CFD of Viscoelastic Fluid in Horizontal Flow Pipes

by

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Final report submitted in partial fulfillment of
the requirement for the
Bachelor of Engineering (Hons)
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

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January 2008

CERTIFICATION OF ORIGINALITY

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

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MUHAMAD ZAINURUL ASYRAF BIN ISMAIL

ABSTRACT

Drilling fluids are non-Newtonian fluids. Non Newtonian fluids mostly are viscoelastic fluid which mean it exhibit both viscosity and elastic properties. Presences of both properties make it hard to predict behavior of the fluid. In order to carry out analysis on it, it is important to understand how viscoelastic fluid works and types that exist.

All viscoelastic fluid can be define using viscosity models. Viscosity models are mathematical equation that describes how the fluid reacts when force is applied.

Beside viscosity model, Navier-Stokes equation is as important as the viscosity model. Navier Stokes or the governing equation is the equation that will describe the flow. As in fluid the Navier Stokes will play very critical role or we can say it is the fundamental of fluid flow. By putting some boundary conditions and assumptions into the equation, the governing equation for the system can be determined.

By combining both, viscosity model and the governing equation, analytical equation for the system can be produce. By solving the equation, the solution for the system can be produce.

Simulation is done using GAMBIT as modeler and FLUENT as solver. Simulation is done by inserting physical properties of the pipe or annulus and the properties of the mud. The simulation is done for all three sample of mud that has been experimented. The variation of the velocity and the pressure is check. The result of the simulation can be compared with the analytical solution once it is solved.

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Additives are added to decrease, increase, and/or maintenance specific properties of the drilling fluids such as density, viscosity, and filtration. In this project, the effect of additives to the viscosity of the fluids is the main concern.

Drilling fluid become thinner or losses it viscosity because the effect of temperature, purification process, and presence of salt. In order to maintain the shear thinning properties of the fluid, additives are added to turn the fluids into viscoelastic fluids.

As viscoelastic fluids is hard to predict, this project aims to understand the viscoelastic behaviour through simulation.

1.2 Objective

The main objective of this project is to study how the viscoelastic fluid behaves when subjected to force and pressure. The study will concentrated on drilling fluids when it is flow in the annulus. The study will be conducted in horizontal flow.

1.3 Scope of Study

The scope of study covers viscoelastic fluid, drilling mud, and Navier Stokes (NS) equation which cover the fluid motion during the drilling operation. Accordingly, understanding of the NS is essential. Also, understanding of the model which describes the non Newtonian is to be accomplished. The application of the boundary condition will applied to NS equation for two cases, firstly the pipe flow then extended to annular flow. The target is to get the analytical model which describes the phenomena. The next step in the analysis is to use the ready CFD codes in the department to model the phenomena under various operating conditions.

1.4 Project Significant

As stated before, this project aims to understand more about the behaviour of viscoelastic fluids. This knowledge will help in:

- Making the right decision about the right drilling fluids to be used.
- Optimization used of the additives can be achieved
- Solve problems that arise because of the viscoelastic effect.
- Reduce time and cost of drilling process as drilling becomes a lot effective.

CHAPTER 2

LITERATURE REVIEW

2.1 Drilling Process

Drilling is a process of creation of wellbores that penetrate from the surface of the earth to underground deposits of hydrocarbons. The hole is created with an oil rig which rotates a drill bit. Up till some depth, a steel pipe or casing will be placed in the hole and will be cemented. The casing provides structural integrity to the newly drilled wellbore in addition to isolating potentially dangerous high pressure zones from each other and from the surface [8]. As the depth increase more and more steel casing will be put on. Thus the diameter of the drilled well will shrink. The wellbore varies from 5 to 30 inches (13 – 76 cm) in diameter. [8]

When drilling process is carry out, drilled solid is produce. The presence of drilled solid will, if not remove, cause the drilling process to become harder and dangerous and of course expensive. In order to remove the drilled solid effectively, drilling fluid or drilling mud is introduce.

Drilling fluid is any of a number of liquid and gaseous fluids and mixtures of fluids and solids (as solid suspensions, mixtures and emulsions of liquids, gases and solids) used in operations to drill boreholes into the earth [9]. The fluid has several functions besides removing the drilled solid which are [5]:

- Cool and clean the bit.
- Reduce the friction between the drill string and the sides of the hole.
- Prevent the inflow of fluids- oil, gas, or water- from permeable rocks penetrated.
- Maintain the stability of uncased sections of the borehole.

The drilling fluid is pumped from the surface through the drillpipe, through nozzles in the rotating drillbit, and back to the mud tank through the annular space between the wellbore wall and the drill pipe [8]. The annular space is the annulus. Annulus can be defined as the space between two concentric objects, such as between the wellbore and casing or between casing and tubing, where fluid can flow [7]. Figure 1 show the diagram of an annulus.

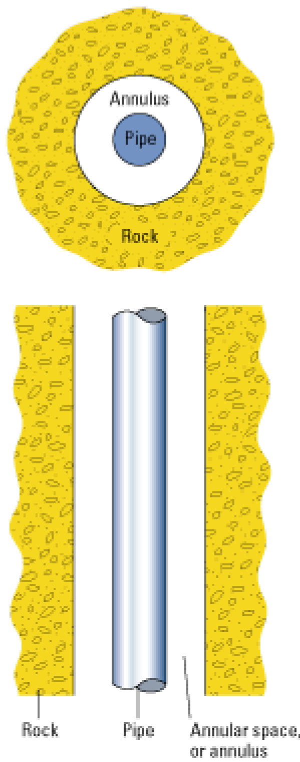


Figure 1 Diagram of an annulus

The fluid flow through the annulus is the main concern in this project. The fluid, which is viscoelastic fluid, behaves differently from normal fluid such as water. Thus, having an understanding about viscoelastic fluid will be crucial.

2.2 Viscoelastic Fluid

Viscoelastic fluid is fluid that exhibit both viscous and elastic property. Viscous fluid resists shear flow and strain with time [6]. When giving enough force the fluid will deform. As long as the force is there, the fluid will deform continuously. Once the force is remove the deformation will stop but it will not return to it original state. The relation between shear stress and strain rate of normal fluid is shown below in Figure 2.

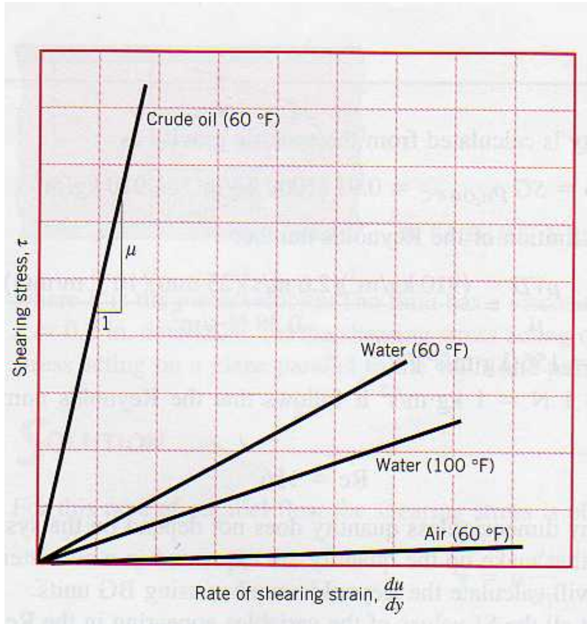


Figure 2 The relationship between shear stress and strain rate

The slope in the figure corresponds to the value of viscosity. For most Newtonian fluid the value is constant as in Figure 2. But for non Newtonian fluid, the viscosity is changing as the shear rate change.

