Effects of Drilling Fluid Rheological Properties on Drill Cuttings Transport

By

Norsaiful Bin Rosli

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

DECEMBER 2010

Universiti Teknologi PETRONAS,

Bandar Seri Iskandar,

31750 Tronoh,

Perak Darul Ridzuan.

CERTIFICATION OF APPROVAL

Effects of Drilling Fluid Rheological Properties on Drill Cuttings Transport

By

Norsaiful Bin Rosli

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

Approved by,

____

(Dr. Azuraien Jaafar)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
DECEMBER 2010

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.

NORSAIFUL BIN ROSLI

ABSTRACT

During well drilling process, drill cuttings were produced. Drill fluid (or mud) has been used to remove the drill cuttings that are produced in the well by transporting it to the surface. The removal of drill cuttings is important in ensuring a smooth drilling process. In order for the drilling fluid to transport the drill cuttings effectively, the rheological properties of the drilling fluid such as viscosity, suspension, yield stress and velocity must be taken into consideration. Biopolymers such as xanthan gum and scleroglucan have been widely used as additives to improve the rheological properties of the cutting fluid. This project is about studying the **Effects of Drilling Fluid Rheological Properties on Drill Cuttings Transport**. The project consists of rheological data gathering of the drilling fluids, performing numerical simulations of the drilling fluids, and study of the relationship between the drill cuttings accumulation and the drilling fluid rheology in achieving optimum drill cuttings management. This report will describe in detail the background study of the project, the problem statement that leads to the objectives of this project, the objectives, the scope of studies during this project, literature review, methodology or steps taken to complete this project, results, discussions and recommendations.

ACKNOWLEDGEMENTS

A bunch of appreciation is given to my supervisor, Dr Azuraien Jaafar, whose encouragement, supervision and support from the beginning to the concluding level enabled me to develop deeper knowledge regarding the subject.

Special thanks to my parents and family members for supporting and encouraging me to pursue this degree. Not to forget, all my friends especially Mechanical Engineering students, class of 2010, who had helped me a lot in conducting the project and shared the opinions and ideas regarding this project.

I would also like to dedicate this report to my late father, Rosli Bin Sapar (15th June 1956 – 4th October 2010). You will always live in my heart. May you rest in peace.

Lastly, I offer my regards and blessings to all of those who supported me in any respect during the completion of the project.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1 Project Background

Well drilling is a process where a hole was drilled in the ground for the purpose of extraction of the natural resources such as natural gas and petroleum.

Drill cuttings will be produced during a well drilling process. Drill cuttings refer to any materials removed from the borehole during well drilling. Sand and shale are the most common drill cuttings encountered while drilling a well. Drill cuttings are usually removed from the borehole by using drilling fluid (or mud).

Drilling fluid plays a few of important roles during the well drilling process. One of the most important roles of drilling fluid is to carry drill cuttings to the ground surface. To perform this action, the rheological properties of the drilling fluid are one of the important things to be considered. Shear thinning fluid with high yield stress is desired so that it could suspend drill cuttings at low shear rates, but offer little resistance to flow at high shear rates. Xanthan gum is the example of one of the polymers commonly used to improve the rheological properties of drilling fluids.

Removal of drill cuttings from below the drill bit to the surface is important in ensuring a smooth drilling process. It is always critical for the fluid velocity in the annulus to exceed the downward falling rate of the cuttings since particle in a rising fluid column will only move upward if these condition is achieved.

Poor cuttings transport could result in undesirable increase of cuttings volume as the drilling proceeds. It has been reported that cuttings concentrations more than about 5% by volume can result in a narrowing of the annular gap due to the build up of cuttings. This narrowing leads to a low penetration rate and a blocked pipe when the circulation is stopped, a situation which can result in costly problems (Vinod, 1994).

This project will be focusing on the study of the effects of rheological properties of drilling fluid such as viscosity, suspension, yield stress and velocity on drill cuttings transport by performing numerical simulations using computational fluid dynamics software.

1.2 Problem Statement

As the well is drilled, the drill cuttings which consist of crushed rock and clay are brought to the surface by the drilling fluid and discharged overboard. The removal of drill cuttings from below the drill bit to the surface is important in ensuring a smooth drilling process. The efficiency of the drill cuttings removal depends on several fluid and flow properties of the drilling fluid such as viscosity, suspension, yield stress and velocity apart from the density and the size of cuttings (Vinod, 1994).

One of the ways to increase the efficiency of the drill cutting removal is to utilize a shear thinning fluid such as biopolymers; xanthan gum and scleroglucan to name a few; as additives to the drilling fluid. The usage of the biopolymers is said to pose a minimal environmental problem. However, there is no complete investigation on the drill cuttings management with biopolymers as additives in the drilling fluid.

1.3 Objectives and Scope of Study

1.3.1 Objectives

The main objective for this study is to perform numerical simulation of the drill cuttings flow using the available rheological data of biopolymers, xanthan gum and scleroglucan and assess the drill cuttings transport efficiency. The simulations will be within the fully developed laminar flow regime.

1.3.2 Scope of Study

Commercial computational fluid dynamics software (CFD) FLUENT v6.1.22 will be utilized together with GAMBIT v2.1.6 for this study. GAMBIT v2.1.6 will be used for producing the geometric modelling and meshing of the annular pipe (a conduit within which transport of drill cuttings takes place) while FLUENT v6.1.22 will be used to perform the numerical simulation of the drill cuttings removal by the drilling fluid during drilling operations.

The study will involve performing numerical simulations for drilling fluid with 0.07% xanthan gum and 0.1% carbopol which also a Yield Stress Fluid. The result of the numerical simulations will then be compared with the available experimental data obtained from the literature. The simulations will then be extended by the addition of 0.1% scleroglucan where no experimental data is available. The drill cuttings will further be incorporated with the simulation. The relationship of the drilling fluid rheological properties and the drill cuttings accumulations will further be studied in order to achieve the amount of less than 5% drill cuttings accumulation which is the optimum drill cuttings management.

CHAPTER 2
LITERATURE REVIEW

2.1 Drilling Fluid Rheological Properties

Drilling fluid's function is to transport drill cuttings to the surface. To accomplish this, the drilling fluid must have sufficient viscosity to transport the cuttings at minimum pumping power from the mud pump. In transporting cuttings, increased viscosity can be achieved at low shear rate i.e. reduced velocity. This is essential in order to suspend the cuttings when the flow is stopped. At the same time, decreased viscosity will require an increase in velocity. According to Berry, of CETCO® Construction Drilling Product, a drilling fluid should be mixed to a minimum viscosity and pumped at a minimum velocity that will still allow cutting removal.

When drilling stops, for whatever reason, the drilling fluid must be able to suspend the cuttings and not allowing them to fall back down the annulus. Once the cuttings reached the surface, they must be separated from the drilling mud which will then be reused again. If the cuttings are not separated, they will cause wear to the pump and increase pressure to the formation due to the increase of the density of the cuttings and mud mixture.

These are some of the important drilling fluid’s rheological properties for the drilling fluids to perform its function:

Viscosity – Yield Point

Viscosity is the resistance of flow caused by mechanical friction between the particles in a drilling fluid. The yield point is dependent on the electro-chemical charges in the fluid under flowing conditions. Particles may be charged so that they attract each other producing a high yield point, or particles may repel one another making the yield point lesser. Yield point may be controlled and changed by the use of chemical additives.

Gel Strength

Gel strength is the measuring of thixotropic properties of a drilling fluid under non-flowing conditions, while the yield point measures these properties under flow conditions. On the other hand, gel strength is a measure of a fluid’s ability to hold particles in suspension.

Filtration

The filtration property of drilling fluids is a measure of the ability of the solid phase of a fluid to form a thin, low-permeability cake of filtered solids (wall building). The less permeability the cake has, the thinner the cake will form. The loss of fluid is also dependent on permeability of the filter cake. By minimizing fluid loss, a thinner filter cake forms and drilling problems are minimized. Excessive filter cake thickness could result in drill sticking.

2.2 Drilling Fluid Additives

The bentonite clay oftenly used as an additive in drilling fluid. It is added to fresh water to: (1) increase the hole cleaning properties, (2) reduce water seepage or filtration into permeable formation, (3) form a thin filter cake of low permeability, (4) promote hole stability in poorly cemented formations and (5) avoid or overcome loss of circulation. (Mahto and Sharma, 2004)

However, a high clay solids content of drilling fluid has several adverse effects: (1) greatly reduces the rate of penetration, (2) increased chances of differential sticking and (3) is the major cause of excessive torque and drag. Thus, low bentonite content is desired to control the total amount of solids. At low concentration, bentonite clay is unable to provide satisfactory rheological properties required for optimum performance in oil well drilling. Hence, polymers are added to achieve the desired result. (Mahto and Sharma, 2004)

One of the biopolymers that are widely used in drilling fluid is xanthan gum (XG). XG is widely used in the oil & gas industry as an effective viscosifier. Xanthan gum remains stable at high temperatures, and in the presence of acids, alkalis, salts and enzymes. Because of its very high low-shear pseudo plastic viscosity and shear-thinning character, Xanthan gum is often used for viscosity control. XG is biodegradable, and thus, is extremely environmentally friendly. (T. Hamida et. al. 2009)

2.3 Project Overview

2.3.1 Previous Research on Drilling Fluid Rheological Properties

Some researches have been done on the rheological properties of drilling fluid and drill cuttings transport, Okrajni and Azar, (1991) amongst others. The authors discuss the effects of drilling fluid additives on the yield point (YP), plastic viscosity (PV), and YP/PV ratio of the drilling fluid. One significant finding was the degree to which increasing YP/PV ratio augments the influence of yield value. They also discussed on how hole angle influences determination of the optimal flow regime. Testing conducted confirmed that laminar flow is preferable for holes from vertical to 45° while turbulent flow is recommended for inclination angles from 55° to horizontal (Okrajni and Azar (1991)).

Bazarnova et al. (2000) introduced the usage of Carboxymethyl cellulose (CMC) as an additive to the drilling fluids. They claimed that Carboxymethyl cellulose Sodium Salt (NaCMC) that has low viscosity is used to reduce the filtration of drilling fluid of very high density and medium-viscosity NaCMC is added to drilling fluid solution with low density of the solid phase. NaCMC suspension has the property of shear thinning; they posses high relative viscosity at low shear rate. They also stated that addition of NaCMC produces better operation of rock cutting tools, increase boring speed and headway per drill bit, and improve mud pumping.

Mahto and Sharma (2004) stated that the usage of 0.5 – 2.5 g/L Tamarind Gum caused increase in apparent viscosity, plastic viscosity (PV), Yield Point (YP), YP/PV ratio, and gel strength of the drilling fluid. They added that the usage of 1 – 5 g/L polyanionic cellulose (PAC) caused same effects as above. They finally relate the effect of these two additives by stating that apparent viscosity, plastic viscosity (PV), Yield Point (YP), YP/PV ratio, and gel strength of the mixture containing 0.1% PAC and 3% bentonite increase with increase in the concentration of tamarind gum.

Hamed and Belhadri (2009) conducted the study on the effect of the components; Clay High Mod Prima (HMP), Calcium carbonate, and potassium chloride on the rheological properties of water-based drilling fluid which contains biopolymers scleroglucan and xanthan gum respectively. Their finding can be summarized as below:

- Consistency is higher for fluid containing xanthan gum than for those containing scleroglucan for various HMP, calcium carbonate and potassium chloride concentration.
- The yield stress in all samples is low which reflects one of the characteristic of a good drilling fluid.
- The rheological property of biopolymers does not vary much with presence of potassium chloride particularly for scleroglucan.
- The result also shows that scleroglucan have higher stability with salinity.
- Scleroglucan was proposed as better alternatives than xanthan gum.
- Disadvantages of scleroglucan, the fluid must be kept lower than 12.5pH or the polymer will irreversibly loss its rheological properties

2.3.2 Oil and Gas Industry Applications

Schlemmer, of Scomi Oiltools, GRTC, Malaysia introduced Scomi's drilling fluid called CONFI-DEEP.CONFI-DEEP has stable rheological properties; yield point and gel strengths that are nearly temperature independent. He stated that CONFI-DEEP improves hole cleaning with its high yield point without accompanying higher plastic viscosity and gels. CONFI-DEEP supports use of higher penetration rates than conventional invert emulsion muds. CONFI-DEEP reduces the chance of whole mud loss and formation damage to productive reservoir rock.

B. Onyekpe of Shell Intensive Training Centre, Shell Petroleum Dev. Co., Warri, Nigeria (2001) conducted an investigation of the effects of carbonate contaminants on the rheological properties of drilling mud. The investigation was done by addition of 0 – 70g of Sodium Carbonate (NA2CO3) in 8 samples (each 500ml) of the same drilling fluid. He concluded that yield point and gel strength increased as the concentration of carbonate increased in the drilling fluid and plastic viscosity has only a slight increase as carbonate concentration is increased.

2.3.3 Drill Cuttings Properties and Numerical Simulation Parameters

Njobbuenwu, D.O. and Wobo, C.A. (2007), conducted a study on the effects of drilled solids on drilling rate and performance. In their study, they used large amounts of API-quality bentonite to simulate drill solids since they have similar average specific gravity of 2.6 according to Lapeyrouse, 1992, BHI, 1998. They also state that, drilled solids such as limestone and dolomite have specific gravity, SG=2.7-2.9, whereas, shale have SG range of 2.4-2.8. In their study, they also assumed that density of drilled solids to be 2.6 g/cm^3.

