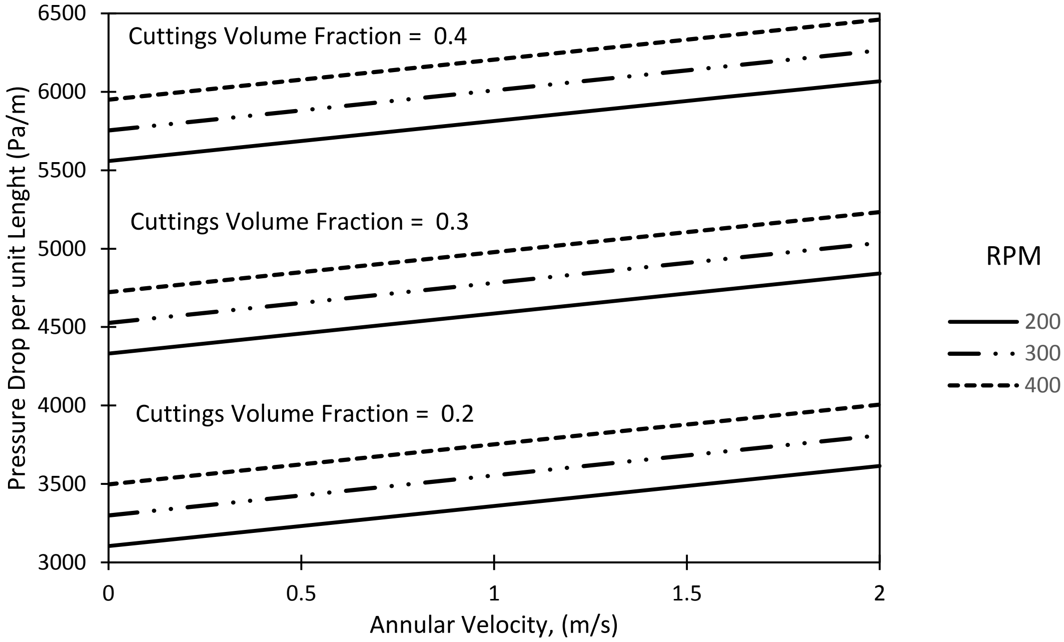


Figure 4.10: Pressure drop per unit length based annular velocity with various cutting volume fraction and casing RPM with casing eccentricity = 0.45 and casing ratio = 0.8

Figure 4.10, analyze the effect of annular velocity, casing rotational speed and cutting volume fraction on pressure drop for plastering effect in CwD. Figure 4.10 explained that by increasing annular velocity, the higher the pressure drop per unit length. Besides that, the pressure drop will be higher if the cutting volume fraction increase and also the casing rotational speed increase.

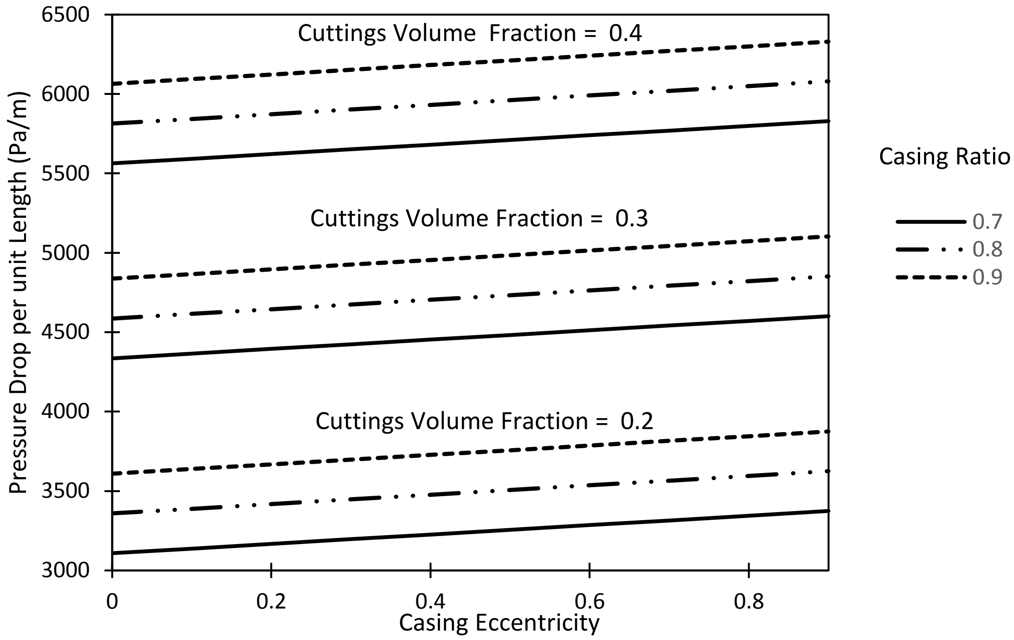


Figure 4.11: Pressure drop per unit length based casing eccentricity with various cutting volume fraction and casing ratio with annular velocity = 0.75 and casing eccentricity = 0.45

Figure 4.11, analyze the effect of casing eccentricity, casing ratio and cutting volume fraction on pressure drop for plastering effect in CwD. Figure 4.11shows that by increasing eccentricity, the higher the pressure drop per unit length. Same goes if the casing ratio increase, the pressure drop will be higher.

From the parametric studies above for pressure drop, Figure 4.12 summarizes the influence of five parameters in percentage upon pressure drop per unit length for plastering effect. It illustrates that cutting volume fraction does the most impact on the plastering effect, and then followed by the casing to wellbore size ratio and casing rotational speed respectively. While, drilling fluid annular velocity and eccentricity have the least impact plastering effect compared to the rest of the parameters.

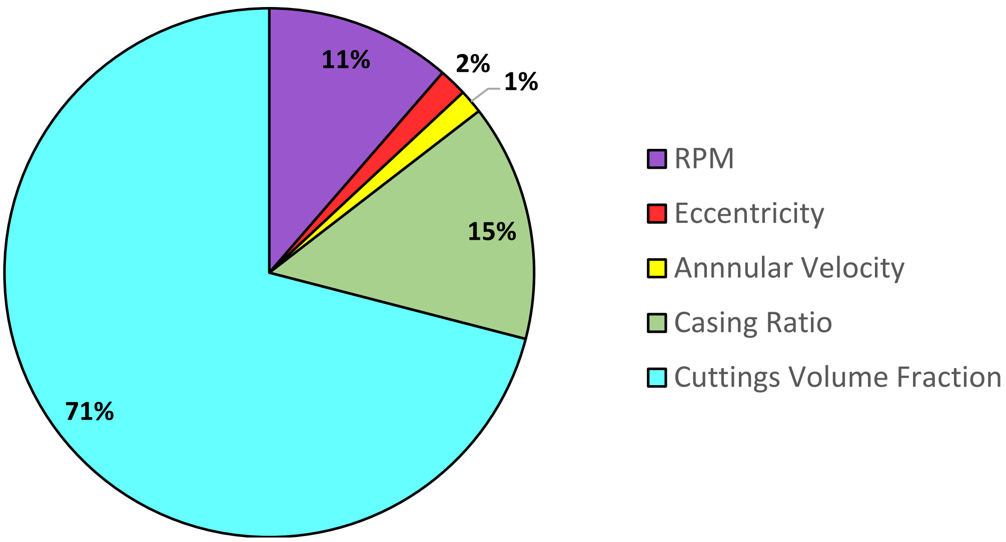


Figure 4.12: Parameter weighting factors based on pressure drop for non-Newtonian fluid