Elastic material return to their original state as the force is removed. Presence of force causes the material strain linearly. Unlike viscous fluid, elastic material strain does not vary with time. Figure 3 below show how shear stress and strain relate for elastic material. Just like viscosity, the elasticity of the material is the slope of the graph. Usually the elasticity of the material is constant and does not vary with time.

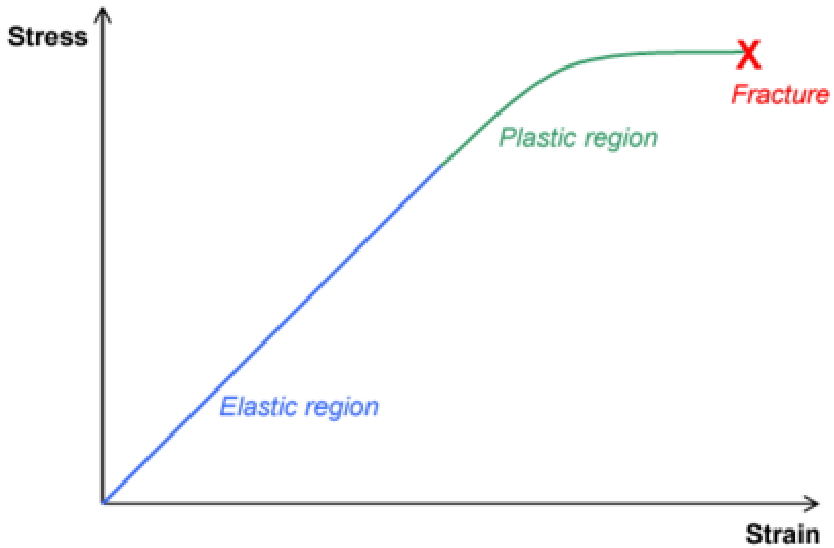


Figure 3 Stress and strain relation for elastic material

Viscoelastic fluid is the fluid that deform as shear stress is applied but as the force is remove, the fluid return to it original state even partially. Consider viscoelastic fluid as a material with a lot of long chain molecules just like polymer material. As stress is applied the long chain moved or changed position. As this occurs back stress is created. Back stress happen as the molecules structure is not as in it natural structure. When another stress is applied, in which it is the same amplitude as the back stress, no change in molecules structure happen. Instead the molecules that change before is riveted back to it old position as the stress is removed [6]. Thus the material resistance is the viscous properties, while the recover position is the elastic properties. Both properties create viscoelastic material.

Viscoelastic fluid is non Newtonian fluid. Thus viscoelastic fluid can be divided to three types, Bingham fluid, pseudoplastic fluid and dilatant fluid. Figure 4 below show stress and strain rate of each fluid.

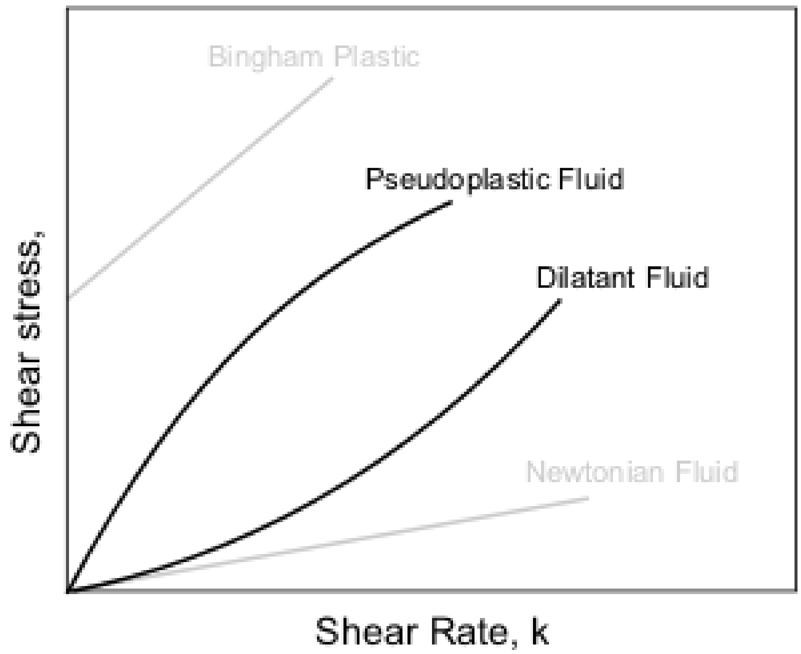


Figure 4 Type of Non Newtonian fluids

Bingham fluid is just like Newtonian fluid. The only difference is that it start deform at certain stress value. If the value is lower than the value needed, then the fluid acts as rigid or solid. Pseudoplastic fluid is also known as shear thinning fluid where the viscosity of the fluid increase as the shear stress increases. The opposite happen with dilatant fluid. This type of fluid becomes thicker as the shear stress increase.

CHAPTER 3

METHODOLOGY

3.1 Analysis Technique

Analysis technique for completing this project can be divided into three; analytical approach, experimental approach, and simulation approach.

3.1.1 Analytical Approach

In this approach, we would like to produce the governing equation. The equation will basically originate from the Navier-Stokes equation. The equation then is reduced to using the assumption. From the governing equation we can see which properties that will affect the flow. Beside, solving the equation by applying the boundary condition will produce figures in which we can compare to the simulation result.

Consider annulus below for the flow:

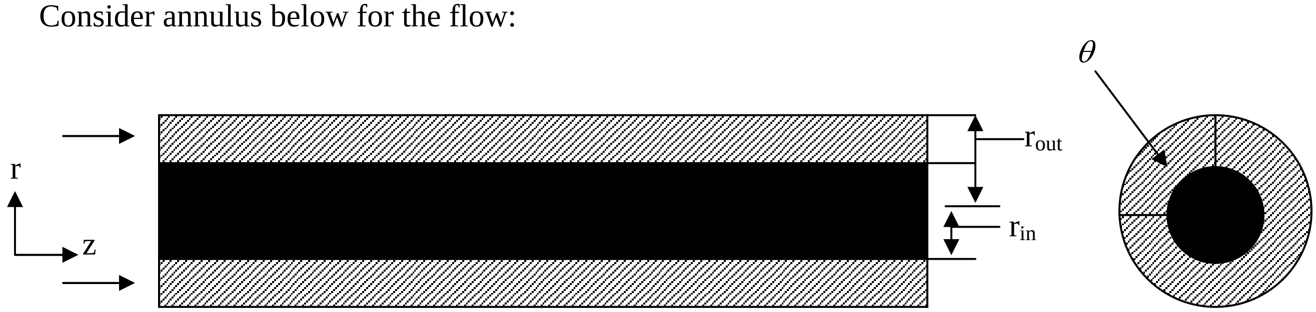


Figure 5 Flow in annulus

In developing the flow governing equation, Continuity and Momentum equation will play very important role. Both equations will be in cylindrical coordinates.