Y. Li, E. Kuru (2005) conducted numerical modelings of cuttings transport with foam in vertical wells. Some of the input variables for his study were 1) Depth of vertical well: 3000ft, 2) Hole diameter: 7-7/8 in, 3) Drill pipe OD: 4-1/2 in, 4) Drill pipe ID: 3.76 in, 5) Cutting size: 0.5 in, 6) Cuttings SG: 2.7, 7) Drilling rate: 60 ft/hr. They also assumed that the drill cuttings have spherical shape with uniform sizes. Some of notable findings in this study were 1) Larger cuttings size yields to higher cuttings concentration, and 2) Cuttings with irregular shapes lead to lower cuttings accumulation.

Y. Li et. al. (2007) on the other hand conducted numerical modeling of cuttings transport in horizontal wells using conventional drilling fluid. Some of the base data used for comparing experimental and numerical results were, 1) Hole diameter: 0.2032m (8.0 in), 2) Drill pipe OD: 0.1143m (4.5 in), 3) Eccentricity: 0.62, 4) Cuttings size: 0.0064m (0.25 in), 5) Rock Density: 2600 kg/m^3 (21.7 lb/gal), 6) Liquid flow rate: 568 – 1325 L/min (150 – 350 gal/min). They also assumed that the drill cuttings have spherical shape with uniform sizes, shape and velocity at a given cross-sectional area of the well.

Syed M. Hussaini, Jamal J. Azar (1983) did the experimental study of drilled cuttings transport using common drilling muds. From this study, it has been shown that in vertical annuluses, the fluid annular velocity has a major effect of the carrying capacity of muds while the other parameters have an effect only at low to medium fluid annular velocity. Some of the input variables for this study were 1) Average annular velocities of 12, 18, and 23.9 in/sec, 2) Cuttings size of 5/16 in (0.76 cm).

CHAPTER 3

METHODOLOGY

3.1 Project Flow Chart

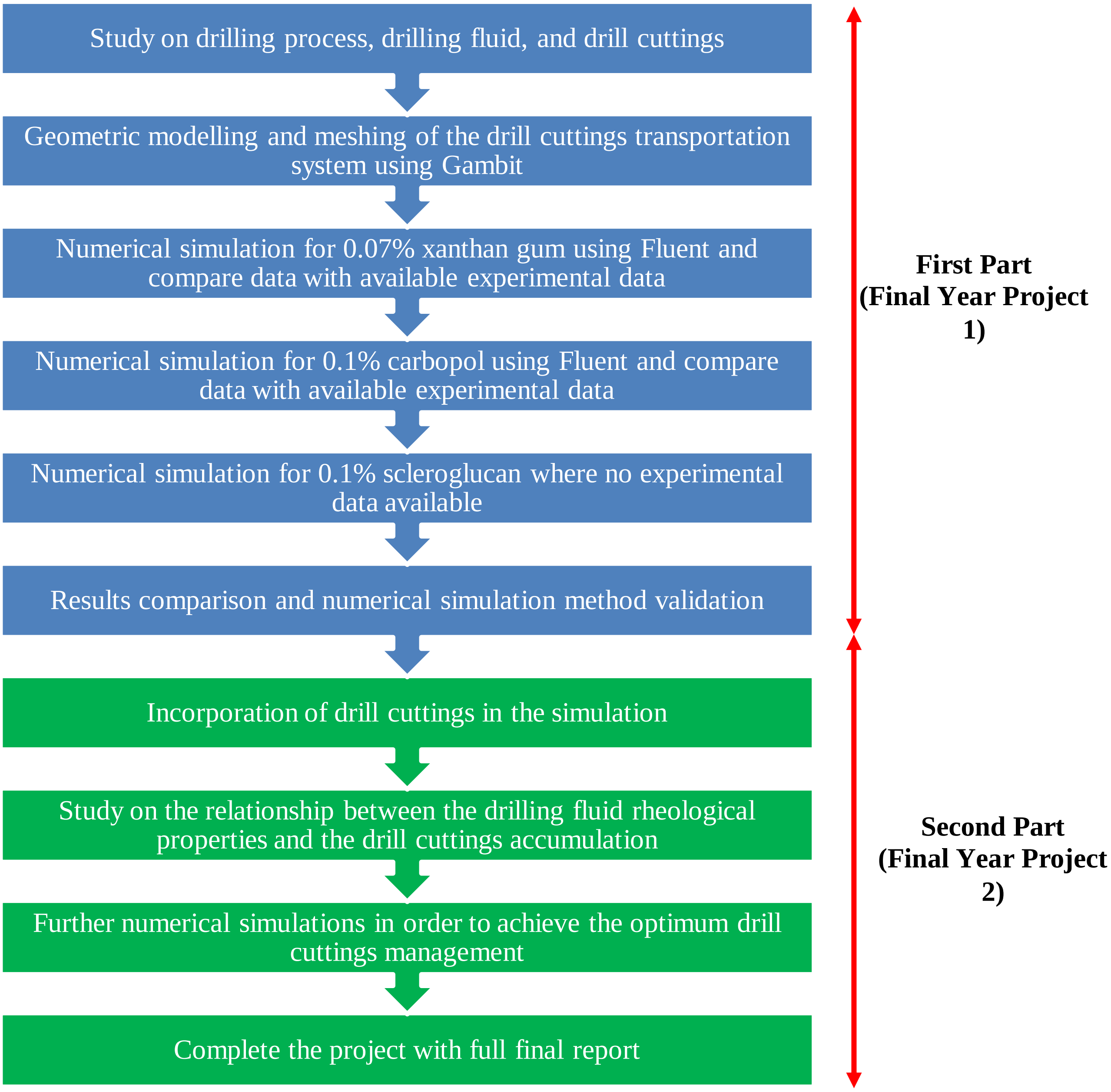


Figure 3.1: Project Flow Chart

The overall project flow are divided into two parts, the first part which is Final Year Project 1 (FYP1), represented by blue colours in the chart and the second part which is Final Year Project 2 (FYP2), represented by green colours in the chart.

3.2 Project Gantt Chart

3.2.1 Gantt Chart for First Part (FYP1)

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Selection of project topic	🟦	🟦						**Mid – Semester Break**								
2	Preliminary Research Work / FLUENT and GAMBIT familiarization		🟦	🟦	🟦												
3	Submission of Preliminary Report					🟥											
4	Geometry modelling and meshing					🟦	🟦	🟦									
5	Submission of Progress Report									🟥							
6	Seminar									🟥							
7	Numerical Simulation of 0.07% Xanthan Gum using FLUENT									🟦	🟦						
8	Numerical Simulation of 0.1% Carbopol using FLUENT											🟦	🟦				
9	Numerical Simulation of Scleroglucan using FLUENT													🟦	🟦		
10	Submission of Interim Report final draft															🟥	
11	Oral presentation																🟥

Legends

🟥 Important Date

🟦 Process

3.2.2 Gantt Chart for Second Part (FYP2)

No	**Detail/Week**	**1**	**2**	**3**	**4**	**5**	**6**	**7**		**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1	Continuation of project works (planning)	🟦							**Mid – Semester Break**								
2	Preliminary Research on drill cuttings properties / FLUENT multiphase flow model familiarization		🟦	🟦	🟦												
3	Submission of Progress Report 1					🟥											
4	Numerical Simulation of 0.07% Xanthan Gum with drill cuttings					🟦	🟦										
5	Numerical Simulation of 0.1% Carbopol with drill cuttings							🟦		🟦							
6	Seminar										🟥						
7	Submission of Progress Report 2										🟥						
8	Numerical Simulation of Scleroglucan with drill cuttings										🟦	🟦					
9	Wrap up project data												🟦				
10	Poster Exhibition													🟥			
11	Overall project review													🟦	🟦		
12	Submission of Dissertation final draft															🟥	
13	Oral Presentation															🟥	
14	Submission of Dissertation (Hard Bound)																

Legends

🟥 Important Date

🟦 Process

3.3 Project Works Overview

The project will begin with finding of literature review from various source of reference such as journals and books for the fundamental understanding about the project. The next steps of project works can be divided into three major parts:

- Geometry modelling and meshing
- Numerical simulation methods validation
- Numerical simulation of drill cuttings accumulation inside the annulus

The first part, geometry modelling and meshing includes utilizing the modelling software, GAMBIT v2. The software will be used to create the geometry model according to the desired dimension and specification. The next step will be meshing of the geometry model created. For this purpose, a computational grid of 10000 cells (100x100 cells) has been chosen. The next step is to set the boundary condition of the geometry. The periodic boundary is the most important boundary condition for the geometry. It is due to the fully-developed nature of the flow; only one row of cells with the length of hydraulic diameter is needed in the direction of the flow as recommended by Escudier et. al. (2002). The final step for the first part is to export the mesh file from GAMBIT v2 software into FLUENT v6 case file (.msh) to enable the geometry and the mesh to be solved using FLUENT v6 software.

The second part of the project includes numerical simulation methods validation. For this part, there are available experimental data for certain drilling fluids, in this case, 0.07% xanthan gum, 0.1% carbopol, and glycerine-water mixture. The numerical simulation input parameters can be calculated based on the available experimental data. The numerical simulation will then be conducted and the result of the numerical simulation will be compared to the result of corresponding experimental data. The numerical simulation method is considered to be “validated” if the result of the numerical simulation shows satisfying agreement with the corresponding experimental data.

The last part of the project is to include the drill cuttings in the numerical simulation for each of the drilling fluids which are xanthan gum, carbopol, scleroglucan, and glycerine. The goal for this part is to study the behaviour of drill cuttings accumulation inside the annulus during the flow of drilling fluid.

As for the time management, the project works are divided into two time sectors according to Final Year Project 1 (FYP I) and Final Year Project 2 (FYP 2). For FYP 1, the project works is up until the numerical simulation methods validation only. The last part which is the numerical simulation of the drilling fluid flow with drill cuttings incorporated will be done during FYP 2.

More detailed descriptions on each stage of project works are available in the next section: *3.4 Project Works Detail Description*.

3.4 Project Works Detail Description

3.4.1 Annulus Geometry Modelling

The annulus can be defined as the space between the outside of the drill string to the borehole wall as illustrated in **Figure 3.2** below.

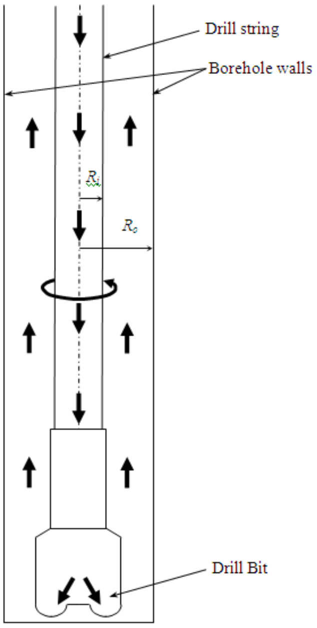


Figure 3.2: Schematic diagram of an annulus in drilling operations

In conventional drilling, a ratio of the inner pipe radius, R_i to the outer pipe radius, R_o of 0.5 is normally used (Escudier et. al., 2002a). The geometry modelling has been done using GAMBIT v2 software using this ratio. The length of the annulus model also has been limited. According to Escudier et. al. (2002), due to the fully-developed nature of the flow, only one row of cells with the length of the hydraulic diameter is needed in the direction of the flow.

The result of the geometry modelling is shown in the **Figure 3.3** to **Figure 3.5** below:

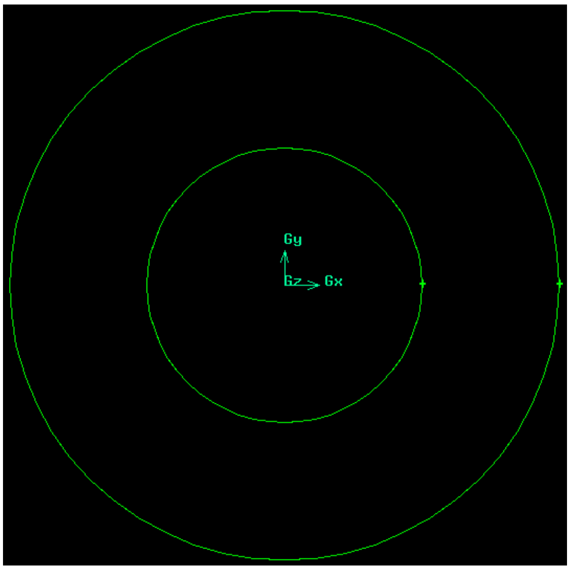


Figure 3.3: Annulus Model Front View

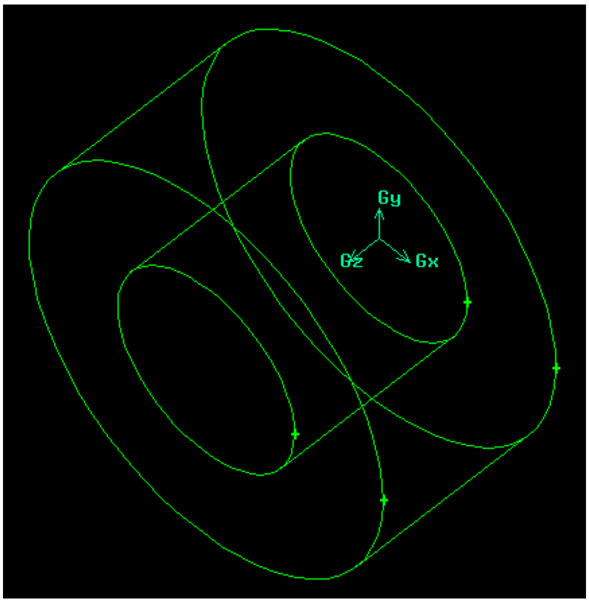


Figure 3.4: Wireframe Annulus Model Isometric View

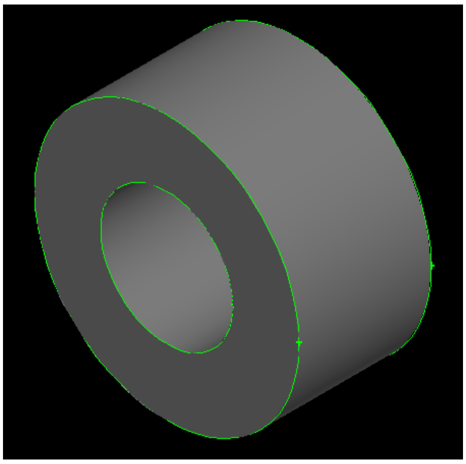


Figure 3.5: Shaded Annulus Model Isometric View

3.4.2 Meshing of Annulus Model

The meshing of the annulus model has been done also by GAMBIT v2 software. A computational grid of 10000 cells has been used, 100x100 in radial and tangential direction. The computational grid of 100x100 cells is selected as it is dense enough to yield an accurate result when compared to the experimental data at optimal time cost. .