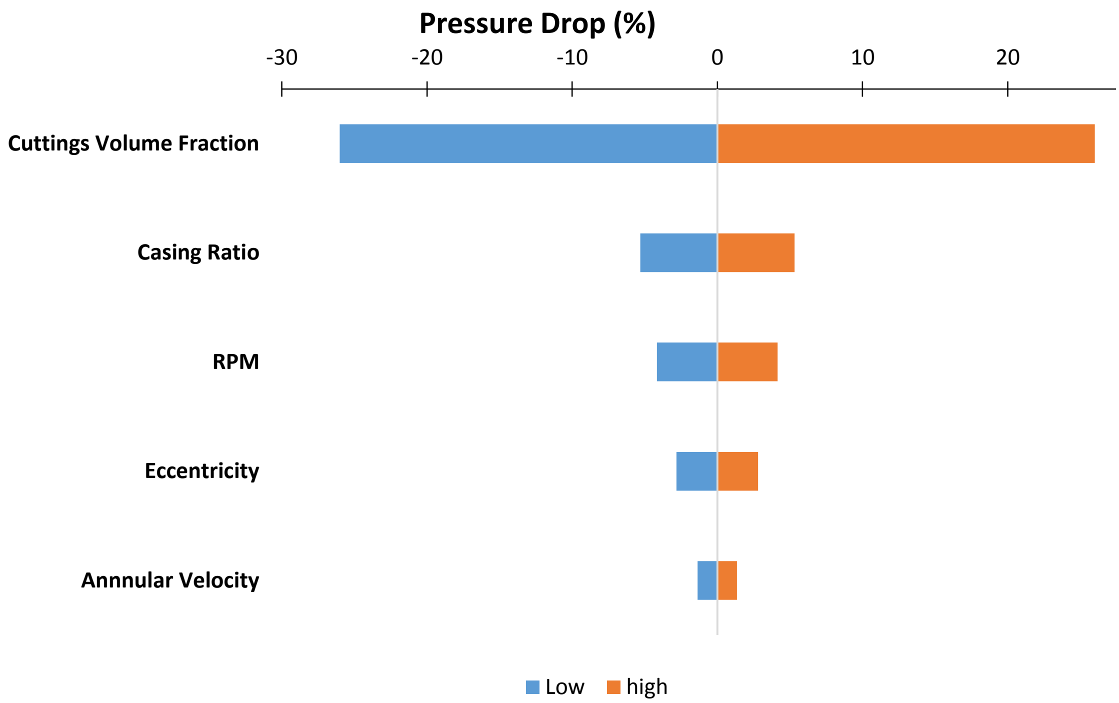


Figure 4.13: Parameters' sensitivity to pressure drop for non-Newtonian fluid

Figure 4.13 shows tornado chart to measure parameters' sensitivity to pressure drop per unit length. From the figure that the most sensitive parameter is cutting volume fraction where it has the affecting percentage more than 20% out of the five parameters. The sensitivity parameters followed by the casing to wellbore size ratio, casing rotational speed, and eccentricity respectively. The least sensitive is the annular velocity.