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial (r v_r)}{\partial r} + \frac{\partial (v_\theta)}{\partial \theta} + \frac{\partial (v_z)}{\partial z} = 0$$

Momentum Equation:

r-component:-

$$\rho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta}-\frac{v^2{}_\theta}{r}+v_z\frac{\partial v_r}{\partial z}\right)=$$
$$\rho g_r-\frac{\partial P}{\partial r}+\mu\left\{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}[rv_r]\right)+\frac{1}{r^2}\frac{\partial^2 v_r}{\partial \theta^2}-\frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta}+\frac{\partial^2 v_r}{\partial z^2}\right\}$$

θ-component:-

$$\rho\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta}-\frac{v_r v_\theta}{r}+v_z\frac{\partial v_\theta}{\partial z}\right)=$$
$$\rho g_\theta-\frac{1}{r}\frac{\partial P}{\partial \theta}+\mu\left\{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}[rv_\theta]\right)+\frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial \theta^2}-\frac{2}{r^2}\frac{\partial v_r}{\partial \theta}+\frac{\partial^2 v_\theta}{\partial z^2}\right\}$$

z-component:-

$$\rho\left(\frac{\partial v_z}{\partial t}+v_r\frac{\partial v_z}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta}+v_z\frac{\partial v_z}{\partial z}\right)=\rho g_z-\frac{\partial P}{\partial z}+\mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2}+\frac{\partial^2 v_z}{\partial z^2}\right\}$$

The flow in annulus is considered 2D flow with the velocity in θ is consider 0 and any change of θ $\left(\frac{\partial}{\partial \theta}\right)$ is also consider 0. The flow is laminar and steady, which mean that it does not change with time, $\frac{\partial}{\partial t}=0$. We also consider the flow only move in one direction which is *z*-direction and no flow in *r*-component. Thus v_r is consider 0. By this assumption the Continuity and Momentum Equation can be reduce.

As any change with θ = 0. Then Continuity equation can be reduced to:

$$\frac{1}{r}\frac{\partial(rv_r)}{\partial r}+\frac{\partial(v_z)}{\partial z}=0$$

For fully developed laminar flow in a pipe as in Figure 5 below. The velocity changes from 0 to maximum as we moved from the wall of the pipe to the center line. As there is no flow in *r* direction, thus for a velocity profile the velocity is in depend on the radius, $v_z = v_z(r)$.

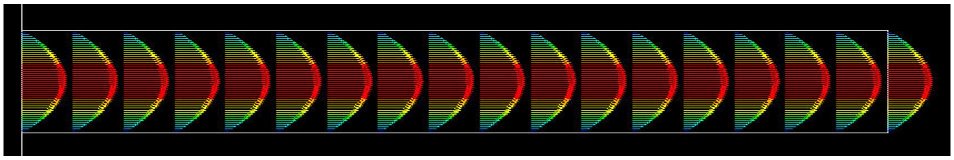


Figure 6 Fully developed laminar flow

Thus for a center line velocity function there is no velocity in *r*-component and $v_z = v_z(r)$. The Continuity equation will be:

$$\frac{\partial(v_z)}{\partial z} = 0 \Rightarrow v_z = v_z(r)$$

By the assumption stated earlier, the momentum equation can be simplified to:

r-component:-

$$\rho\left(v_r \frac{\partial v_r}{\partial r} + v_z \frac{\partial v_r}{\partial z}\right) = \rho g_r - \frac{\partial P}{\partial r} + \mu\left\{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}[r v_r]\right) + \frac{\partial^2 v_r}{\partial z^2}\right\}$$

As $v_r = 0$, then:

$$0 = \rho g_r - \frac{\partial P}{\partial r} \Rightarrow \frac{\partial P}{\partial r} = \rho g_r$$

Assuming that the pressure distribution in the cross section is constant, then:

$\frac{\partial P}{\partial r} =$ constant.

As the only force that act in the r-direction is the gravity, then $g_r = g$. Thus the pressure distribution in r-direction will be because the affect of gravity.

In annulus, the pressure change or the pressure gradient is very large compare to weight. Hence $\frac{\partial P}{\partial z} = \frac{dP}{dz}$.

θ-component:-

The momentum equation in θ-component is reduced to zero as no change in θ.

z-component:-

$$\rho\left(v_r \frac{\partial v_z}{\partial r} + v_z \frac{\partial v_z}{\partial z}\right) = \rho g_z - \frac{\partial P}{\partial z} + \mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) + \frac{\partial^2 v_z}{\partial z^2}\right\}$$

As $v_z = v_z(r)$, then:

$$\rho\left(v_r \frac{\partial v_z}{\partial r}\right) = \rho g_z - \frac{\partial P}{\partial z} + \mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)\right\}$$

As $v \ \ = v_z(r)$, then $\frac{\partial v_z}{\partial r} = \frac{dv_z}{dr}$, the equation is reduced further:

$$\rho\left(v_r \frac{dv_z}{dr}\right) = \rho g_z - \frac{\partial P}{\partial z} + \mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{dv_z}{dr}\right)\right\}$$

As the flow is in z direction while the gravity act downward, then we can assume that g_z=0.

As $\frac{\partial P}{\partial z} = \frac{dP}{dz}$ ➔ $\rho\left(v_r \frac{dv_z}{dr}\right) = -\frac{dP}{dz} + \mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{dv_z}{dr}\right)\right\}$

As there is no flow in r- direction:

$$0 = -\frac{dP}{dz} + \mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{dv_z}{dr}\right)\right\}$$

$$\frac{r}{\mu}\frac{dP}{dz} = \frac{\partial}{\partial r}\left(r\frac{dv_z}{dr}\right)$$

In order to solve the equation, double integration is done.

$$r\frac{dv_z}{dr} = \int \frac{r}{\mu}\frac{dP}{dz}\partial r$$

By treating $\frac{dP}{dr}$ and μ as constant:

$$r\frac{dv_z}{dr} = \frac{P(z)}{\mu}\left(\frac{r^2}{2}\right) + C_1$$

$$v_z(r) = \int \frac{1}{r}\left(\frac{P(z)}{\mu}\left(\frac{r^2}{2}\right) + C_1\right)dr$$

$$v_z(r) = \frac{P(z)}{\mu}\int\left(\frac{r}{2} + \frac{C_1}{r}\right)dr$$

$$v_z(r) = \frac{P(z)}{\mu} \times \frac{r^2}{4} + C_1 \ln r + C_2$$

By applying boundary condition, value of C_1 and C_2 can be solved.