The result of the meshing of annulus model is shown in **Figure 3.6** below:

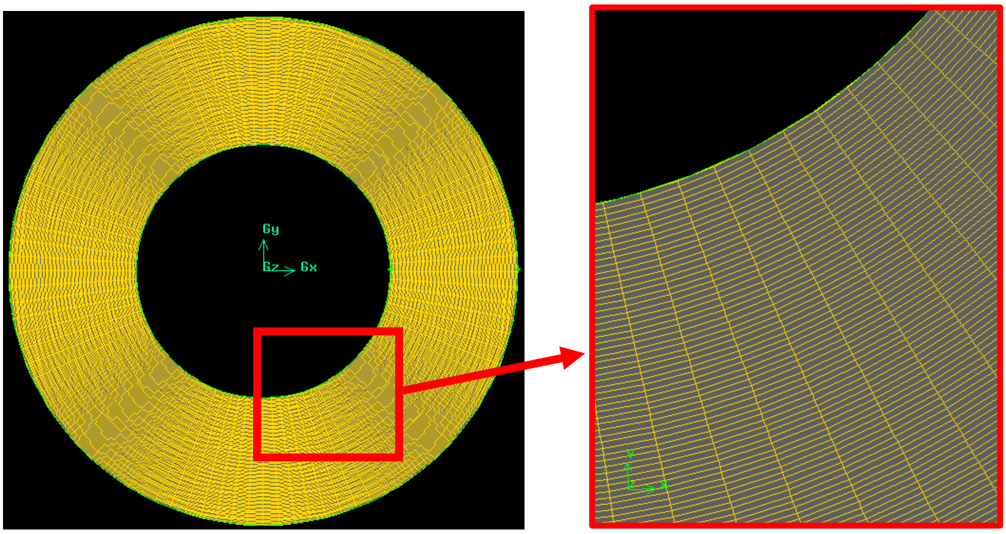


Figure 3.6: Computational Grid 100x100 Meshing

3.4.3 Setting Boundary Condition

The inside and outside wall of the cylinder are set to be wall boundaries. Both ends of the cylinder set to be periodic boundaries. Due to the fully-developed nature of the flow, only one row of cells with the length of the hydraulic diameter is needed in the direction of the flow as recommended by Escudier et. al. (2002).

Figure 3.7 below shows the detail of the boundary condition setting.

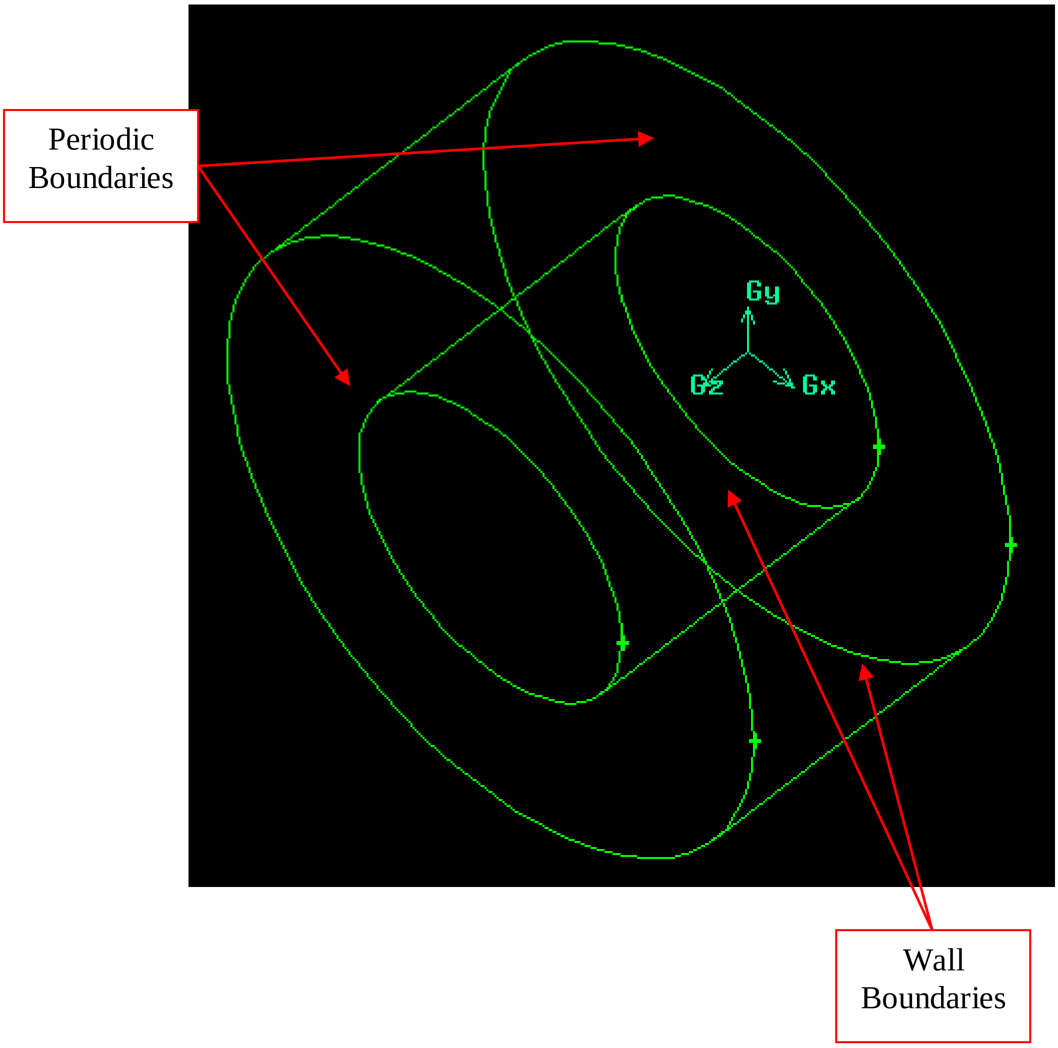


Figure 3.7: Boundary Condition Setting

3.4.4 Numerical Simulation Method Validation

For numerical simulation purposes, computational fluid dynamic (CFD) software, FLUENT v6 was utilized. The software was used to numerically simulate the velocity distribution and the drill cuttings accumulation in the annulus in a laminar regime for both Newtonian and Non-Newtonian fluids. For non-Newtonian fluids, power law model were utilized.

The laminar, fully-developed numerical simulation were carried out by setting the mass flow rate calculated from the power law Reynolds number,

$$Re_{PL} = \frac{\rho U_B^{2-n} D_H^n}{k} \qquad [3.1]$$

as recommended by Escudier et. al. (2002), at periodic boundaries where n is the power-law index and k is the power-law consistency.

The numerical simulation was further divided into two parts. The first part was to plot the velocity distribution graph and compare it with the available experimental data to validate the methods used in the numerical simulation. If the data from the numerical simulation shows an agreement with the experimental data, the methods used in the numerical simulations is considered “validated”. The second part of the numerical simulation is to include the drill cuttings in the simulation and study the behaviour of the drill cuttings accumulation in the different drilling fluid composition.

For Final Year Project 1 (FYP I), the main focus of the project is up until the validation of the numerical simulations methods used by comparing the numerical simulation data and the available experimental data.

For this purpose, few different drilling fluid compositions were chosen where their experimental data is available. The experimental data for each drilling fluid composition was obtained from Jaafar, A., 2009, *Duct flow of polymer solutions*, PhD thesis, University of Liverpool.

3.4.4.1 Numerical Simulation of 0.07% Xanthan Gum (non-Newtonian Fluid)

The available rheological data from the experiment for 0.07% xanthan gum solution at Reynolds number, Re=900, includes:

Power-law Index, *n* = 0.608213
Power-consistency index, *k* = 0.041639
Bulk Velocity, U_B = 0.148822 m/s
Hydraulic Diameter, D_H = 0.0496 m

The velocity distribution graph from the experiment is shown in the **Figure 3.8** below:

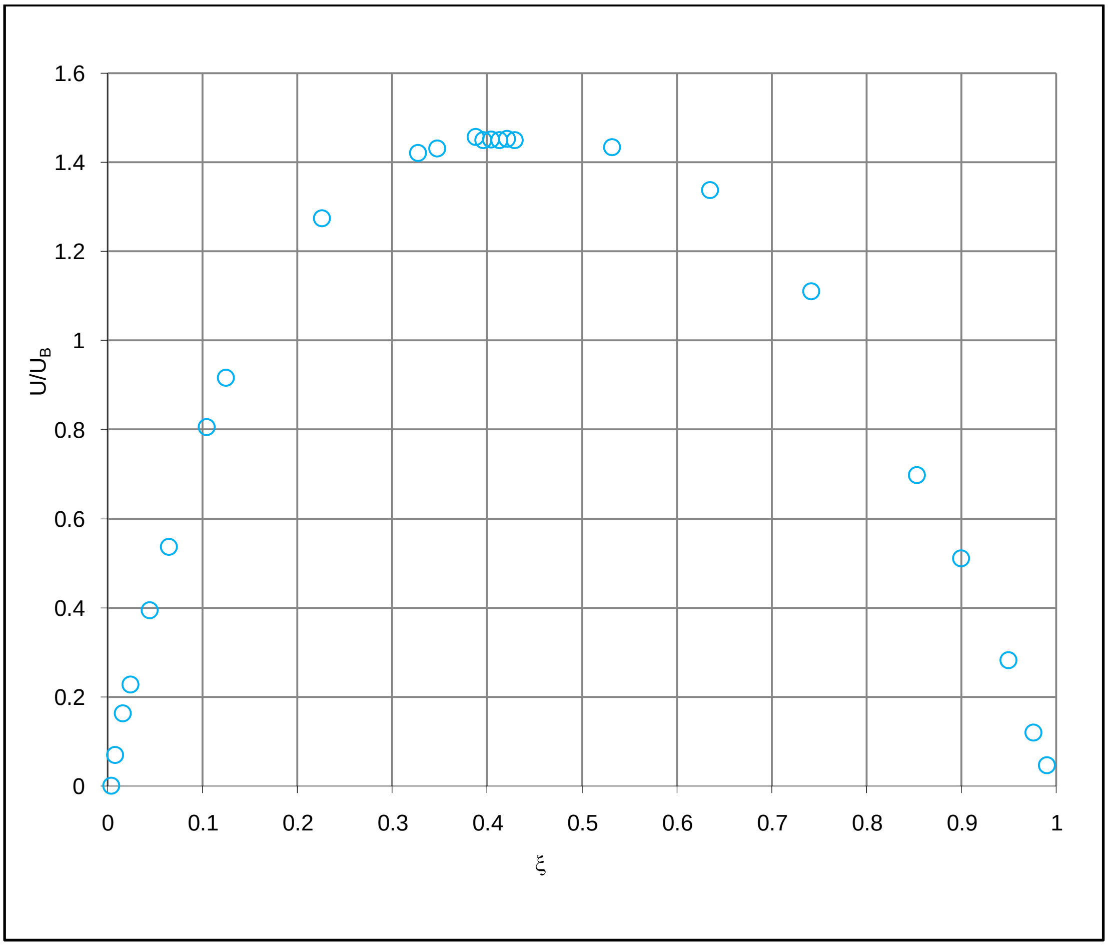


Figure 3.8: Experimental data for Velocity distribution in the annulus for 0.07% xanthan gum composition

For numerical simulation, all the input parameters are calculated by substituting the experimental data of power-law index, *n*, power-law consistency index, *k*, and bulk velocity, U_B, and hydraulic diameter, D_H into equation [4.1].

Calculating power-law Reynolds number

$$Re_{PL} = \frac{\rho U_B^{2-n} D_H^n}{k}$$

$$Re_{PL} = \frac{(1000)(0.148822)^{2-0.608213}(0.0496)^{0.608213}}{0.041639}$$

$$Re_{PL} = 272.6487947$$

Calculating bulk velocity, U_B for numerical simulation

U_B for numerical simulation is calculated by substituting $Re_{PL} = 272.6487947$ into equation [4.1]. The hydraulic diameter D_H for numerical simulation is based on the dimension of the geometry created earlier using GAMBIT v2. (R_I = 0.5m, R_O = 1.0m)

$$Re_{PL} = \frac{\rho U_B^{2-n} D_H^n}{k}$$

$$Re_{PL} = \frac{(1)(U_B^{2-0.608213})(2.0 - 1.0)^{0.608213}}{0.041639}$$

$$U_B = 5.729185994$$

The density, ρ of fluid for the numerical simulation is considered to be equal to 1 for the purpose of simplification of the simulation. It is the Reynolds number for experimental and numerical simulation matching that is more important.