4.3 Result visualization for Newtonian fluid

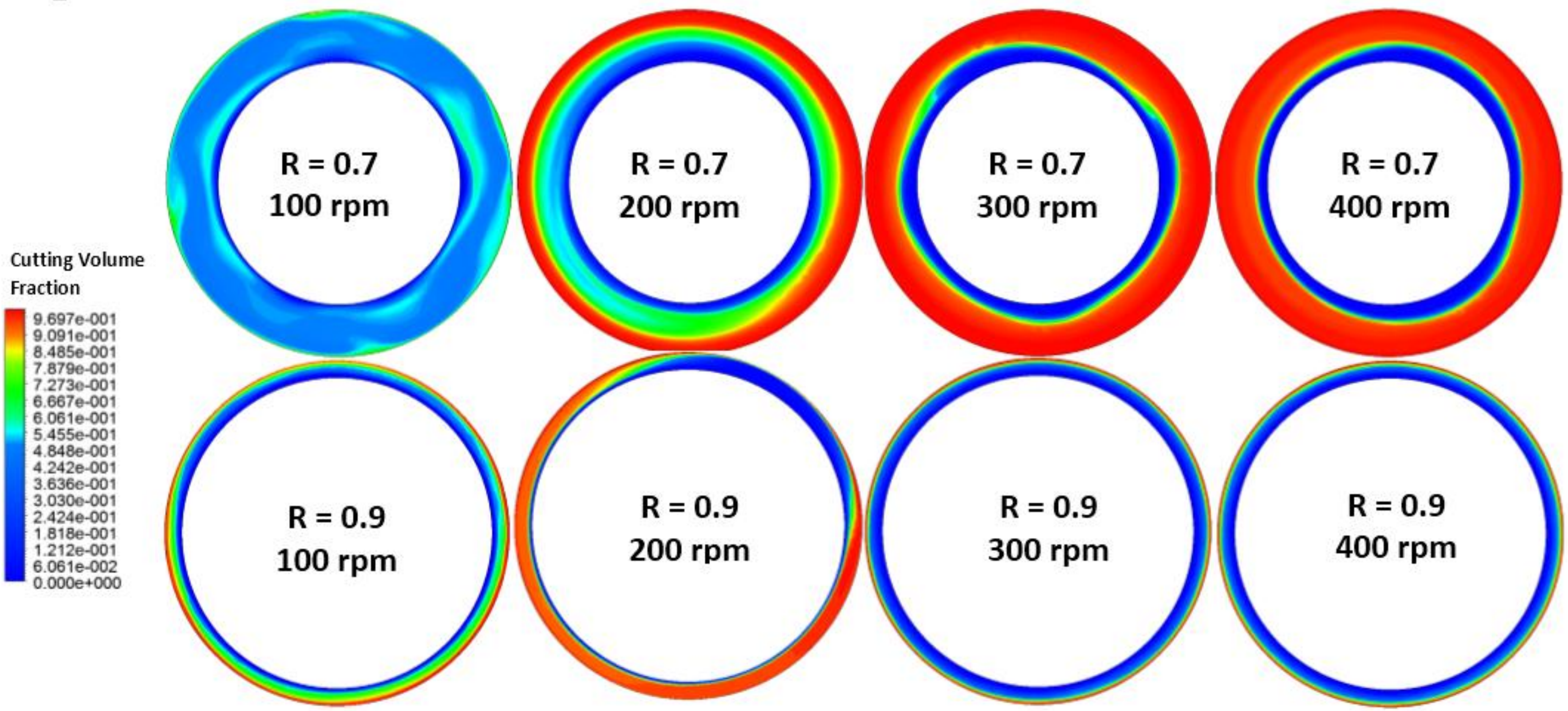
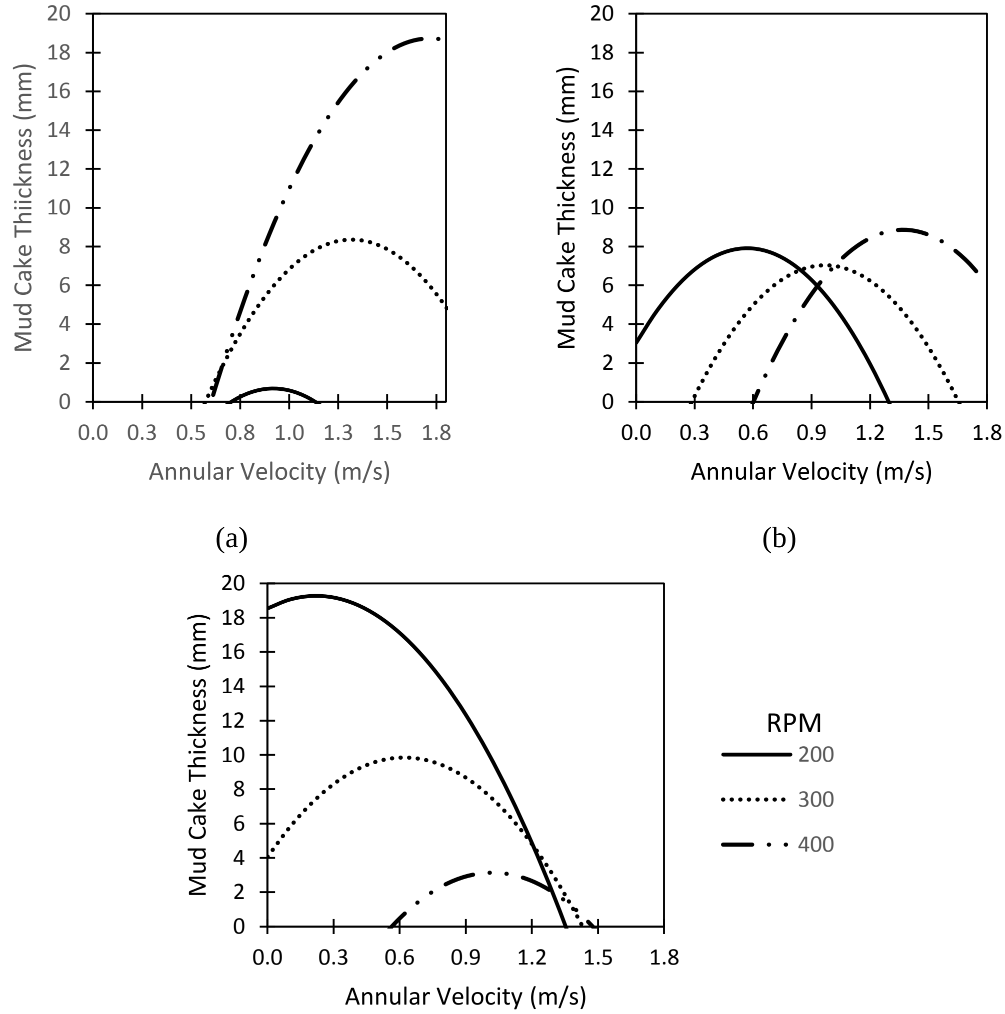


Figure 4.14: Results for Newtonian fluid with varying casing rotational speed (RPM) and different casing to open hole size ratio (R). Eccentricity = 0, Annular Velocity = 0.5 m/s and Cutting Volume Fraction = 0.4

4.4 Parametric studies on Newtonian fluid

Parametric studies for Newtonian fluid will be based on three results which are (1) mud cake thickness on outer flow, (2) mud cake length on wellbore surface, and (3) pressure drop per unit length at the annular of the wellbore.



(a) (b)

(c)

Figure 4.15: Mud cake thickness based on annular velocity with various casing rotational speed and cutting volume fraction (a) 0.2, (b) 0.3 and (c) 0.4 with eccentricity = 0.45 and casing ratio = 0.8

4.4.1 Mud Cake Thickness

Figure 4.15 (a), (b) and (c), analyze the effect of casing rotational speed in RPM, annular velocity and cuttings volume fractions on mud cake thickness for plastering effect in CwD using Newtonian fluid. Based on the Figure 4.15 (a), the graph shows the mud cake become thicker when the annular velocity of the fluid is increase, however, at the certain annular velocity, the mud cake thickness start to decrease. The graph shows that the mud cake thickness has it maximum value. The maximum mud cake thickness vary with the value of casing rotational speed. In figure 4.15 (a) shows the maximum mud cake thickness will increase when the casing rotational speed increase.

Table 4.1: Maximum mud cake thickness value in (mm)
from figure 4.15 (a), (b) and (c)

	Cutting Volume Fraction		
Casing Rotational Speed (RPM)	**0.2**	**0.3**	**0.4**
200	0.7	7.9	19.3
300	8.3	7.0	9.8
400	18.7	8.9	3.1

The situation differ in figure 4.15 (b) and (c) due to change of cutting volume fraction value, where in (b) the maximum values for different casing rotational speed are approximately equal. While in (c), casing rotational speed increase will produce thinner mud cake. By comparing figure 4.15 (a), (b) and (c) and referring to table 4.1, in low casing rotational speed, increasing the cutting volume fraction will increase the mud cake thickness on the wellbore. In high casing rotational speed, the situation is opposite, because increase the cutting volume fraction will decrease the mud cake thickness.