Boundary condition 1: At $r = r_1$, $v_z(r_1) = 0$

Boundary condition 2: At $r = r_2$, $v_z(r_2) = 0$

Thus:

$$v_z(r) = 0 = \frac{P(z)}{\mu} \times \frac{{r_1}^2}{4} + C_1 \ln r_1 + C_2 \text{------- (1)}$$

$$v_z(r_2) = 0 = \frac{P(z)}{\mu} \times \frac{{r_2}^2}{4} + C_1 \ln r_2 + C_2 \text{------- (2)}$$

(1) – (2)

$$0 = \left[\frac{P(z)}{\mu}\left(\frac{{r_1}^2}{4}\right) + C_1 \ln r_1\right] - \left[\frac{P(z)}{\mu}\left(\frac{{r_2}^2}{4}\right) + C_1 \ln r_2\right]$$

$$0 = \frac{P(z)}{4\mu}\left(r_1 - r_2\right) + C_1 \ln \frac{r_1}{r_2}$$

$$C_1 = \frac{\frac{P(z)}{4\mu}\left(r_2 - r_1\right)}{\ln \frac{r_1}{r_2}}$$

Put $C_1 = \frac{\frac{P(z)}{4\mu}\left(r_2 - r_1\right)}{\ln \frac{r_1}{r_2}}$ in (1)

$$0 = \frac{P(z)}{\mu} \times \frac{{r_1}^2}{4} + \left(\frac{\frac{P(z)}{4\mu}\left(r_2 - r_1\right)}{\ln \frac{r_1}{r_2}}\right) \ln r_1 + C_2$$

$$C_2 = -\frac{P(z)}{\mu}\left(\frac{{r_1}^2}{4}\right) - \left(\frac{\frac{P(z)}{4\mu}\left(r_2 - r_1\right)}{\ln \frac{r_1}{r_2}}\right) \ln r_1$$

Thus by knowing the value of r_1 *and* r_2 then the equation will be usable. The solved equation still used μ as it viscosity. For the Non-Newtonian, the value will be replaced by the viscosity model that will be developed.

3.1.2 Experimental Approach

In this approach, water-based mud is tested for its density and viscosity. Each differs in the type of viscosifier and the percentage of viscosifier added.

3.1.2.1 Preparing Drilling Mud Sample

Introduction:

Drilling mud varies as different additives are added. Additives, as its function, change the properties of the drilling mud. As density and viscosity of the mud will be tested in this experiment, few drilling mud is prepared.

Objectives:

Preparing the drilling mud with viscosifier.

Equipment:

Multimixer is used in this experiment. Multimixer is use to mix the drilling mud and the additives together so that the mixture become homogeneous.

Figure 7 Multimixer machine

Figure 8 Types of Viscosifier

Procedures:

1. Prepare 350 ml of distilled water.
2. Stir the water using the Multimixer for 5 minutes. Stirring will remove the gas bubble that may exist in the water.
3. Prepare 22.5g of bentonite.
4. Mix the bentonite in the stirring water bit by bit until all the bentonite is added.
5. Prepare the viscosifier at the desired weight.

6. Mix the viscosifier at bit by bit until all viscosifier is added.

3.1.2.2 Density Measurement

Introduction:

It is extremely important that the density of the drilling fluid be known throughout the drilling operation. This is true whether drilling through gas, oil, or salt water sands; shale, where relatively high density may be required; or into low pressure production zones, where low density colloidal mud is advantageous. Frequent density tests aid in preserving a safety factor by disclosing any changes taking place in the unit weight of the fluid. The most practical instrument for measuring fluid density is the Mud Balance.

Objectives:

Measuring the density of drilling fluid using the Mud Balance.

Equipment:

The Fann Four Scale Mud Balance is an accurate, self-contained measuring device used to determine the density of drilling fluid. It has range of 7 to 24 pounds per gallon or specific gravity of 0.84 to 2.88. The Mud Balance consists of a constant-volume sample cup and lid connected to a balance arm that has four graduated scales. On one side are scales for measuring density in pound per gallon (lb/gal) and specific gravity (SP GR – g/cm^3). On the other side are scales for measuring density in pound per cubic feet (lbs/cu.ft) and pounds per square inch per 1000 feet or depth (lbs/sq.in./1000ft). A rider is moved along the balance arm to indicate the scale readings. There is a knife edge attached to the arm near the balance cup, and a bubble level built into the knife edge to level the arm. A fulcrum is mounted on a based stand, if used, or in the plastic carrying case, if it is used.

Figure 9 Mud Balance

Procedures:

1. The balance cup should be clean and dry before it is filled with the drilling fluid sample.
2. Drilling fluid samples containing large amounts of gas should be deaerated using the Fann Dearator before a density measurement is attempted.
3. Place the base stand or the carrying case on the surface that is approximately level.
4. Fill the balance cup with the sample to be tested. Tap the side of the balance cup several times to break up any entrained air or gases. Put the lid onto the balance cup by pushing it downward with a slow rotating motion until it is firmly seated. Make sure that some of the test sample is forced out through the vent hole in the lid. This action will also help to rid the sample of any entrained air or gas.
5. Clean any sample from the outside of the balance cup and lid.
6. Fit the knife edge of the balance arm into the fulcrum and balance the assembly by moving the rider along the arm. The Mud Balance is horizontal when the level bubble fluctuates an equal distance to their side of the centre line.
7. Take the reading from the side of the rider nearest to the balance cup. (The arrow on the rider is pointing to this side). The measurement reading should be reported

to the nearest 0.1 lbs/gal, 0.5 lbs/cu.ft, or 0.01 g/cm^3 (which is equivalent to specific gravity).

8. Empty the sample from the cup. Clean and dry the entire assembly as soon as possible.
9. Repeat steps 1 to 8 to measure the density of all the sample of drilling fluid that has been prepared.

3.1.2.3 Measurement of Viscosity by Viscometer

Introduction:

The development of satisfactory instruments for measuring the viscosity of drilling fluids has been the subject of much effort. This is due largely to the fact that most of drilling fluids are fundamentally non-Newtonian fluids and the viscosity characteristics of such fluids cannot be described by means of single measurement. The indicated viscosity as obtained on any instrument is valid only for that rate of shear and will differ when measured at a different rate of shear. The instrument will be used in this experiment is viscometer. The rotational viscometer can provide more meaningful measurement of the rheological characteristics of the fluid than the Marsh Funnel. The fluid is sheared at a constant rate between an inner bob and outer rotating sleeve.

Objectives:

Measuring viscosity of drilling fluid using the viscometer.

Equipments:

FANN Model 35SA viscometer, as shown in Figure 10, is an instrument with the ability to test at six different speeds. The range is from 3 rpm up to 600 rpm with the speed switch located on the right side of the base to the high or low speed position as desired.

Then turn the motor on and move the viscometer gear shift knob located in the center of the top of the instrument to its desired position.