Calculating the mass flow rate for numerical simulation

The mass flow rate can be calculated using the equation,

$$Mass\ Flow\ Rate = \rho U_B A$$

$$Mass\ Flow\ Rate = (1)(5.729185994)[(1^2 \times \pi) - (0.5^2 \times \pi)]$$

$$Mass\ Flow\ Rate = 13.49907647$$

Based on input parameters calculated as shown before, the numerical simulation for 0.07% xanthan gum composition has been performed and the result is shown in the **Figure 3.9** below:

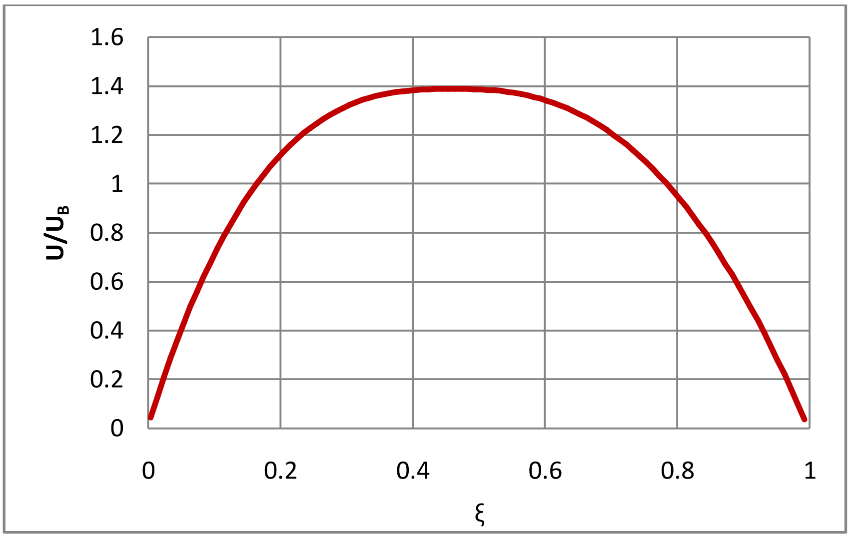


Figure 3.9: Velocity distribution in the annulus for 0.07% xanthan gum composition (numerical simulation)

The comparison between experimental data and numerical simulation data of the velocity distribution in the annulus for 0.07% xanthan gum is shown in **Figure 3.10** below:

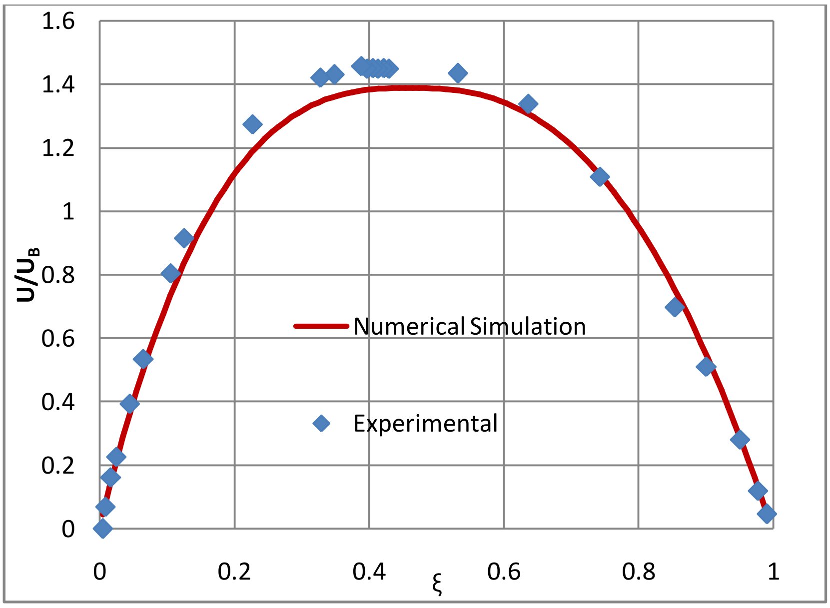


Figure 3.10: Comparison between experimental data and numerical simulation data of the velocity distribution in the annulus for 0.07% xanthan gum

3.4.4.2 Numerical Simulation of 0.1% Carbopol (non-Newtonian Fluid)

The available rheological data from the experiment for 0.1% carbopol solution at Reynolds number, Re=100, includes:

Power-law Index, n = 0.407307
Power-consistency index, k = 1.25
Bulk Velocity, U_B = 0.199846 m/s
Hydraulic Diameter, D_H = 0.0496 m

The velocity distribution graph from the experiment is shown in the **Figure 3.11** below:

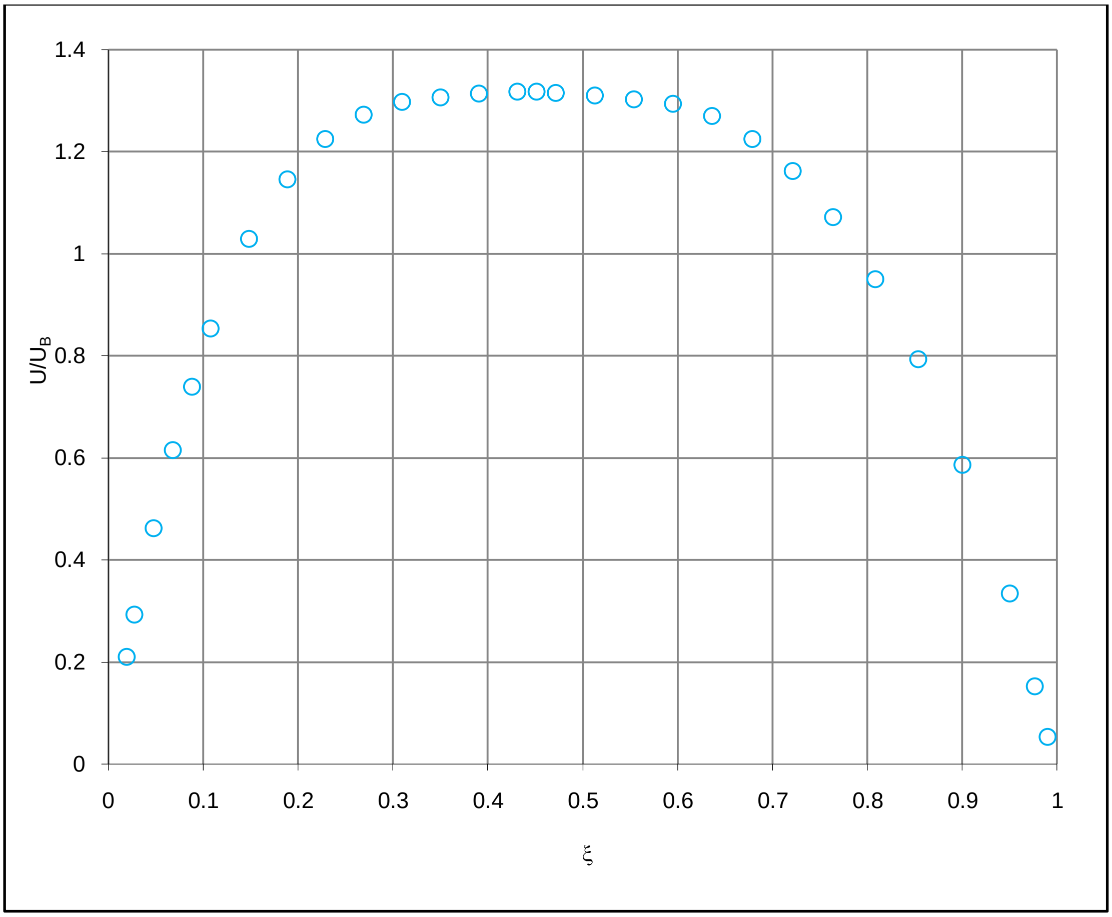


Figure 3.11: Experimental data for velocity distribution in the annulus for 0.1% carbopol composition

For numerical simulation, all the input parameters are calculated by substituting the experimental data of power-law index, *n*, power-law consistency index, *k*, and bulk velocity, U_B and hydraulic diameter, D_H into equation [4.1]. The steps taken in calculating those parameters are the same as the steps taken in calculating numerical simulation parameters for xanthan gum.

The calculated numerical simulation input parameters for 0.1% carbopol is shown below:

Power-law Reynolds number = 18.11227888
Bulk Velocity, U_B = 7.090664295
Mass flow rate = 16.70698414

Based on input parameters calculated, the numerical simulation for 0.1% carbopol composition has been performed and the result is shown in the **Figure 3.12** below:

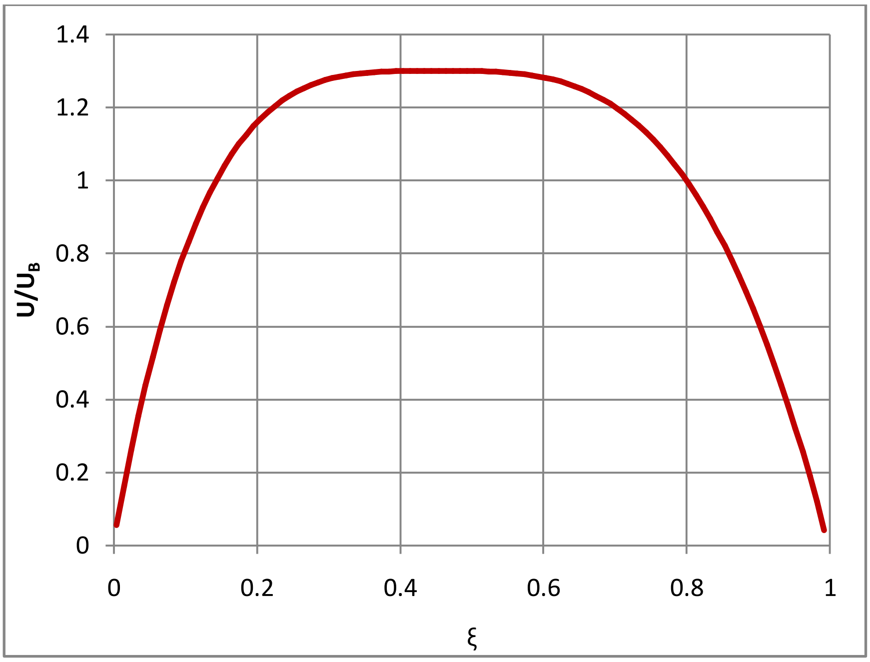


Figure 3.12: Velocity distribution in the annulus for 0.1% carbopol composition (numerical simulation)

The comparison between experimental data and numerical simulation data of the velocity distribution in the annulus for 0.07% carbopol is shown in **Figure 3.13** below:

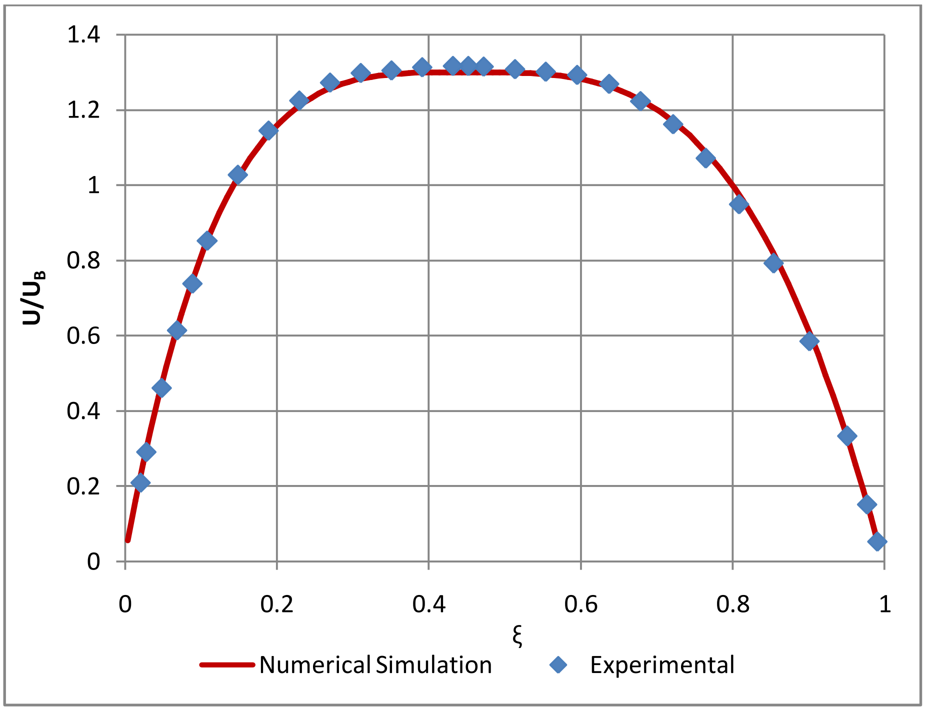


Figure 3.13: Comparison between experimental data and numerical simulation data of the velocity distribution in the annulus for 0.1% carbopol

3.4.4.3 Numerical Simulation of 0.1% Scleroglucan (non-Newtonian Fluid)

The available rheological data from the experiment for 0.1% scleroglucan includes:

Power-law Index, n = 0.547965
Power-consistency index, k = 0.031289
Bulk Velocity, U_B = 0.15 m/s

The velocity distribution for Scleroglucan was not obtainable during the experiment. Therefore, the graph of velocity distribution in the annulus cannot be plotted. The value of U_B = 0.15 m/s was selected to match the Bulk Velocity, U_B of both 0.07% xanthan gum and 0.1% carbopol.