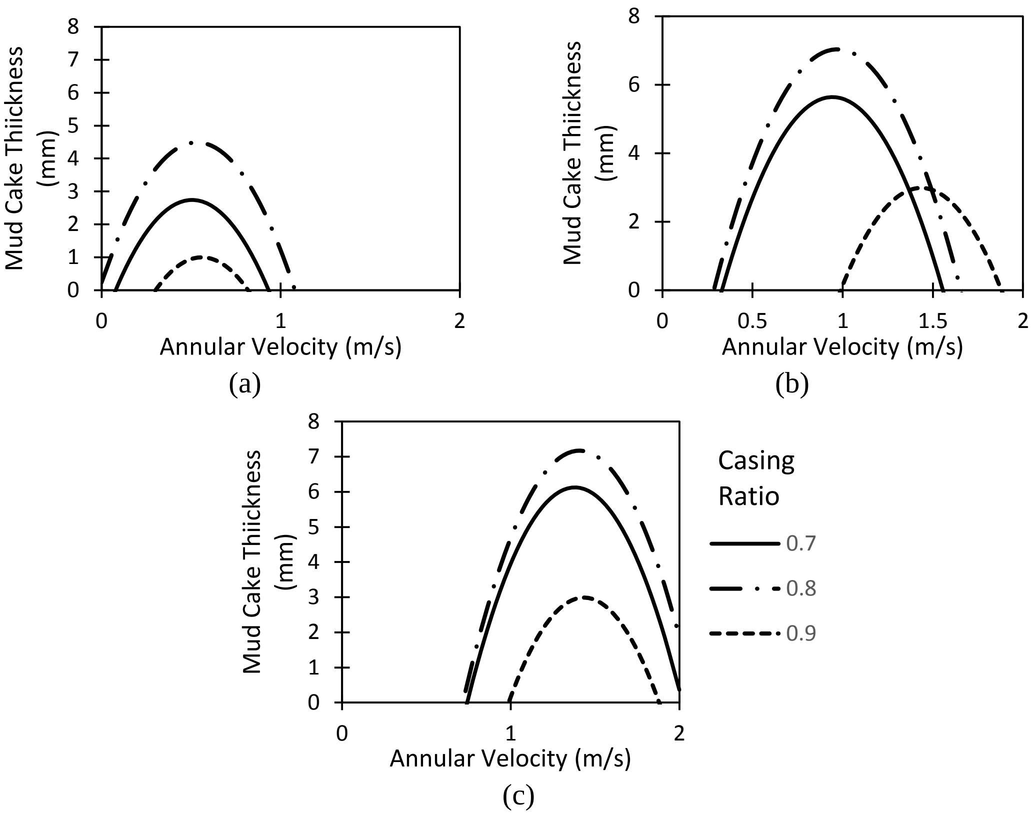


Figure 4.16: Mud cake thickness based on annular velocity with various casing ratio and eccentricity (a) 0, (b) 0.45 and (c) 0.9
with casing rotational speed = 300 RPM and cutting volume fraction = 0.3

In figure 4.16 (a), (b) and (c), the annular velocity, casing to open hole size ratio and eccentricity on mud cake thickness were analyzed. For annular velocity, the mud cake thickness growth trend is similar to figure 4.15. Observing from three graphs in figure 4.16, casing ratio of 0.8 produce highest maximum mud cake thickness followed by casing ratio 0.7 and 0.9 respectively. This shows that large casing size will produce thinner mud cake.

Table 4.2: Maximum mud cake thickness value in (mm)
from figure 4.16 (a), (b) and (c)

	Casing Eccentricity (E)		
Casing Ratio (R)	**0**	**0.45**	**0.9**
0.7	2.7	5.6	6.1
0.8	4.5	7.0	7.2
0.9	1.0	2.9	3.0

Referring to table 4.2, figure 4.16 shows that the higher the eccentricity, will produce higher mud cake thickness regardless the size of casing ratio. Therefore, eccentric casing will produce thicker mud cake compared to concentric casing. Besides that, in different eccentricity, the thickest mud cake value will produce when the casing ratio is 0.8 and the thinnest would be casing ratio of 0.9.

From the parametric studies above for mud cake thickness, Figure 4.17 summarizes the influence of five parameters in percentage upon mud cake thickness for plastering effect in Newtonian fluid. It illustrates that cutting volume fraction does the most impact on the plastering effect, and then followed by the casing to wellbore size ratio and casing rotational speed respectively. While, drilling fluid annular velocity and eccentricity have the least impact plastering effect compared to the rest of the parameters.

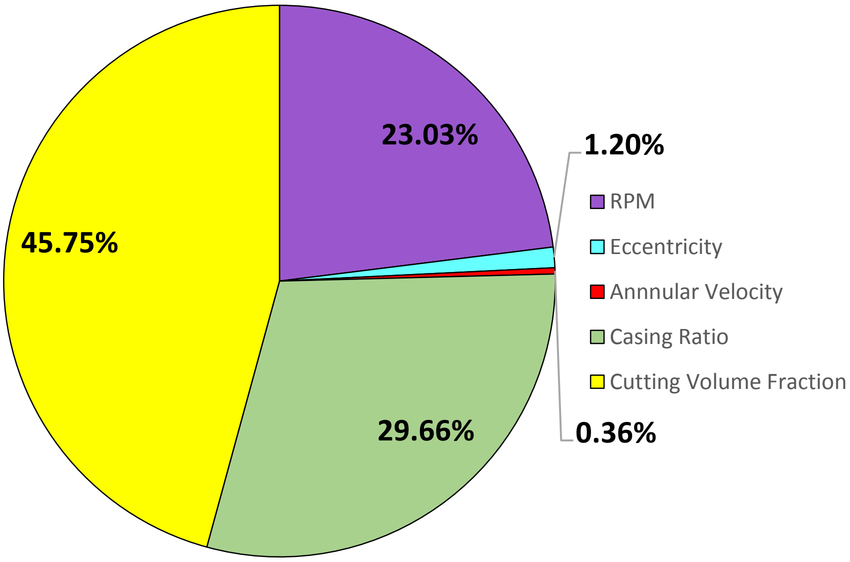


Figure 4.17: Parameter weighting factors based on mud cake thickness for Newtonian fluid