Table 1 lists the proper positions for the viscometer switch and the gear knob combinations to obtain the desired speed. The viscometer gear shift knob may be engaged while the motor is running. Read the dial for shear stress value.

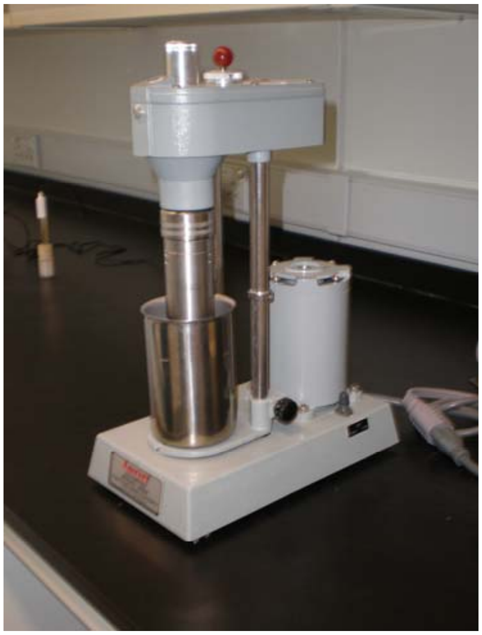


Figure 10 FANN Viscometer

Table 1 Six speed testing combination

Speed (RPM)	Viscometer Switch	Gear Knob
600	High	Down
300	Low	Down
200	High	Up
100	Low	Up
6	High	Center
3	Low	center

Procedures:

1. Place sample of the drilling fluid in the mud cup, and tilt the instrument head into the cup until the rotor sleeve is immersed into the fluid.

2. Stir the sample for about 15 seconds at 600 rpm.
3. Read the meter deflection at the following RPMs: 3, 6, 100, 200, 300 and 600. (NOTE: the meter whose deflection is to be read is labeled VISCOSITY. This label is incorrect. The meter deflection indicates shear stress; to calculate viscosity).

3.1.2.4 Result and Discussion

<u>Mud density</u>

Table 2 Mud Density

Type	Density (lbs/gal)
Basic Mud	8.61
Mud + 2g Xanthan Gum	8.7
Mud + 2.5g Xanthan Gum	8.65
Mud + 3g Xanthan Gum	8.45

From the experiment carried out it can be seen that the viscosifier change the density of the mud. As xanthan gum is used, the viscosity decreases as more viscosifier is added.

<u>Mud viscosity</u>

Basic Mud

Table 3 Basic Mud Dial Reading

RPM	Dial Reading
3	1
6	2
100	5
200	8
300	10
600	15

Mud + Xanthan Gum

Table 4 Xanthan gum mud dial reading

	Dial Reading		
RPM	2 gram	2.5 gram	3 gram
3	53	55	61
6	58	66	68
100	78	94	110
200	90	105	125
300	92	110	131
600	118	132	145

The value of the RPM and the dial reading is then converted to shear stress and the shear rate. As stated in by Darley and Gray in Composition and Properties of Drilling and Completion Fluids book [5]:

1^{o} dial reading = 5.11 dynes/cm²

= 0.511 N/m²

1 rpm = 1.703 reciprocal seconds

Table 5 Xanthan Gum Mud Shear Stress

Shear Rate	Shear Stress		
	2 gram	2.5 gram	3 gram
5.109	27.08	28.11	31.17
10.218	29.64	33.73	34.75
170.3	39.86	48.03	56.21
340.6	45.99	53.66	63.88
510.9	47.01	56.21	66.94
1021.8	60.30	67.45	74.10

Figure 11 shows the graph of shear stress versus the shear rate not only for the basic mud also for xanthan gum mud. From the graph, we can see that basic mud create a straight line, while the xanthan gum mud create more likely curve graph. As the concentration of the xanthan gum viscosifier increase, the shear stress also increases.

From the graph, the xanthan gum mud had shown almost the basic shape of graph for 2 gram, 2.5 gram and 3gram of xanthan gum in the mud. At low shear rate, the slope of the graph is high, while the slope of the graph is small at high shear rate. The slopes, change of shear stress over the change in shear rate, indicate the viscosity of the fluid. Thus at low shear rate, the fluid have high viscosity and low viscosity at high shear rate.

By constructing trendline, the type of graph produce by the xanthan gum mud can be known. The graph type can be used to determine what type of xanthan gum mud is, whether it is bingham plastic fluid or shear thinning fluid. Three type of trendline is used; power, linear and logarithm. Each graph is shown in Figure 12, 13 and 14 respectively.