For numerical simulation, all the input parameters are calculated by substituting the experimental data of power-law index, n, power-law consistency index, k, and bulk velocity, U_B and hydraulic diameter, D_H into equation [4.1]. The steps taken in calculating those parameters are the same as the steps taken in calculating numerical simulation parameters for xanthan gum and carbopol.

The calculated numerical simulation input parameters for 0.1% scleroglucan is shown below:

Bulk Velocity, U_B = 5.621621479
Mass flow rate = 13.24563355

Based on input parameters calculated, the numerical simulation for 0.1% scleroglucan composition has been performed and the result is shown in the **Figure 3.14** below:

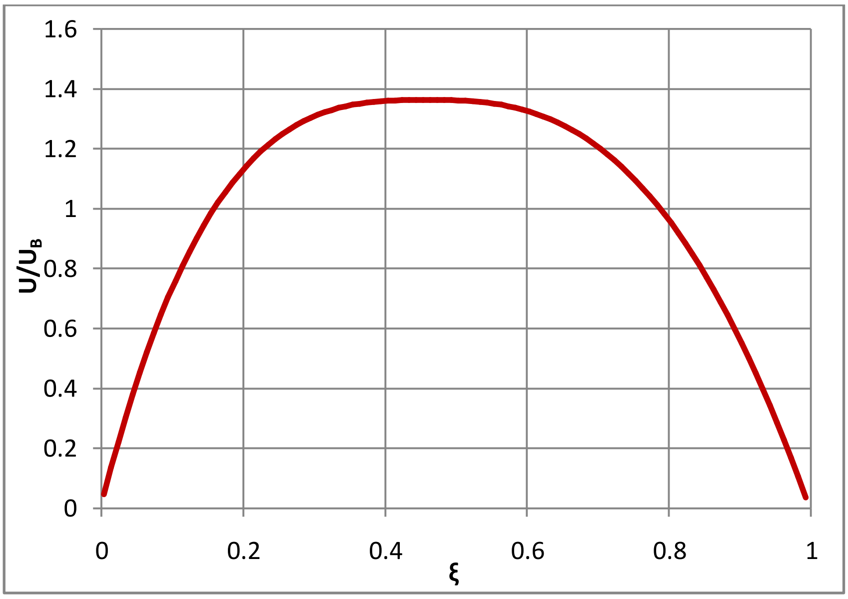


Figure 3.14: Velocity distribution in the annulus for 0.1% scleroglucan composition (numerical simulation)

3.4.4.4 Numerical Simulation of Glycerine (Newtonian Fluid)

Glycerine is a viscous Newtonian liquid widely used in the pharmaceutical and food industries as a thickening agent or as a solvent. The glycerine-water mixture (40% w/w) utilized in this study has a density of 1070 kg/m^3 and a shear viscosity, measured at 20°C, of 0.00386 Pa.s.

The experiment has been done for glycerine-water mixture at Reynolds number, Re=2019.485845. The Reynolds number is chosen to be that number so that the value of bulk velocity, U_B for glycerine-water solution is about the same with the value of bulk velocity, U_B for three previous non-Newtonian fluids.

The rheological data available from the experiment includes:

Density, ρ = 1070 kg/m^3
Viscosity, μ = 0.00386 Pa.s
Bulk velocity, U_B = 0.14688

The velocity distribution graph from the experiment is shown in the **Figure 3.15** below:

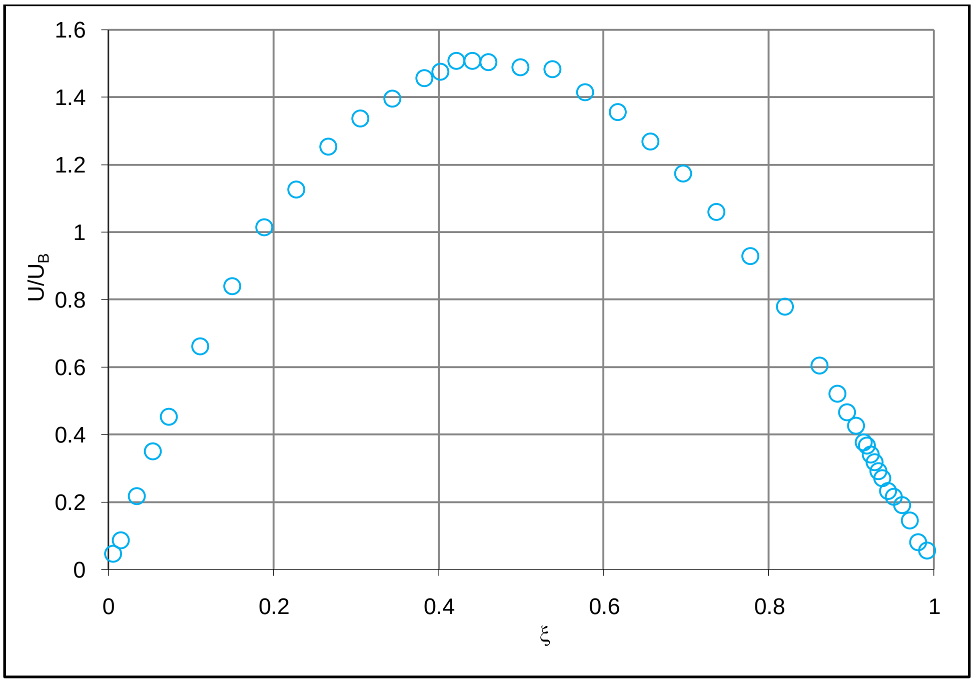


Figure 3.15: Experimental data for velocity distribution in the annulus for glycerine-water mixture

Based on the experimental data available, the input parameters for numerical simulation can be calculated.

Calculating bulk velocity, U_B for numerical simulation

U_B for numerical simulation is calculated by substituting all the data available in the equation as shown below. The hydraulic diameter D_H for numerical simulation is based on the dimension of the geometry created earlier using GAMBIT v2. ($R_I = 0.5m$, $R_O = 1.0m$)

$$Re = \frac{\rho U_B D_H}{\mu}$$

$$2019.485845 = \frac{(1070)(U_B)(1.0)}{0.00386}$$

$$U_B = 0.007285248$$

Calculating the mass flow rate for numerical simulation

The mass flow rate can be calculated using the equation,

$$Mass\ Flow\ Rate = \rho U_B A$$

$$Mass\ Flow\ Rate = (1070)(0.007285248)[(1^2 \times \pi) - (0.5^2 \times \pi)]$$

$$Mass\ Flow\ Rate = 18.3670$$

Based on input parameters calculated as shown before, the numerical simulation for glycerine-water mixture has been performed and the result is shown in the **Figure 3.16** below:

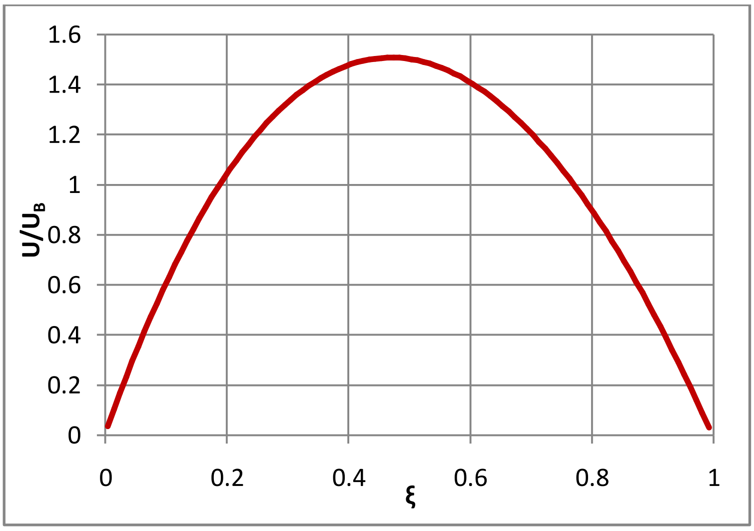


Figure 3.16: Velocity distribution in the annulus for glycerine-water mixture (numerical simulation)

The comparison between experimental data and numerical simulation data of the velocity distribution in the annulus for glycerine water mixture is shown in **Figure 3.17** below:

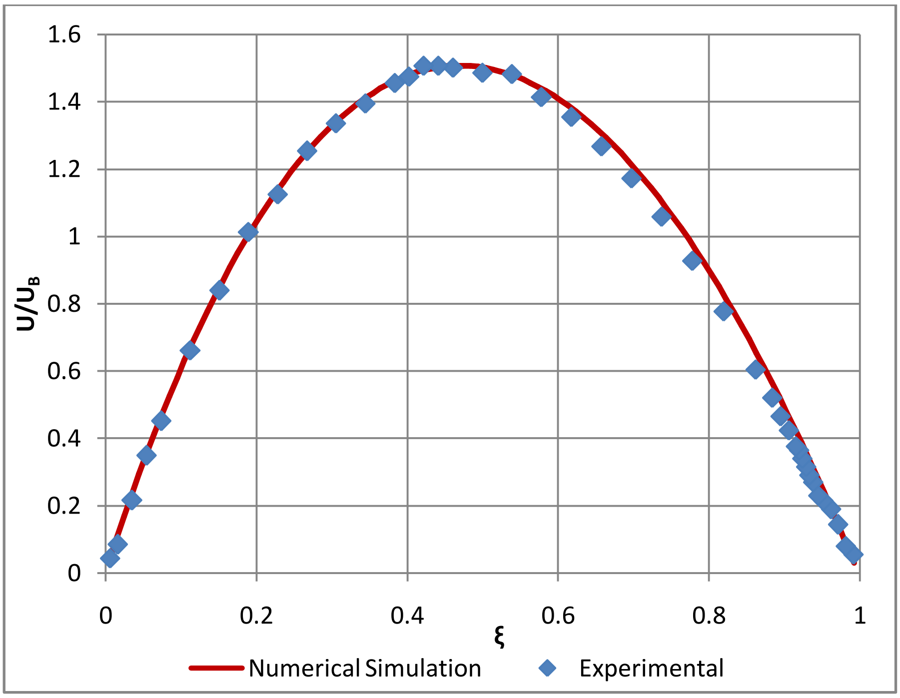
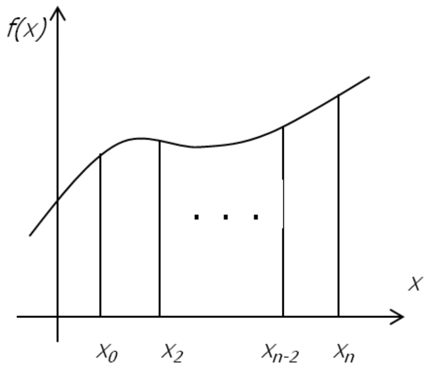


Figure 3.17: Comparison between experimental data and numerical simulation data of the velocity distribution in the annulus for glycerine-water mixture

After the comparison between experimental data and numerical simulation data of the velocity distribution in the annulus, it can be concluded that there is an agreement between the experimental data and numerical data for both carbopol and glycerine-water mixture.

For xanthan gum, there are slight different between the experimental data and the numerical simulation data as shown in **Figure 3.10**. The integration of the profile has to be conducted to check for any experimental error. The integration of the profile will give the value of area under the curve and it has to give the value of 0.5 or otherwise there are errors in the experimental data and scaling of the data has to be done to make the correction.

Multiple Segment Simpson’s 1/3 Rule was used to integrate the velocity profile of the experimental data. Multiple Segment Simpson’s 1/3 Rule can be described as below:



$$\int_a^b f(x)dx = \int_{x_0}^{x_2} f(x)dx + \int_{x_2}^{x_4} f(x)dx + \ldots\ldots \ldots. + \int_{x_{n-4}}^{x_{n-2}} f(x)dx + \int_{x_{n-2}}^{x_n} f(x)dx$$

Apply Simpson’s 1/3rd Rule over each interval,

$$\int_a^b f(x)dx = (x_2 - x_0)\left[\frac{f(x_0) + 4f(x_1) + f(x_2)}{6}\right] + (x_4 - x_2)\left[\frac{f(x_2) + 4f(x_3) + f(x_4)}{6}\right] + \ldots$$

$$+ (x_n - x_{n-2})\left[\frac{f(x_{n-2}) + 4f(x_{n-1}) + f(x_n)}{6}\right]$$

Since,

$$x_i - x_{i-2} = 2h \qquad i = 2, 4, \ldots, n$$

$$\int_a^b f(x)dx = 2h\left[\frac{f(x_0) + 4f(x_1) + f(x_2)}{6}\right] + 2h\left[\frac{f(x_2) + 4f(x_3) + f(x_4)}{6}\right] + \ldots.$$

$$2h\left[\frac{f(x_{n-2}) + 4f(x_{n-1}) + f(x_n)}{6}\right]$$

$$\boxed{\int_a^b f(x)dx = \frac{h}{3}\left[f(x_0) + 4\sum_{\substack{i=1\\ i=odd}}^{n-1} f(x_i) + 2\sum_{\substack{i=2\\ i=even}}^{n-2} f(x_i) + f(x_n)\right]}$$

The integration of the velocity profile for the experimental data of 0.07% xanthan gum has been done and yields the result of 0.491859 instead of 0.5. In order for the experimental data to achieve an agreement with numerical simulation data, the experimental data has to be scaled down by the ratio of 0.491859/0.5 = 0.983718.