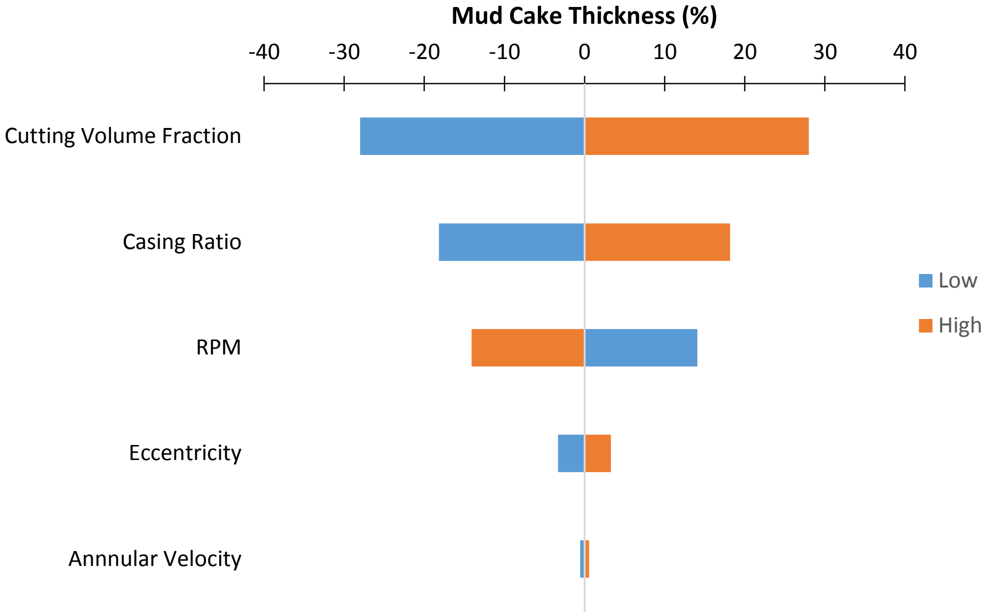
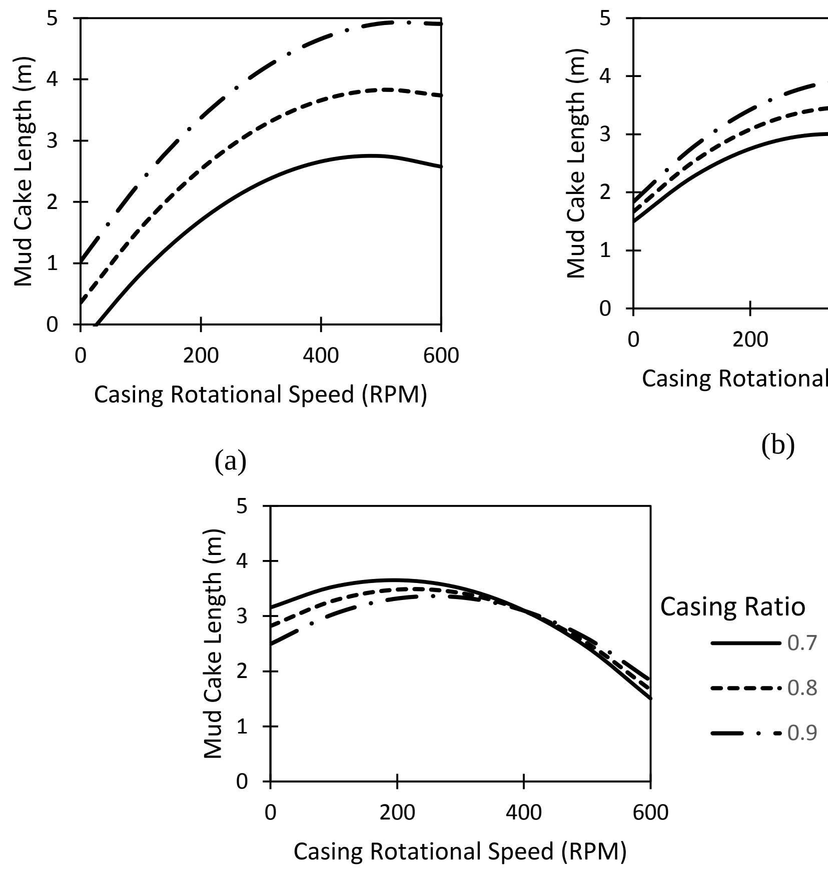


Figure 4.18: Parameters' sensitivity to mud cake thickness for Newtonian fluid

The parameters' sensitivity on mud cake thickness in Newtonian fluid is constructed in tornado chart as shown in Figure 4.18. This chart clearly illustrates the sensitivity of parameters to the solution. It reveals that the most sensitive parameters are the cutting volume fraction has the affecting percentage more than 25% out of the five parameters. The least sensitive parameters include the casing ratio and casing rotational speed with sensitive range of 15% to 20%. While casing eccentricity and fluid annular velocity almost not effecting the mud cake thickness with sensitivity value less than 5%.

4.4.2 Mud Cake Length



(c)

Figure 4.19: Mud cake length based on casing rotational speed with various casing ratio and eccentricity (a) 0, (b) 0.45 and (c) 0.9 with annular velocity = 0.75 m/s and cutting volume fraction = 0.3

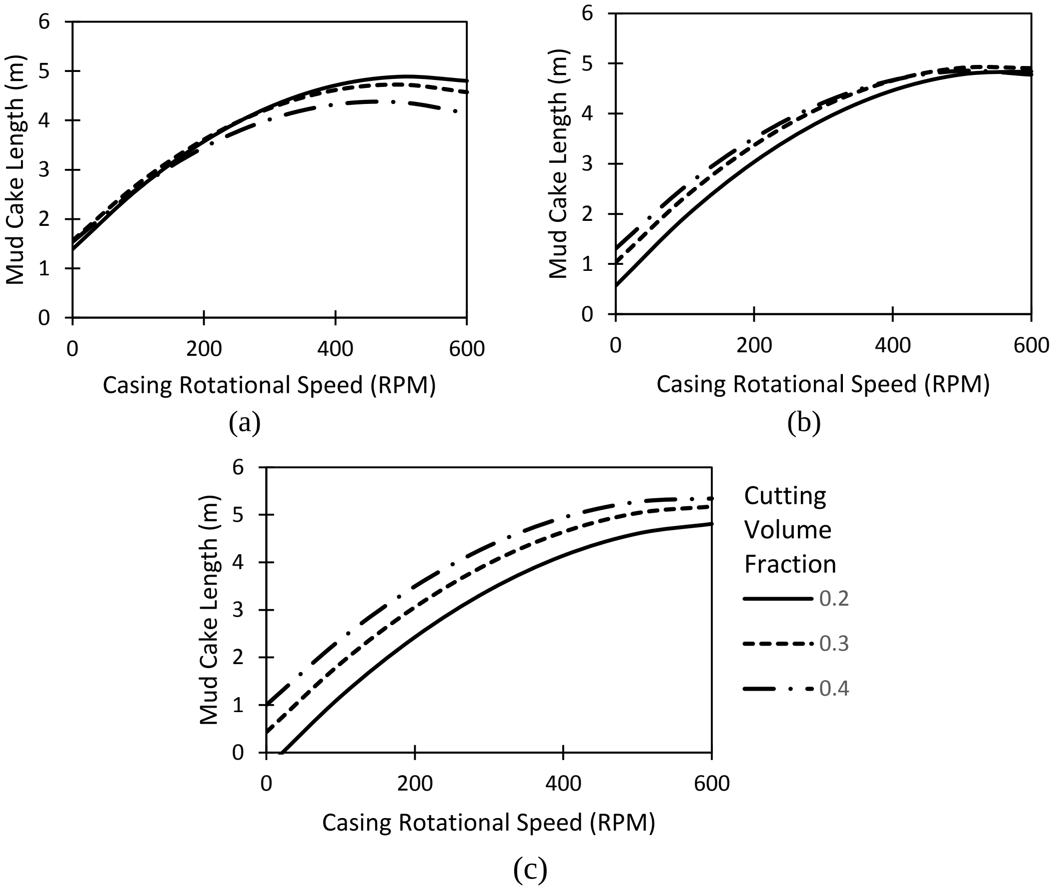
In figure 4.19 (a), (b) and (c), mud cake length were analyze based on casing rotational speed, casing to open hole size ratio and eccentricity. From all the graphs in figure 4.19, the higher the casing rotational speed will produce longer mud cake on the wellbore. But when it reach maximum length, the mud cake length start decreasing even casing rotational speed is increase.