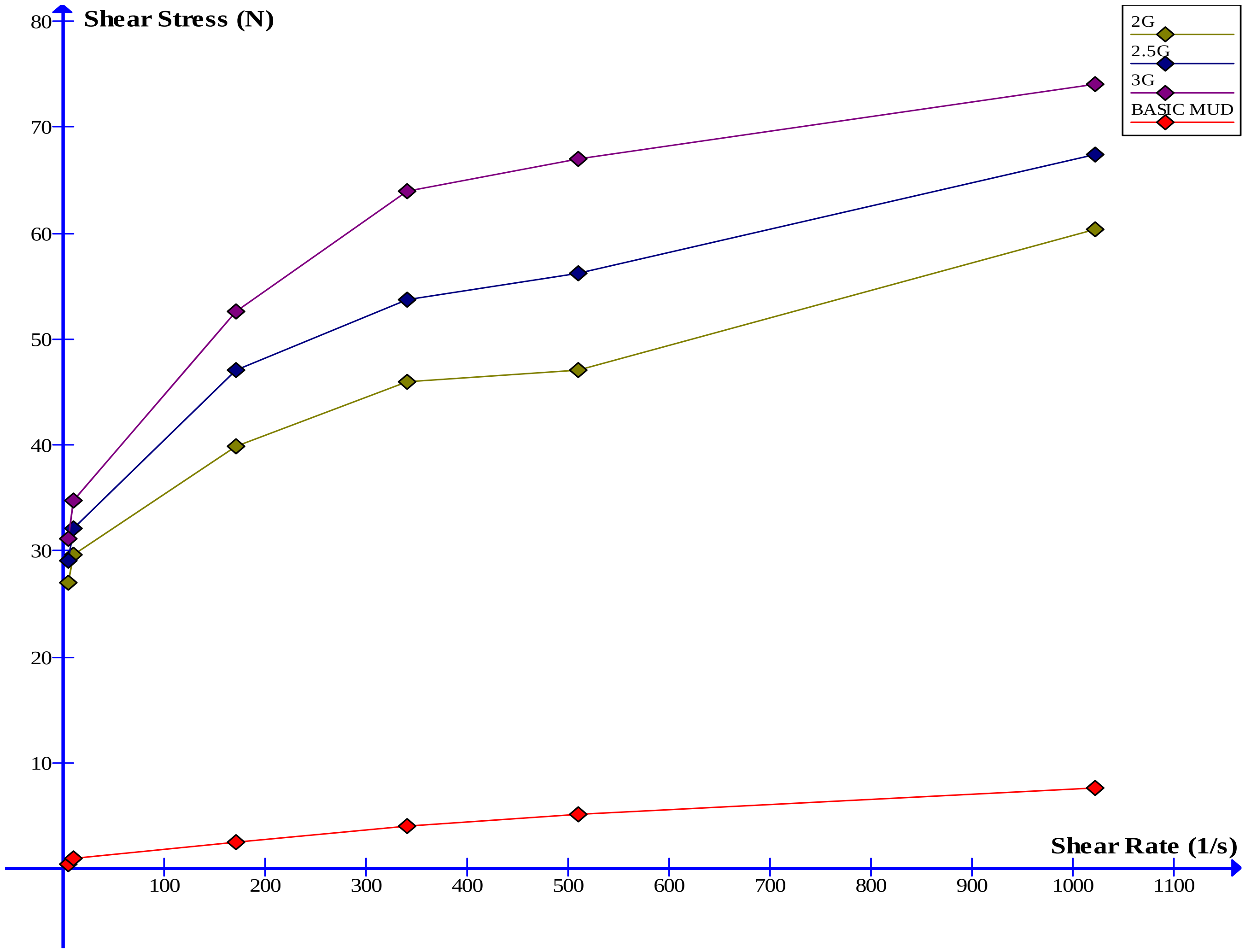


Figure 11 Shear Stress vs. Shear Rate for Basic and Xanthan Gum Mud

Data from each trendline and the experimental data are then being compared. Using standard deviation and mean squared error, the error for each data is then calculated.

Standard Deviation Formula:

$$\sigma = \frac{\sum | Experiment - Trendline |}{n}$$

Mean Squared Error Formula:

$$\sigma^2 = \frac{\sum(Experiment - Trendline)^2}{n}$$

Where *n* is the number of the sample.

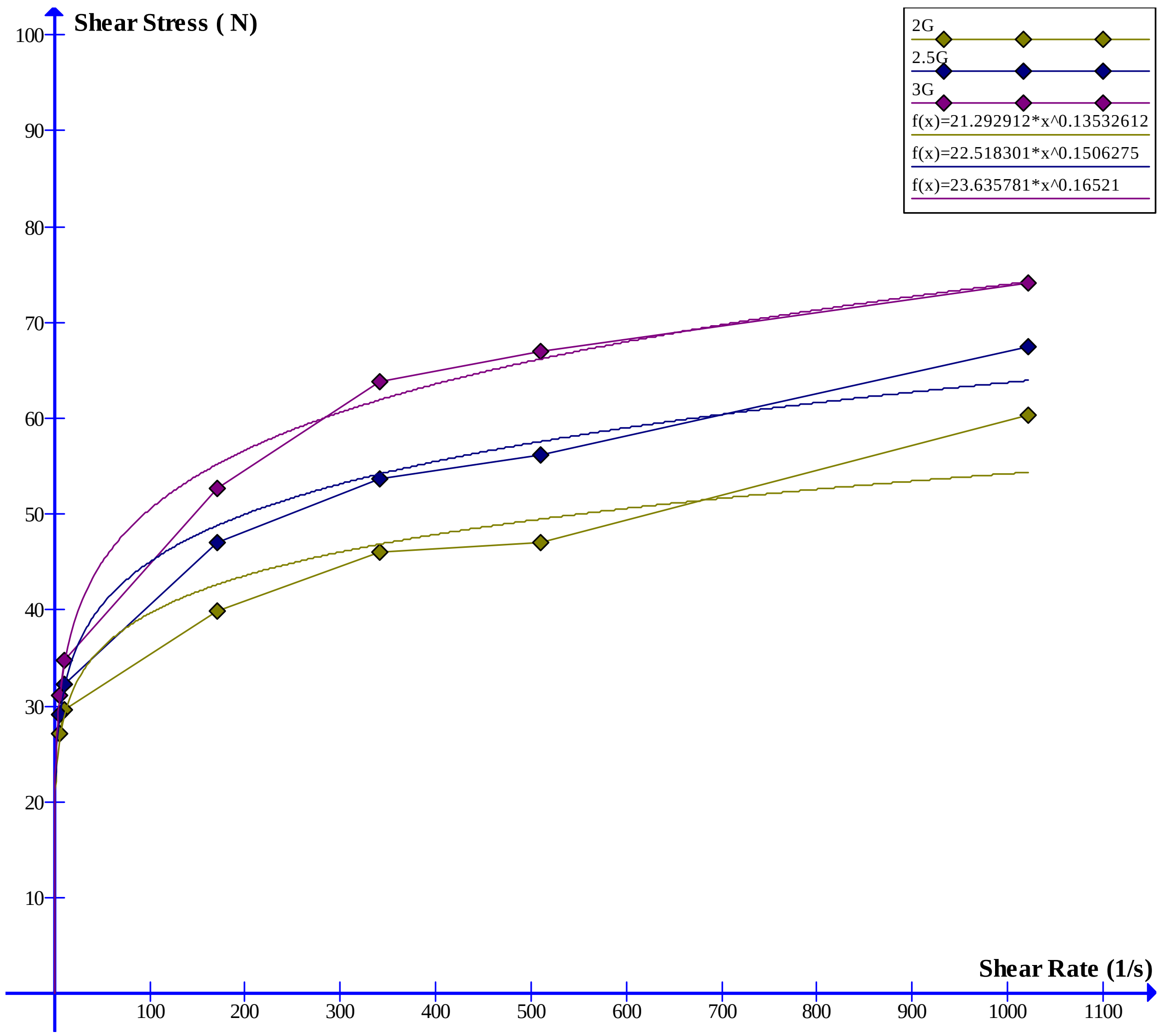


Figure 12 Graph of Xanthan Gum Mud with Power Trendline

Figure 12 show the Xanthan gum mud graph with constructed power trendline. Using the standard deviation and mean squared error (MSE) method, both experimental and trendline data in calculated.

Table 6 Standard Deviation and MSE for Power Trendline

For 2gram Xanthan Gum

Shear Rate	Data		Error	Error²
	Experiment	Power		
5.109	27.08	26.55	0.53	0.28
10.218	29.64	29.16	0.48	0.23
170.300	39.86	42.68	2.82	7.93
340.600	45.99	46.87	0.88	0.78
510.900	47.01	49.52	2.51	6.28
1021.800	60.30	54.39	5.91	34.98
Total Error			13.12	50.47
Standard Deviation			2.19	
MSE				8.41

For 2.5gram Xanthan Gum

Shear Rate	Date		Error	Error²
	Experiment	Power		
5.109	29.13	28.79	0.34	0.12
10.218	32.19	31.96	0.23	0.05
170.300	47.01	48.82	1.81	3.28
340.600	53.66	54.20	0.54	0.29
510.900	56.21	57.61	1.40	1.96
1021.800	67.45	63.95	3.50	12.2619
Total Error			7.82	17.96
Standard Deviation			1.30	
MSE				2.99