The velocity distribution in the annulus for the experimental data is shown in **Figure 3.18** below:

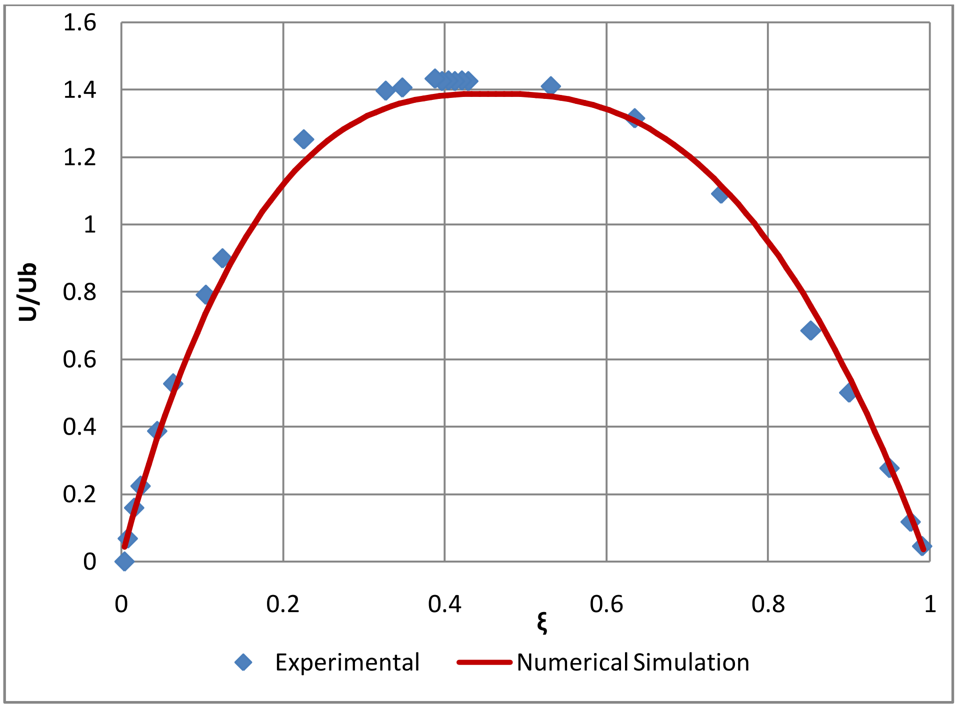


Figure 3.18: Scaled down experimental data for 0.07% xanthan gum

In conclusion, the agreement between the experimental data and the numerical simulation data are clearly satisfactory and represent a validation of the methods used in the numerical simulation.

3.4.5 Numerical Simulation for Multiphase Flow

For the second part of the project which is FYP2, the objective is to include the drill cuttings in the numerical simulation for each of the drilling fluids which are xanthan gum, carbopol, scleroglucan, and glycerine. The behaviour of drill cuttings accumulation in the annulus with different composition of drilling fluid will then be studied.

The flow of the drilling fluid with drill cuttings will be numerically simulated in this part. Due to the multiphase nature of the flow; drilling fluid in liquid phase and drill cuttings in solid phase, a few adjustment will be made in the numerical simulation model.

The numerical simulation will be done using FLUENT Eulerian multiphase model in addition of laminar model instead of normal laminar model that has been used in the previous part of the project.

The Eulerian multiphase model in FLUENT allows for the modelling of multiple separate, yet interacting phases. The phases can be liquids, gases, or solids in nearly any combination. An Eulerian treatment is used for each phase, in contrast to the Eulerian-Lagrangian treatment that is used for the discrete phase model.

The FLUENT solution for Eulerian multiphase model is based on the following:

- A single pressure is shared by all phases.
- Momentum and continuity equations are solved for each phase.

In the Eulerian multiphase model, the drilling fluid will be defined as the primary phase of the flow while the drill cuttings will be defined as the secondary phase.

3.4.5.1 Defining Material Properties of Drill Cuttings

A new material for drill cuttings will be introduced in the numerical simulations in addition of the existing material properties for each drilling fluid composition.

In this study, the drill cuttings were assumed to be Granite. Some of the important material properties of granite that will be used in the numerical simulations are as follows:

- Density, ρ – 2750 kg/m^3
- Viscosity, μ – 3.6 x 10^{19} Pa.s

There is additional assumption for drill cuttings which are the drill cuttings were assumed to have spherical shape and uniform size with diameter 0.0127 meter or 0.5 inch. (Li, Bjorndalen, Kuru, 2007)

3.4.5.2 Defining Periodic Condition for Multiphase Flow

There was one major problem encountered during the stage of defining periodic condition for multiphase flow. The previous single-phase numerical simulation was carried out by setting the mass flow rate as the periodic condition. However, there is a limitation for Eulerian multiphase flow model which is periodic flow with specified mass flow rate cannot be modeled. Instead, the user is allowed to specify a pressure gradient as periodic condition.

The experimental data for pressure gradient for each drilling fluid composition was obtained from Jaafar, A., (2009) and used in this study.

Due to the changing of the periodic condition specified, the re-simulation has to be done for all drilling fluid composition to verify that the pressure gradient input will yield the same velocity profile of drilling fluid inside the annulus as the velocity profile produced by mass flow rate input previously.

The comparison of the velocity profile of each drilling fluid formulation with corresponding mass flow rate and pressure gradient input are shown in **Figure 3.19** to **Figure 3.21** below:

Xanthan Gum

- Mass flow rate = 13.4991 kg/s
- Pressure Gradient = - 1.339 Pa/s

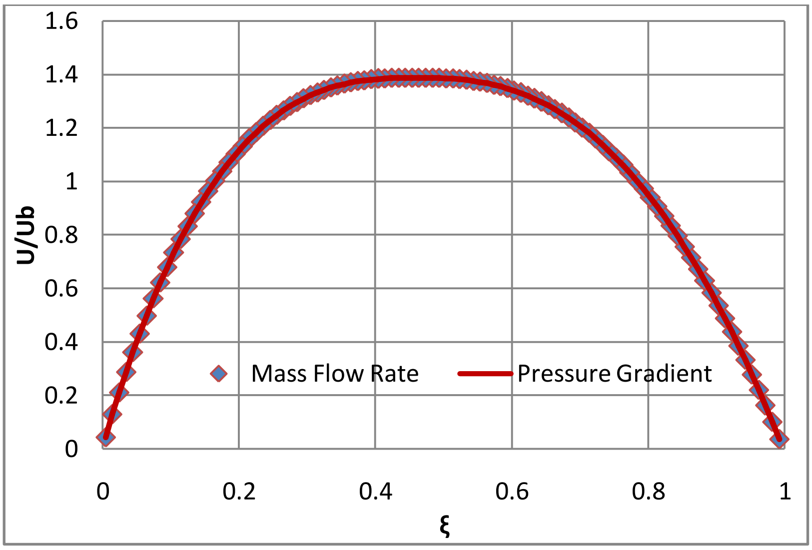


Figure 3.19: Velocity Profile Comparison of Mass Flow Rate and Pressure Gradient Input for Xanthan Gum

Scleroglucan

- Mass flow rate = 13.2456 kg/s
- Pressure Gradient = - 88.61 Pa/s

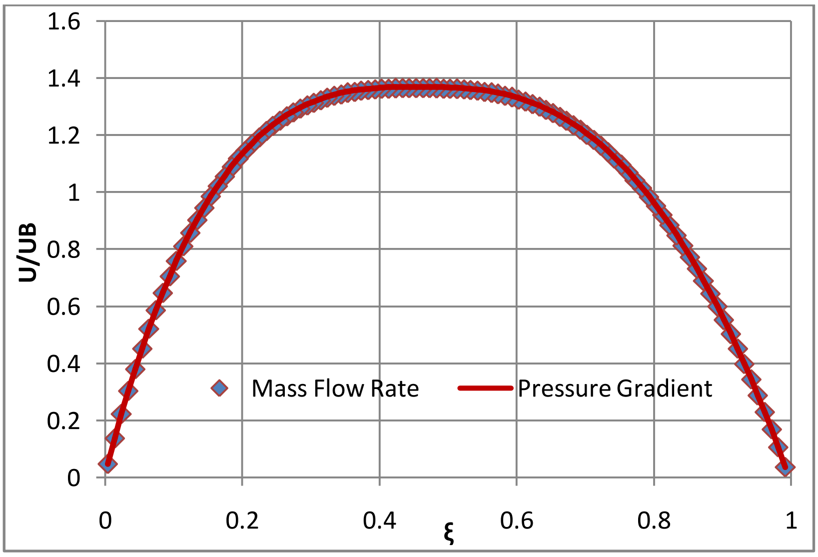


Figure 3.20: Velocity Profile Comparison of Mass Flow Rate and Pressure Gradient Input for Scleroglucan

Glycerine

- Mass flow rate = 18.3670 kg/s
- Pressure Gradient = - 1.339 Pa/s

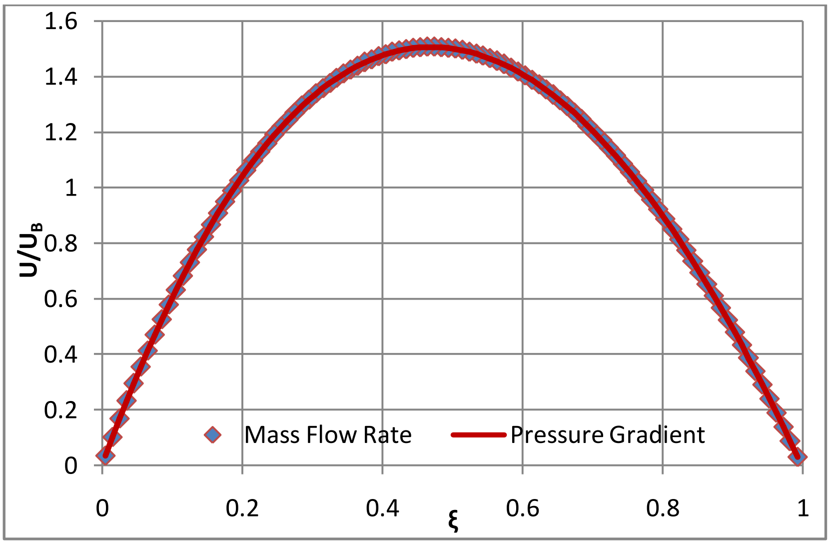


Figure 3.21: Velocity Profile Comparison of Mass Flow Rate and Pressure Gradient Input for Glycerine

Figure 3.19 to **Figure 3.21** clearly shown that data obtained from pressure gradient input shows satisfactory agreement to the corresponding data obtained from mass flow rate input. Hence, the multiphase numerical simulation can be carried out using pressure gradient input as periodic condition.

3.4.5.3 Additional Settings for Multiphase Flow Numerical Simulation

Other than described in the previous sections, there are several important parameters used in the numerical simulation for multiphase flow: the gravitational acceleration is set opposite to the flow direction with value of 9.81 m/s^2. The velocity of the drill cuttings was calculated to be 0.00508 m/s based on the drilling rate of 60 ft/hr. The drill cuttings volume fraction was specified at the beginning of each simulation to correspond to the desired solids loading of 0.08 or 8% as used by Han et al, 2010. There is no energy or mass transfer between particles during the upward motion in the annulus. The other FLUENT Eulerian multiphase settings were kept default.

CHAPTER 4

RESULTS AND DISCUSSIONS

The results and discussions focuses on the findings on the comparison of the drilling fluid flow inside the annulus with and without drill cuttings included for each drilling fluid formulations namely xanthan gum, scleroglucan, carbopol and glycerine. The behavior of the drill cuttings inside the annulus during each drilling fluid flow will also be discussed.