Table 4.3: Maximum mud cake length value in (m) from figure 4.19 (a), (b) and (c)

	Casing Eccentricity (E)		
Casing Ratio (R)	**0**	**0.45**	**0.9**
0.7	2.75	2.99	3.65
0.8	3.83	3.45	3.47
0.9	4.92	3.96	3.34

In term of maximum length of mud cake on the wellbore surface, for figure (a) and (b) when eccentricity is 0 and 0.45 respectively, casing ratio of 0.9 has the longer mud cake followed by 0.8 and 0.7 respectively. Therefore, the larger the casing ratio, will produce longer mud cake length. However, in figure 4.19 (c) when eccentricity is 0.9, it in reverse order, where casing ratio 0.7 produce longest mud cake followed by 0.8 and 0.9 respectively.

Referring to table 4.3, only in casing ratio 0.7 case, where mud cake length will increase casing eccentricity will increase the length of mud cake. Different situation happen in casing ratio 0.8 and 0.9 case, when the casing eccentricity increase, the mud cake length will decrease.



(c)

Figure 4.20: Mud cake length based on casing rotational speed with various cutting volume fraction and annular velocity (a) 0.5 m/s, (b) 0.75 m/s and (c) 1.0 m/s with eccentricity = 0 and casing ratio = 0.9

Table 4.4: Maximum mud cake length value in (m)
from figure 4.20 (a), (b) and (c)

	Annular Velocity (m/s)		
Cutting Volume Fraction	**0.5**	**0.75**	**1**
0.2	4.89	4.84	4.81
0.3	4.72	4.91	5.17
0.4	4.36	4.85	5.35

From figure 4.20 (a) and table 4.4, when annular velocity is 0.5 m/s, the maximum mud cake length decrease if the cutting volume fraction increase. However, for annular velocity is 1 m/s. the maximum mud cake increase when cutting volume fraction increase. For every cutting volume fraction, the maximum mud cake length produce are approximately the same by varying the annular velocity.

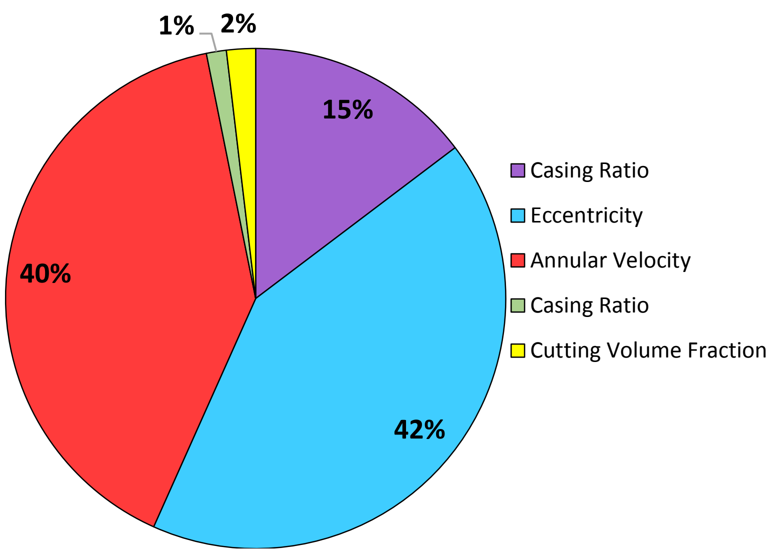


Figure 4.21: Parameter weighting factors based on mud cake length for Newtonian fluid

From the parametric studies above for mud cake length, Figure 4.21 summarizes the influence of five parameters in percentage upon mud cake length for plastering effect in Newtonian fluid. It illustrates that casing eccentricity does the most impact on the plastering effect, and then followed by the annular velocity and casing rotational speed respectively. Cutting volume ratio and casing size ratio have the least impact plastering effect compared to the rest of the parameters.

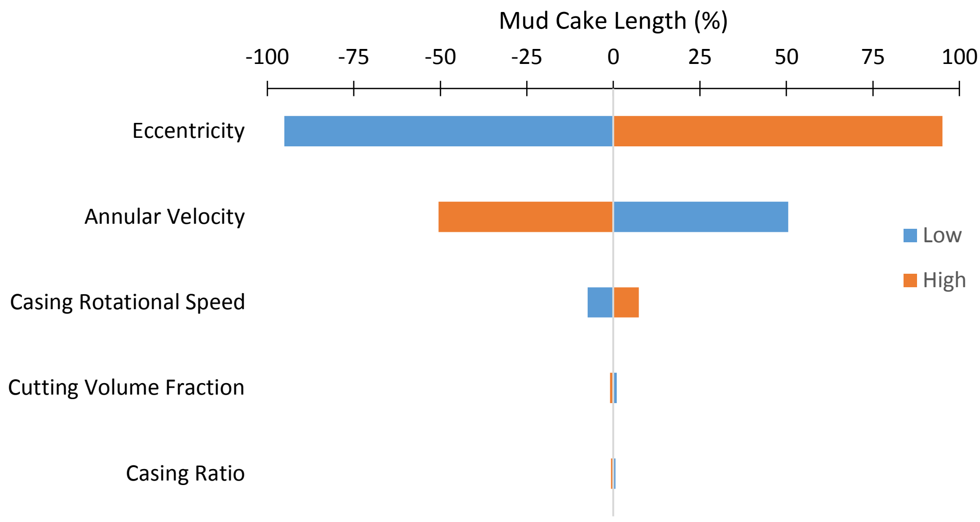
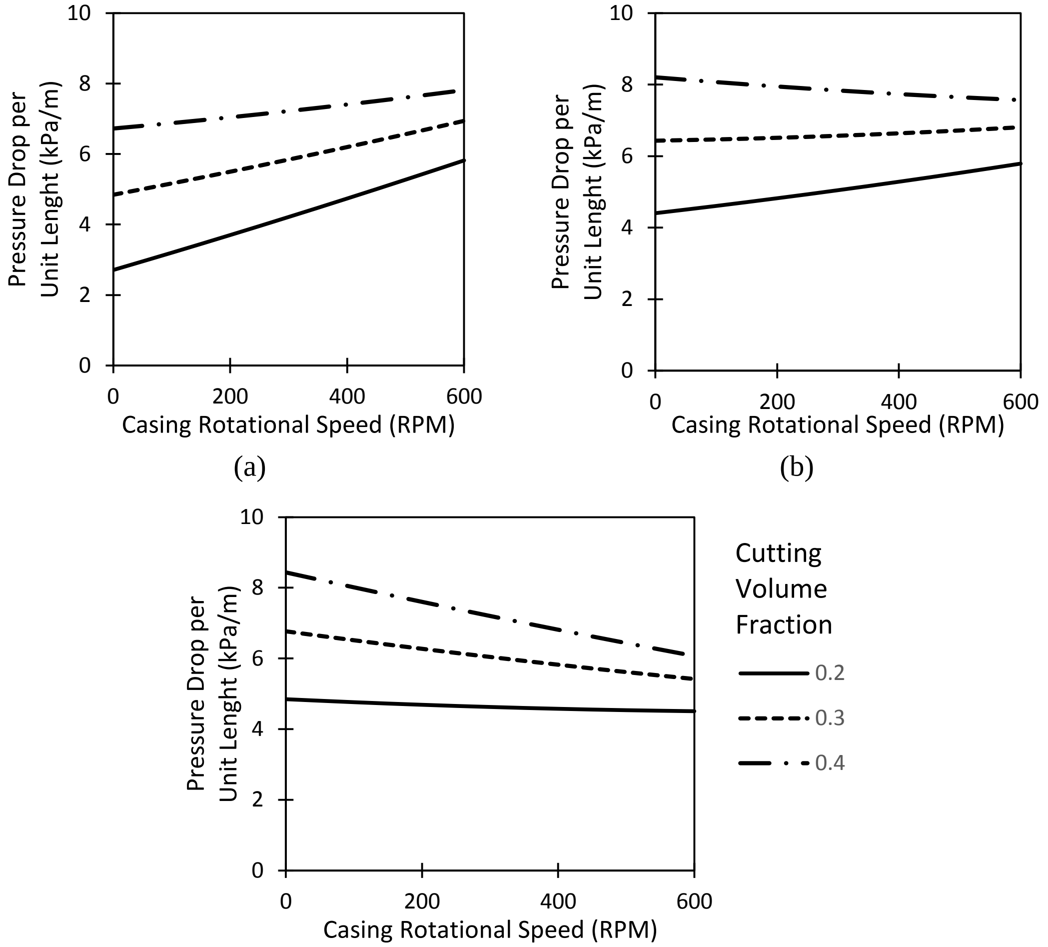