For 3gram Xanthan Gum

Shear Rate	Data		Error	Error²
	Experiment	Power		
5.109	31.17	30.9453	0.2247	0.05049
10.218	34.75	34.6998	0.0502	0.00252
170.300	52.63	55.2318	2.6018	6.769363
340.600	63.88	61.933	1.947	3.790809
510.900	66.94	66.2238	0.7162	0.512942
1021.800	74.10	74.2587	0.1587	0.025186
Total Error			5.6986	11.15131
Standard Deviation			0.949767	
MSE				1.858552

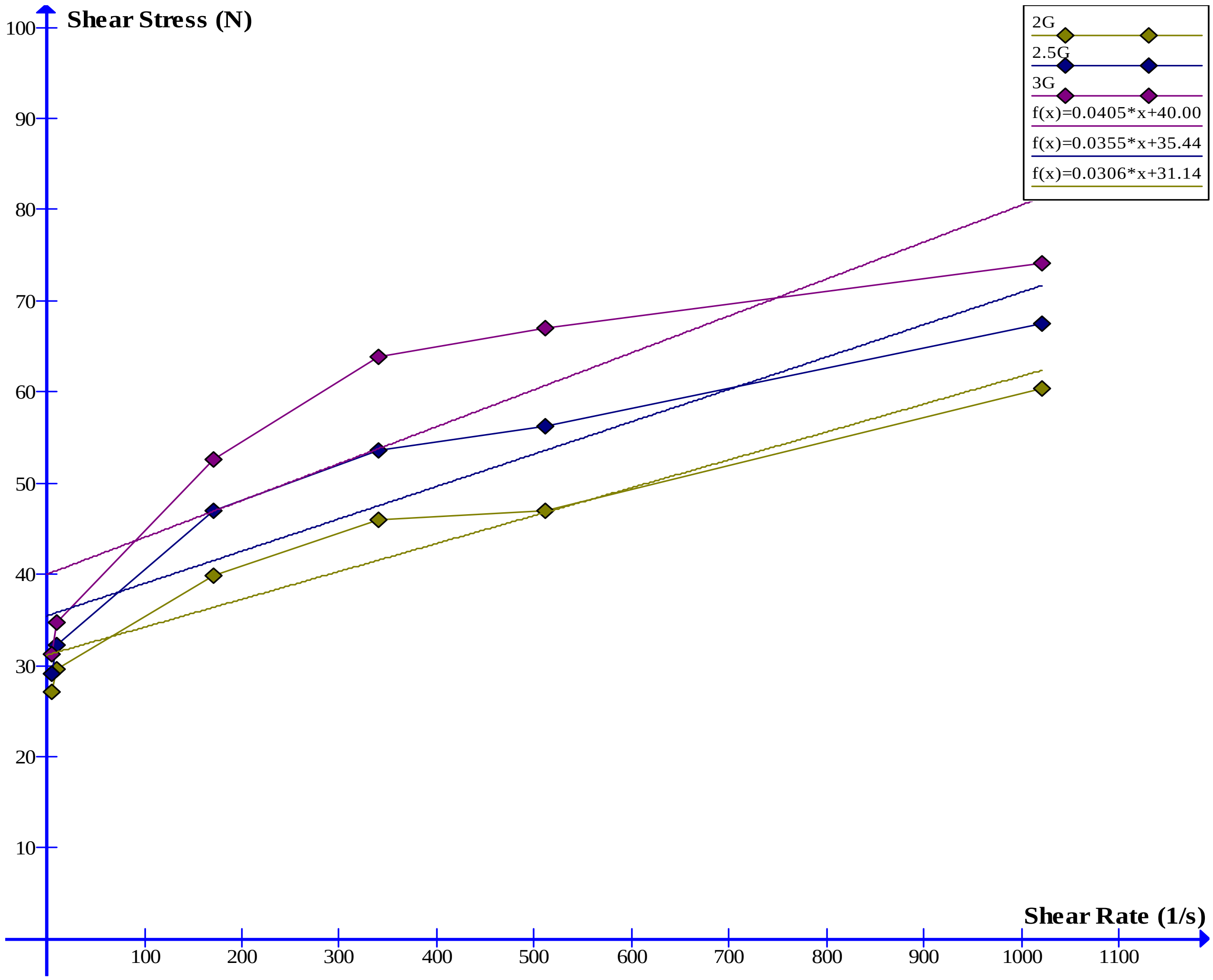


Figure 13 Graph of Xanthan Gum Mud with Linear Trendline

Figure 13 show the linear trendline developed for the xanthan gum mud. Table below show the standard deviation and mean squared error carried out for the linear trendline.

Table 7 Standard Deviation and MSE for Linear Trendline

For 2gram Xanthan Gum

Shear Rate	Data		Error	Error²
	Experiment	Linear		
5.109	27.08	31.29	4.21	17.75
10.218	29.64	31.45	1.81	3.27
170.300	39.86	36.35	3.51	12.30
340.600	45.99	41.56	4.42	19.55
510.900	47.01	46.78	0.23	0.05
1021.800	60.30	62.43	2.13	5
Total Error			16.31	57.47
Standard Deviation			2.72	
MSE				9.58

For 2.5gram Xanthan Gum

Shear Rate	Data		Error	Error²
	Experiment	Linear		
5.109	29.13	35.62	6.49	42.11
10.218	32.19	35.80	3.61	13.03
170.300	47.01	41.48	5.53	30.60413
340.600	53.66	47.52	6.14	37.73
510.900	56.21	53.56	2.65	7.04
1021.800	67.45	71.68	4.23	17.87
Total Error			28.65	148.38
Standard Deviation			4.78	
MSE				24.73

For 3gram Xanthan Gum

Shear Rate	Data		Error	Error²
	Experiment	Linear		
5.109	31.17	40.21	9.04	81.67
10.218	34.75	40.41	5.66	32.09
170.300	52.63	46.90	5.73	32.78
340.600	63.88	53.81	10.07	101.44
510.900	66.94	60.71	6.23	38.79
1021.800	74.10	81.42	7.32	53.64
Total Error			44.05	340.41
Standard Deviation			7.34	
MSE				56.74