4.1 Comparison of Single Phase Flow and Multiphase Flow of Drilling Fluid

<u>Xanthan Gum</u>

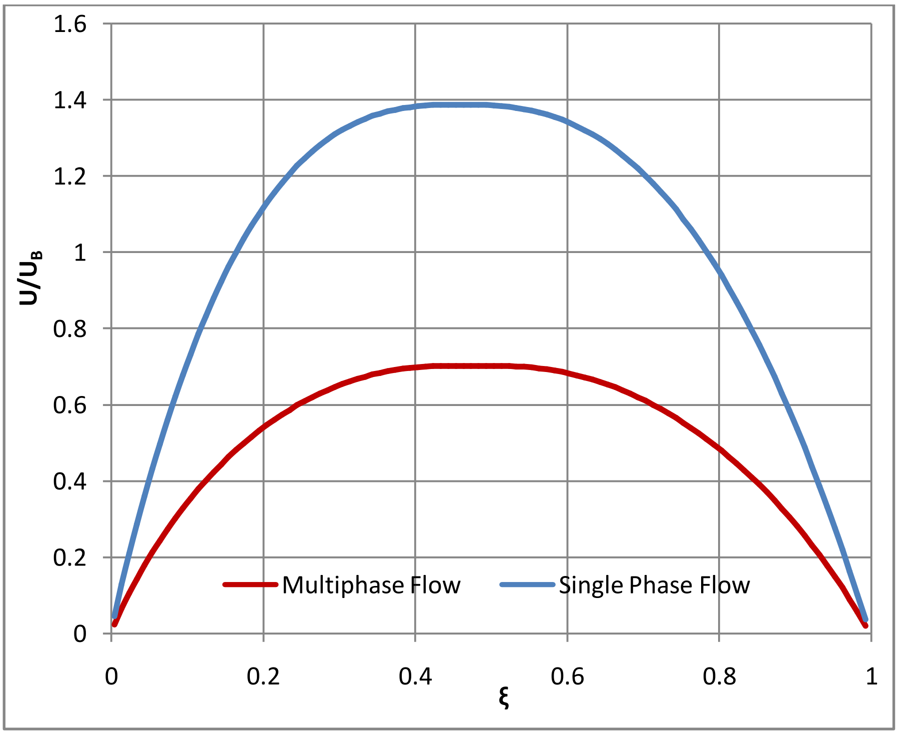


Figure 4.1: Single Phase and Multiphase Flow of Xanthan Gum

Table 4.1: Single Phase and Multiphase Flow Data of Xanthan Gum

	Single Phase Flow	**Multiphase Flow**
Max Velocity (m/s)	1.38725 at position, 0.453725	0.701846 @ position 0.453725
Plug Region (Radial Pos.)	0.393775 to 0.533513	0.393775 to 0.563459
Inner Wall Shear Stress (Pa)	5.1731	3.17756
Outer Wall Shear Stress (Pa)	4.25627	2.75877
Wall Shear Stress Ratio	1.2154	1.1518
Area Under Curve	2.020044	1.015494127

Scleroglucan

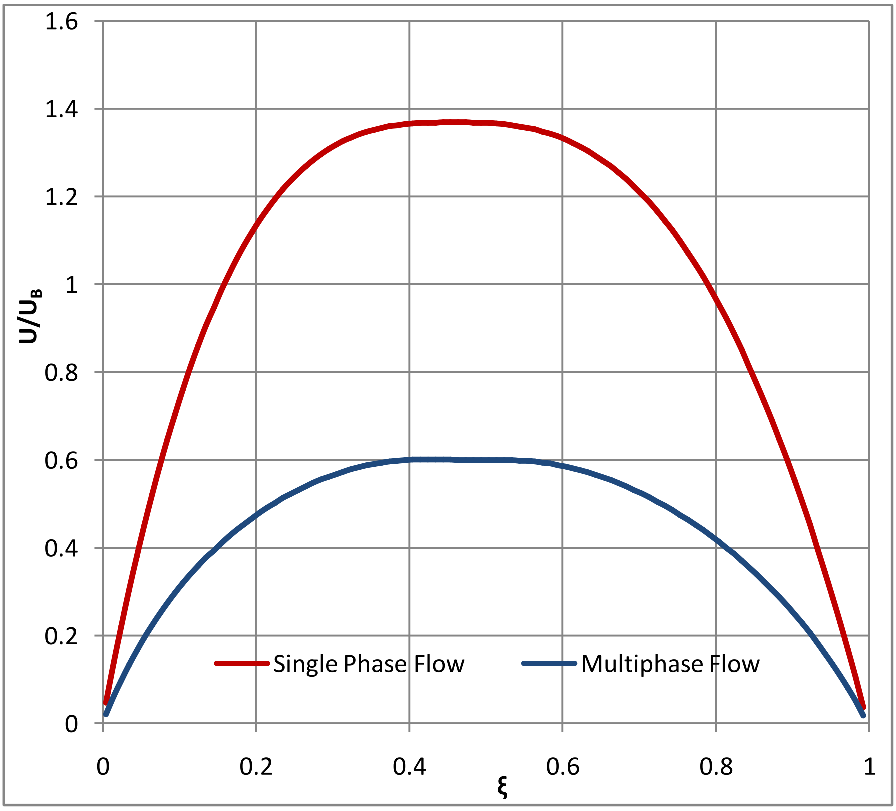


Figure 4.2: Single Phase and Multiphase Flow of Scleroglucan

Table 4.2: Single Phase and Multiphase Flow Data of Scleroglucan

	Single Phase Flow	**Multiphase Flow**
Max Velocity (m/s)	1.36898 at position 0.453725	0.601696 at position 0.42371
Plug Region (Radial Pos.)	0.403753 to 0.523531	0.373817 to 0.583423
Inner Wall Shear Stress (Pa)	2.49638	1.39852
Outer Wall Shear Stress (Pa)	2.07326	1.2121
Wall Shear Stress Ratio	1.2041	1.1538
Area Under Curve	2.028868	0.881302

Carbopol

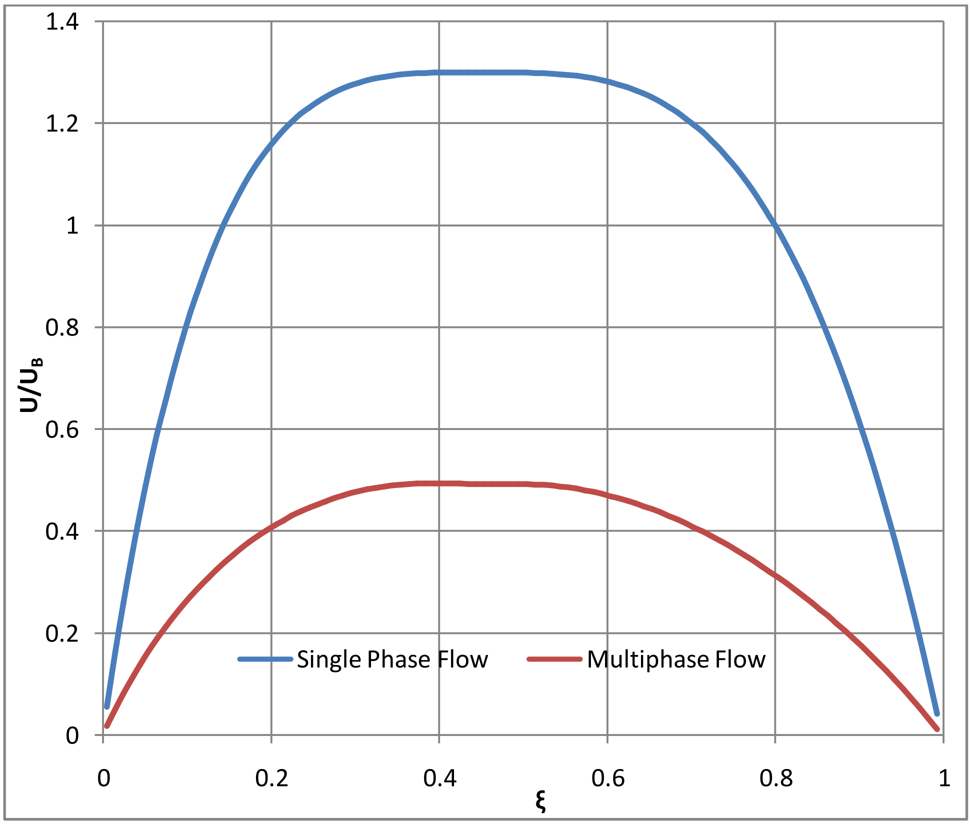


Figure 4.3: Single Phase and Multiphase Flow of Carbopol

Table 4.3: Single Phase and Multiphase Flow Data of Carbopol

	Single Phase Flow	**Multiphase Flow**
Max Velocity (m/s)	1.29971 at position 0.443758	0.493958 at position 0.403753
Plug Region (Radial Pos.)	0.363867 to 0.563459	0.334098 to 0.553477
Inner Wall Shear Stress (Pa)	32.085	19.3547
Outer Wall Shear Stress (Pa)	27.3676	15.7488
Wall Shear Stress Ratio	1.1797	1.2290
Area Under Curve	2.021924	0.711792

Glycerine

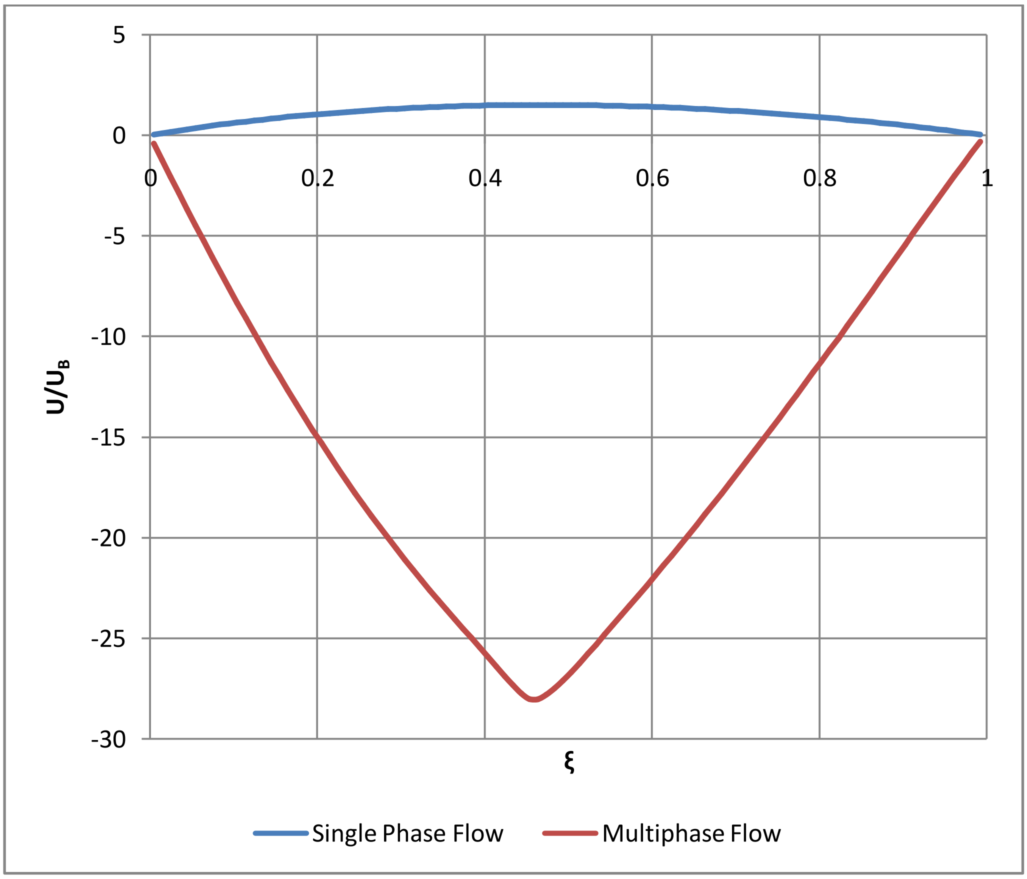


Figure 4.4: Single Phase and Multiphase Flow of Glycerine

Table 4.4: Single Phase and Multiphase Flow Data of Glycerine

	Single Phase Flow	**Multiphase Flow**
Max Velocity (m/s)	1.50607 at position 0.473658	-28.0267 at position 0.463692
Inner Wall Shear Stress (Pa)	0.038946	0.465502
Outer Wall Shear Stress (Pa)	0.030711	0.309413
Wall Shear Stress Ratio	1.2681	1.5045
Area Under Curve	2.015162	-30.8141

Figure 4.1 until **Figure 4.4** above shows the comparison of the velocity profile for single phase flow; drilling fluid, and multiphase flow; drilling fluid with drill cuttings for drilling fluid contains each xanthan gum, scleroglucan, carbopol, and glycerine. **Table 4.1** until **Table 4.4** shows data regarding the flow for each of the above drilling fluid formulation.

The results for all numerical simulations show that the maximum velocity of the non-newtonian drilling fluid was achieved at the plug region where xanthan gum has the highest maximum velocity while carbopol has the minimum. The velocity profile of each drilling fluid decreased when drill cuttings were incorporated in the numerical simulation. It is possibly due to larger drag in the flow. The percentage decrease in velocity profile can be observed by the difference between the area under the curve for both single-phase and multiphase flow. **Figure 4.4** shows that the velocity profile of glycerine for multiphase flow becomes negative even though the method used was the same with the other drilling fluid formulation.

It was also observed that the plug region of each drilling fluid flow increased with decreasing velocity profile. For Newtonian fluid flow, glycerine, the maximum velocity achieved was higher than any non-newtonian fluid while there is no plug region for Newtonian fluid.

Plug region of non-Newtonian fluid flow is where the velocity profile of the flow is flattening around the center of the annulus. The flow with plug region is called "Plug Flow". Other characteristic of plug flow is the velocity gradient near the annulus wall is higher when compared to Newtonian fluid flow. For drill cuttings transport purpose, plug flow is desirable because the plug region will reduce the rotation of the particles during its motion within the mud towards the surface and reduce its trend to rotate and move towards the wall of the annulus. It is the region where most of the drill cuttings will be transported to the surface. Hence the drill cuttings management will improve with plug flow. **Figure 4.5** below shows the comparison of plug flow characteristics of drilling fluid consisting xanthan gum, scleroglucan, carbopol, and glycerine. There is plug region and the velocity gradient near the wall is higher for non-Newtonian drilling fluid (xanthan gum, scleroglucan, carbopol) compared to Newtonian drilling fluid (glycerine).