Figure 4.22: Parameters' sensitivity to mud cake length for Newtonian fluid

Figure 4.22 is a tornado chart to measure parameters' sensitivity to mud cake length. From the figure that the most sensitive parameter is eccentricity where it has the affecting percentage more than 90% out of the five parameters. The sensitivity parameters followed by the annular velocity and casing rotational speed respectively. The least sensitive is the cutting volume fraction and casing to open hole size ratio respectively with less than 1% of percentage.

4.4.3 Pressure Drop per Unit Length



(c)

Figure 4.23: Pressure drop per unit length based on casing rotational speed with various cutting volume fraction and casing size ratio (a) 0.7, (b) 0.8 and (c) 0.9 with eccentricity = 0.45 and annular velocity = 0.75

Figure 4.23, analyze the effect of casing rotational speed, casing size ratio and cutting volume fraction on pressure drop for plastering effect in CwD. From figure 4.23 (a), (b) and (c), for all cases, the pressure drop increase when the cutting volume fraction increase. However, for casing ratio case, casing ratio 0.7 will produce a positive gradient. Where casing rotational speed increase, pressure drop will be increase. The gradient trend is changing when casing ratio increase. Casing ratio 0.9 give a negative gradient that decrease pressure drop when increasing the casing rotational speed.

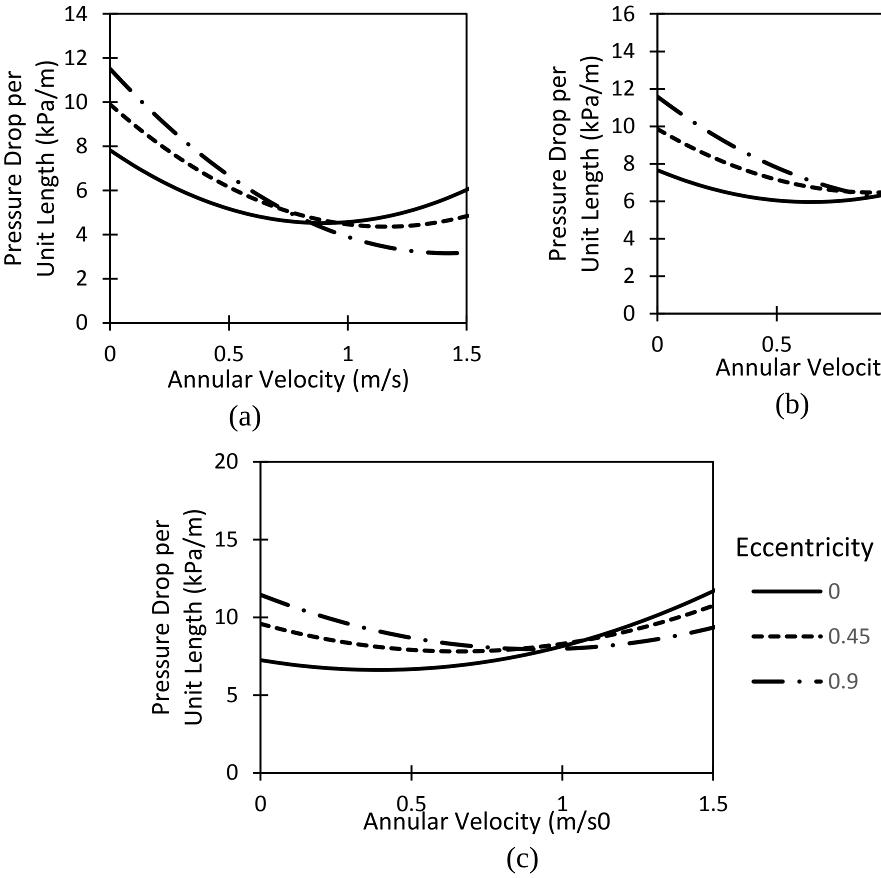


Figure 4.24:Pressure drop per unit length based on annular velocity with various eccentricity and cutting volume fraction (a) 0.2, (b) 0.3 and (c) 0.4 with casing rotational speed = 300 RPM and casing ratio = 0.8

Figure 4.24, analyze the effect of annular velocity, eccentricity and cutting volume fraction on pressure drop for plastering effect in CwD. From figure 4.24, the pressure drop per unit length decrease when annular velocity increase until the minimum point. After the minimum point, pressure drop start to increase.

Table 4.5:Minimum pressure drop per unit length value in (kPa/m) from figure 4.24 (a), (b) and (c)

	Cutting Volume Fraction		
Eccentricity	**0.2**	**0.3**	**0.4**
0	4.52	5.97	6.62
0.45	4.37	6.47	7.81
0.9	4.28	5.95	7.95

Table 4.5 referring to the minimum value of pressure drop per unit length for graph in figure 4.24 (a), (b) and (c). For cutting volume fraction 0.2, the minimum pressure drop decrease when eccentricity increases. Different situation when cutting volume fraction is 0.4, the minimum pressure drop increase with increase of eccentricity. For all cases in different eccentricity, the pressure drop increases when cutting volume fraction increases.

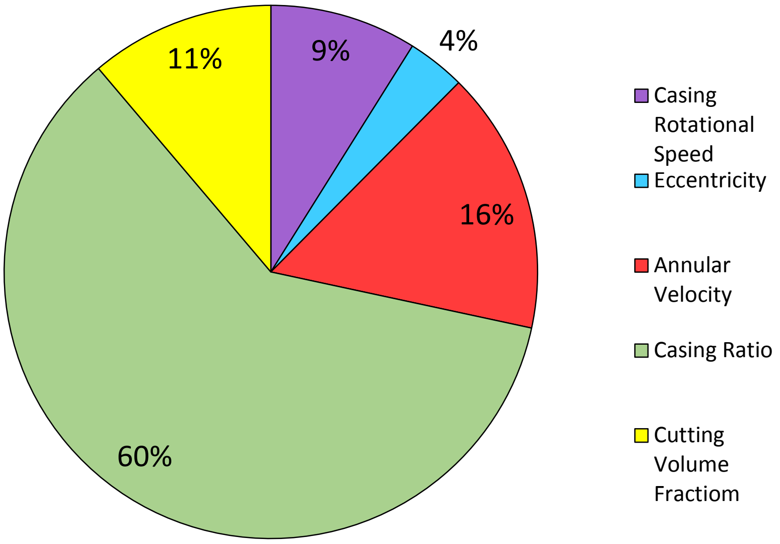


Figure 4.25: Parameter weighting factors based on pressure drop per unit length for Newtonian fluid

From the parametric studies above for pressure drop, Figure 4.25 summarizes the influence of five parameters in percentage upon pressure drop per unit length for plastering effect. It illustrates that casing to wellbore size ratio does the most impact on the plastering effect, and then followed by the cutting volume fraction, drilling fluid annular velocity and casing rotational speed respectively. While, eccentricity have the least impact plastering effect compared to the rest of the parameters.

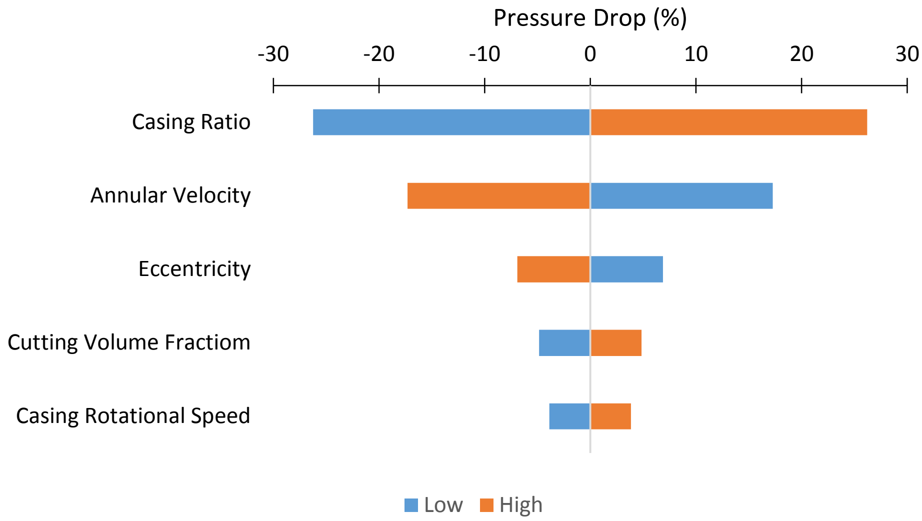


Figure 4.26: Parameters' sensitivity to pressure drop per unit length for Newtonian fluid

Figure 4.26 shows tornado chart to measure parameters' sensitivity to pressure drop per unit length. The most sensitive parameter is casing ratio where it has the most dominating effects of more than 20% of the five parameters. The sensitivity of the parameters is as followed: annular velocity, eccentricity, and casing to wellbore size ratio. The least sensitive parameter is the casing rotational speed.

CHAPTER 5

CONCLUSION and RECOMMENDATION

From the research, the factors enhancing plastering effect can from drilling parameter and condition such as type of drilling fluids, casing size to wellbore size ratio, casing eccentricity, casing rotational speed, drilling fluid annular velocity and cutting volume fraction. The contribution of all the factors been measured from three outcomes which are mud cake thickness, mud cake length on wellbore surface and also pressure drop per unit length in the annulus.

Conclusion from the parametric study, in non-Newtonian fluid, the most contributing factors are cutting volume fraction, casing size to wellbore size ratio and casing rotational speed. While annular velocity and casing eccentricity does not contribute much. In addition, casing eccentricity does not make any significant in plastering effect for non-Newtonian fluid. For Newtonian fluid, the most contributing factors are cutting volume fraction and casing size to open hole size ratio. While annular velocity, casing rotational speed and casing eccentricity still give lesser contribution in plastering effect. Comparing non-Newtonian and Newtonian fluid based on mud cake thickness and length, plastering effect are easily to produce in Newtonian fluid. This is because the viscosity of Newtonian fluid is lesser than the non-Newtonian fluid used in this research.

In real world, drilling fluid that been use in the industry is non-Newtonian fluid. Therefore, future research for plastering effect in CwD more detail studies can focus on non-Newtonian fluid. Using power law for non-Newtonian fluid, the value of viscosity consistency index, K and power-law index, n can be vary for next study. Besides that, cutting size or particle size also can be consider as one of the factor for future studies. Lastly, vertical well also important that need to be considered as one of drilling condition for plastering effect in CwD.

APPENDIX

Designing the Wellbore Model

Designing Length of the Wellbore Model

The length of wellbore model must be long enough to ensure that the end effect of an annular pipe can be eliminate.

$$\boldsymbol{L > L_e} \qquad \textbf{A. 1}$$

To determine the length of end effect, L_e, Reynolds number need to be calculated first.

For water (Newtonian fluid),

$$N_{Re} = \frac{\rho V(D_0 - D_i)}{\mu} \qquad \textbf{A. 2}$$

For non-Newtonian Fluid (power law)

$$\boldsymbol{N_{Re} = \frac{(D_0 - D_i)^n V^{2-n} \rho}{K8^{n-1}(3n+1/4n)^n}} \qquad \textbf{A. 3}$$

Where N_{Re}< 2100 is laminar flow and N_{Re}>2100 is turbulent flow

From the Reynolds number, end effect length can be calculated using two equations below according to the flow type.

For laminar flow,

$$\boldsymbol{L_e = 0.06\,(D_0 - D_i)N_{Re}} \quad \textbf{\textit{unit in meter}} \qquad \textbf{A. 4}$$

For turbulent flow,

$$\boldsymbol{L_e = 4.4(D_0 - D_i)(N_{Re})^{1/6}} \quad \textbf{\textit{unit in meter}} \qquad \textbf{A. 5}$$

Determining Offset for Casing Eccentricity

Formula below is to determine the offset value of casing from the center of wellbore base on eccentricity factor.

$$\boldsymbol{Offset\ Distance = \frac{eccentricity\ factor\ (D_0 - D_i)}{2}} \quad \textbf{\textit{unit in meter}} \qquad \textbf{A. 6}$$

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