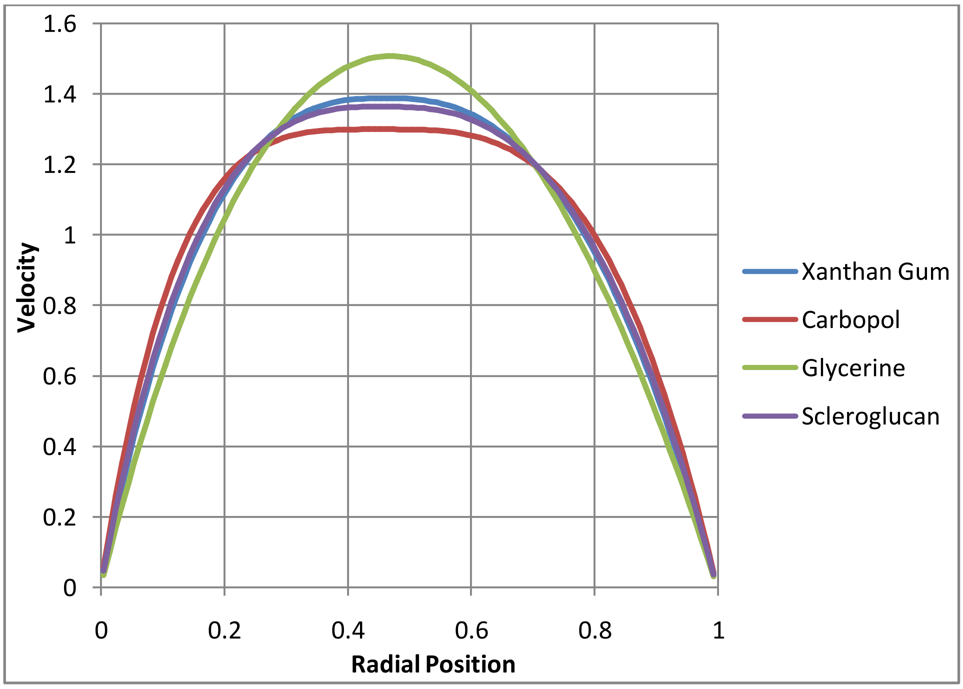


Figure 4.5: Comparison of Plug Flow Characteristics

It is shown in **Figure 4.1** to **Figure 4.3**, that the maximum velocity and the plug region in all non-Newtonian drilling fluid for both single phase and multiphase flow is not occurring at the center of the annulus, but it is skewed slightly near to the inner wall of the annulus. It is due to the higher wall shear stress at the inner wall of the annulus compared to the outer wall causing the flow move faster at that region. The data shows agreement with the findings from Escudier et al (2002a) where he performed the numerical simulations within the laminar flow regimes, and found out that the velocity distributions, were skewed towards the inner pipe of the annulus and the velocity distribution were slightly flatter with reduced peak velocity levels when compared to the Newtonian flow. It is also observed in this study that the inner and outer wall shear stress for single phase flow were always higher than that of multiphase flow.

4.2 Drill Cuttings Behavior during Drilling Fluid Flow

Xanthan Gum

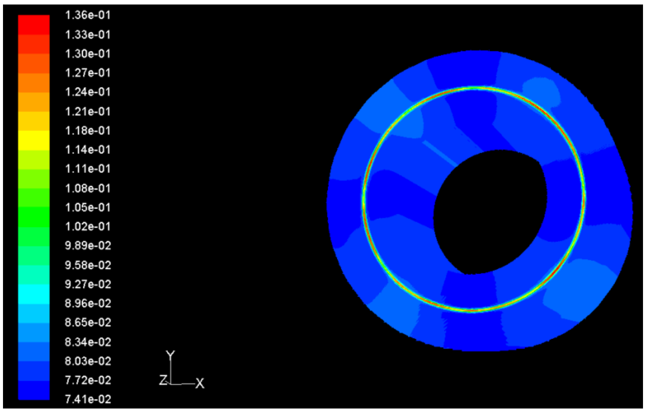


Figure 4.6: Contour of Volume Fraction of Drill Cuttings in Xanthan Gum

Scleroglucan

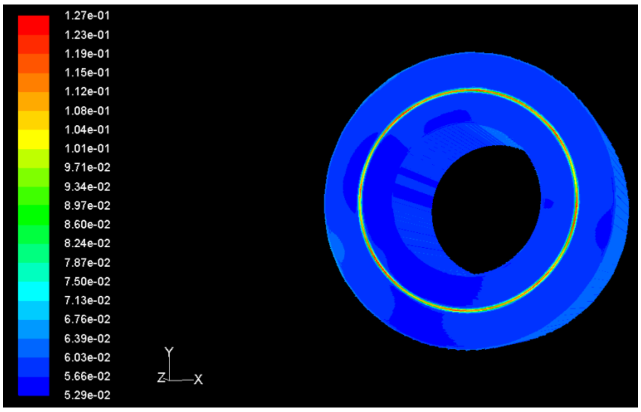


Figure 4.7: Contour of Volume Fraction of Drill Cuttings in Scleroglucan

Carbopol

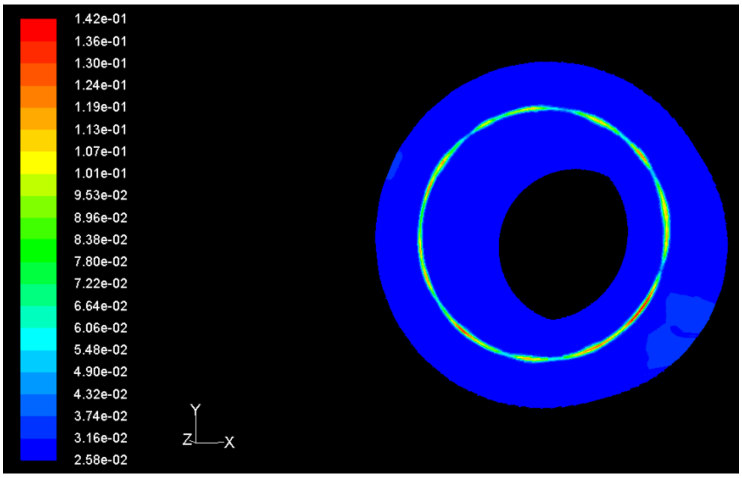


Figure 4.8: Contour of Volume Fraction of Drill Cuttings in Carbopol

Glycerine

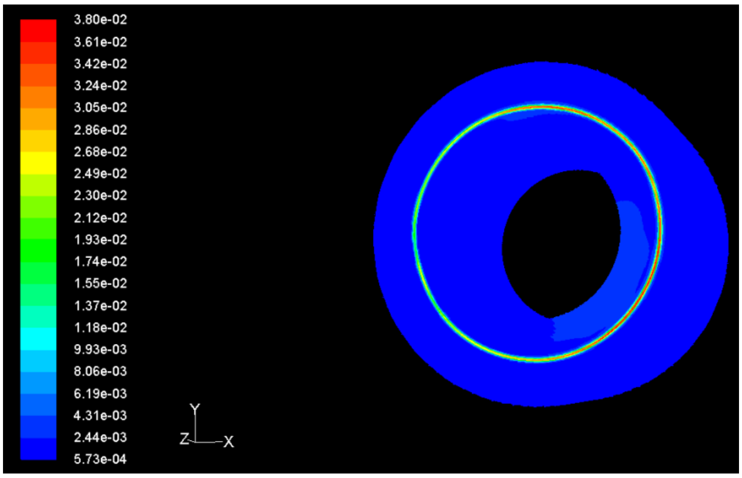


Figure 4.9: Contour of Volume Fraction of Drill Cuttings in Glycerine

Table 4.5: Volume Fraction of Drill Cuttings in Drilling Fluids

	Average Volume Fraction of Drill Cuttings
Xanthan Gum	0.07973
Sceroglucan	0.05947
Carbopol	0.03152
Glycerine	0.002953

Figure 4.6 to **Figure 4.9** shows the volume fraction of drill cuttings inside drilling fluid for each drilling fluid consisting xanthan gum, scleroglucan, carbopol and glycerine.

The drill cuttings volume fraction was specified at the beginning of each simulation to correspond to the desired solids loading of 0.08 or 8%. The numerical simulations should yield the average volume fraction distribution of 0.08 for each drilling fluid formulation.

Based on **Table 4.5**, it can be said that xanthan gum gives good result of the volume fraction distribution inside the annulus during drilling fluid flow. The volume fraction distribution of drill cuttings in drilling fluid, xanthan gum, as in **Figure 4.6**, shows that the highest concentration of drill cuttings is at the middle of the annulus, where the plug region of the flow occur, with moderate concentration near the outer wall of the annulus. It is good indication of drill cuttings transport as the plug region of the flow will carry the highly concentrated drill cuttings on that region to the surface. However, the accuracy of the result cannot be measured because there is no experimental data to compare with. Hence, the experimental data is needed to validate the result of numerical simulation.

Unlike xanthan gum, all other drilling fluid includes scleroglucan, carbopol, and glycerine did not yield good result in term of average volume fraction distribution as the result is no where near the desired value of 0.08. It was possibly due to some errors during conducting the numerical simulation. Hence, the volume fraction distribution of drill cuttings inside annulus for all other drilling fluid is not accepted and need to be re-simulated once the errors has been detected and clarified.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

In conclusion, the study on the effects of drilling fluid rheological properties on drill cuttings transport has been completed. The behavior of drilling fluid in the presence of drill cuttings has been studied and can be concluded that the velocity profile and wall shear stress of drilling fluid reduced in the presence of drill cuttings. The distribution of drill cuttings inside the annulus during drilling fluid flow also has been studied, however, the result was not acceptable due to some unexpected errors except for xanthan gum drilling fluid which shows good drill cuttings transport characteristics. Due to unavailability of experimental data, the numerical simulation results cannot be validated at the present.

There are few recommendations on ways to improve this study for future references:

- Use transient flow model instead of steady-state flow model that is used in this study so that the behaviour of drill cuttings inside the annulus during drilling fluid flow can be monitored with respect to time
- Apply different multiphase model such as Mixture multiphase model rather than Eulerian multiphase model that is used in this study. Mixture multiphase model is generally less complex compared to Eulerian model.
- Simplified the modelling by simulating only a portion of cross sectional of the annulus by applying “symmetry” boundary condition. It will also reduce computational time.
- Change current average particle rise velocity used. The current average particle rise velocity was calculated based on drilling rate.
- Try different type of drill cuttings. Change the density, viscosity, diameter, shape, and other properties of current drill cuttings used in this study.
- Vary the volume fraction and study the effect of various concentrations of drill cuttings on the drill cuttings transport behaviour instead of fixing the value of volume fraction as being done in this study.
- Conduct experimental study together with numerical simulation so that the result of both tests can be compared and validated.

REFERENCES

1. B. Onyekpe, 2001, *Investigation of the effects of carbonate contaminants on the rheological properties of drilling mud,* Shell Intensive Training Centre, Shell Petroleum Dev. Co., Warri, Nigeria
2. Ronald P. Bernhard, B.S., 1981, *Rheological Properties of High-Temperature Drilling Fluids*, M.Sc. Thesis, Texas Tech University, United States of America
3. T.E. Becker, J.J. Azar, S.S. Okrajni, 1991, "Correlations of Mud Rheological Properties With Cuttings-Transport Performance in Directional Drilling", *Journal of SPE Drilling Engineering*
4. T. Hamida, E. Kuru, M. Pickard, 2009, *Rheological characteristics of aqueous waxy hull-less barley (WHB) solutions,* University of Alberta, Canada
5. Vikas Mahto, V.P. Sharma*, 2004, *Rheological study of a water based oil well drilling fluid,* Department of Petroleum Engineering, Indian School of Mines
6. Samira Baba Hamed, Mansour Belhadri, 2009, *Rheological properties of biopolymers drilling fluids,* Laboratory of Rheology, Transport and Treatment of the Complex Fluids, University of Sciences and Technology-Mohamed Boudiaf
7. Njobbuenwu, D.O., Wobo, C.A., 2007, *Effect of drilled solids on drilling rate and performance,* Journal of Petroleum Science and Engineering 55 (2007), 271-276.
8. Y. Li, E. Kuru, 2005, *Numerical Modelling of Cuttings Transport With Foam in Vertical Wells,* Journal of Canadian Petroleum Technology, March 2005, Volume 44, No. 3.
9. Y. Li, N. Bjorndalen, E. Kuru, 2007, *Numerical Modelling of Cuttings Transport in Horizontal Wells Using Conventional Drilling Fluid,* Journal of Canadian Petroleum Technology, July 2007, Volume 46, No. 7.
10. Hussain H. Al-Kayiem, Nadia Mohd Zaki, Muhamad Z. Asyraf and Mahir Elya Elfeel, 2010, *Simulation of the Cuttings Cleaning During the Drilling Operation*, American Journal of Applied Sciences 7 (6)
11. Sang-Mok Han, Young-Kyu Hwang, Nam-Sub Woo, Young-Ju Kim, 2010, *Solid–liquid hydrodynamics in a slim hole drilling annulus*, Journal of Petroleum Science and Engineering 70 (2010) 308–319
12. Jaafar, A., 2009, *Duct flow of polymer solutions*, PhD thesis, University of Liverpool.

13. Syed M. Hussaini, Jamal J. Azar, 1983, *Experimental Study of Drilled Cuttings Transport Using Common Drilling Muds,* Society of Petroleum Engineers.
14. John H. Berry, P.G., *Drilling Fluid Properties and Functions*
15. Robert Schlemmer, Scomi Oiltools, GRTC, Malaysia, *Supporting the South China Sea*
16. Exploration & Wells, WDC, *Drilling Fluid Fundamentals*, http://www.wdcexploration.com/what_we_do/pdf/drilling_fluid_fundamentals.pdf
17. Autar Kaw, Charlie Barker, 2010, *Simpson's 1/3 Rule of Integration*, http://numericalmethods.eng.usf.edu
18. Drilling Fluid, http://en.wikipedia.org/wiki/Drilling_fluid
19. Drill Cuttings, http://en.wikipedia.org/wiki/Drill_cuttings
20. Well Drilling, http://en.wikipedia.org/wiki/Well_drilling