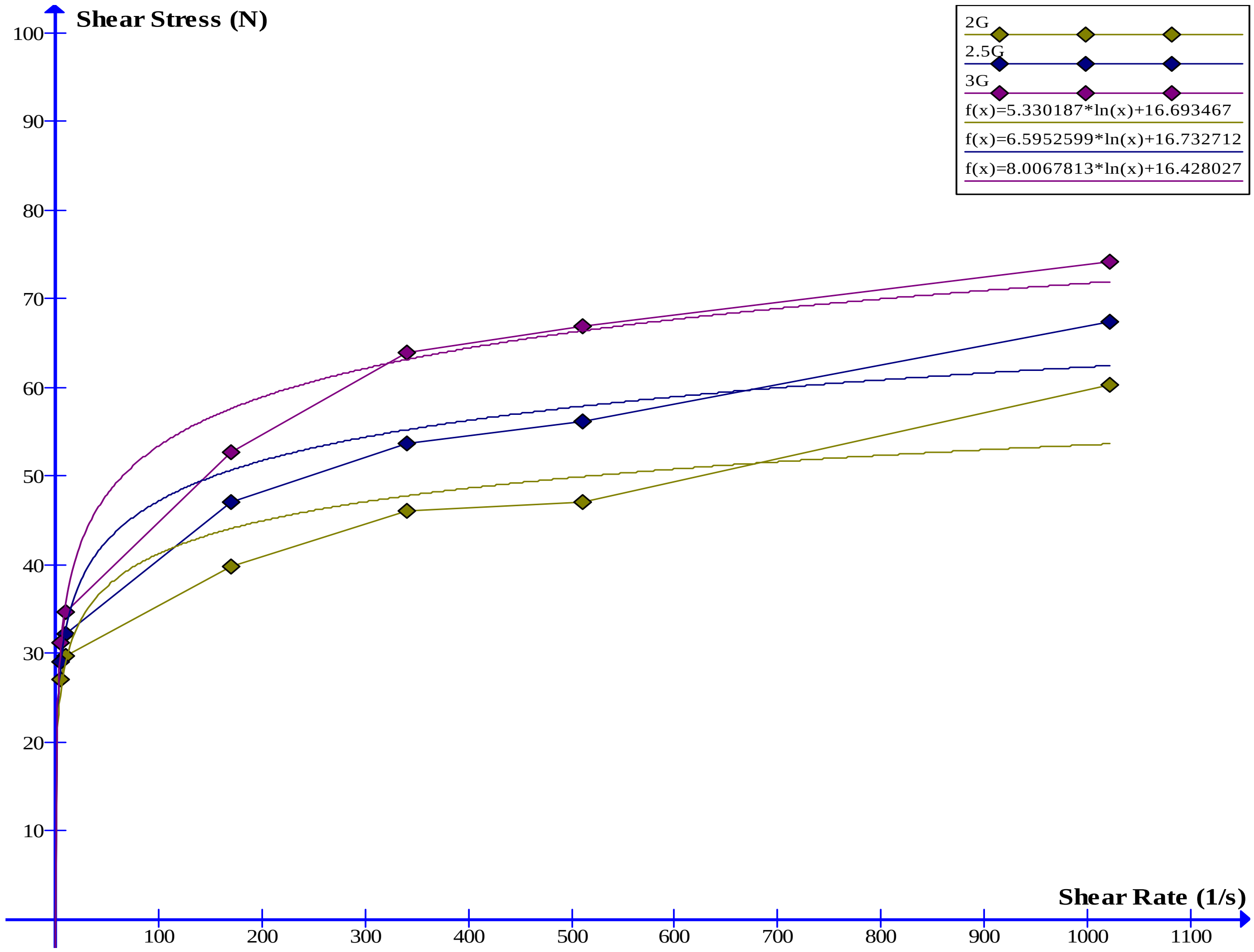


Figure 14 Graph of Xanthan Gum Mud with Logarithm Trendline

Figure 14 shows the last trendline, logarithm, which is developed for xanthan gum mud. The standard deviation and mean squared error also use for this trendline.

Table 8 Standard Deviation and MSE for Logarithm Trendline

For 2gram Xanthan Gum

Shear Rate	Data		Error	Error²
	Experiment	Log		
5.109	27.08	25.39	1.69	2.87
10.218	29.64	29.08	0.56	0.31
170.300	39.86	44.08	4.22	17.79
340.600	45.99	47.78	1.78	3.18
510.900	47.01	49.94	2.92	8.55
1021.800	60.30	53.63	6.67	44.52
Total Error			17.85	77.20
Standard Deviation			2.97	
MSE				12.87

For 2.5gram Xanthan Gum

Shear Rate	Data		Error	Error²
	Experiment	Log		
5.109	29.13	27.49	1.64	2.69
10.218	32.19	32.06	0.13	0.02
170.300	47.01	50.62	3.61	13.01
340.600	53.66	55.19	1.53	2.33
510.900	56.21	57.86	1.65	2.73
1021.800	67.45	62.43	5.02	25.17
Total Error			13.57	45.94
Standard Deviation			2.26	
MSE				7.66

For 3gram Xanthan Gum

Shear Rate	Data		Error	Error²
	Experiment	Log		
5.109	31.17	29.49	1.68	2.83
10.218	34.75	35.04	0.29	0.08
170.300	52.63	57.56	4.93	24.34
340.600	63.88	63.11	0.77	0.59
510.900	66.94	66.36	0.58	0.34
1021.800	74.10	71.91	2.19	4.80
Total Error			10.44	32.98
Standard Deviation			1.74	
MSE				5.50

Table 9 Summary of Standard Deviation and MSE for All Trendline

Trendline	**Standard Deviation**			**MSE**		
	2g	2.5g	3g	2g	2.5g	3g
Power	2.19	1.30	0.95	8.41	2.99	1.86
Linear	2.72	4.78	7.34	9.58	24.73	56.74
Logarithm	2.97	2.26	1.74	12.87	7.66	5.50

From the standard deviation and mean squared error calculated for each trendline developed, the Power trendline gives the lowest error. Thus Power trendline fit most the experimental graph. The Power trendline for all the mud sample gives the equation:

$f(x) = 21.29x^{0.135}$ - For 2g of xanthan gum

$f(x) = 22.52x^{0.151}$ - For 2.5g of xanthan gum

$f(x) = 23.64x^{0.165}$ - For 3g of xanthan gum

The general equation that describes the relationship of shear stress and shear rate is given by:

$$\tau = K\gamma^n \text{ [2]}$$

where

τ = shear stress $\quad$ K = Consistency Index

γ = shear rate $\quad$ n = flow behavior index.

Value of *n* will give the type of fluid the drilling mud is. As *n* is lower than 1 then it will be shear thinning fluid. If *n* is 1 then the fluid is Newtonian fluid. The value more than 1 will correspond when the fluid is shear thickening fluid.

Comparing the equation given by the Power trendline with the general equation will give:

$$\tau = K\gamma^n \Leftrightarrow f(x) = 21.29x^{0.135}$$

$$\tau = K\gamma^n \Leftrightarrow f(x) = 22.52x^{0.151}$$

$$\tau = K\gamma^n \Leftrightarrow f(x) = 23.64x^{0.165}$$

Table 10 Summary of *K* and *n* for All Concentration

	K	*n*
2g of Xanthan Gum	21.29	0.135
2.5g of Xanthan Gum	22.52	0.151
3g of Xanthan Gum	23.64	0.165

As all the value of *n* given by xanthan gum mud is less than 1, then xanthan gum mud is the shear thinning fluid. The statement is supported by C. Kim and B. Yoo in their research which says that,

"The shear-thinning character of xanthan gum is more pronounced than those of other polysaccharide gums….[1]"

The value of *K*, which is the consistency index, increase as the concentration of the xanthan gum increase. The same behaviour also indicated in the value of *n*. The equation then can be used in simulating the flow.

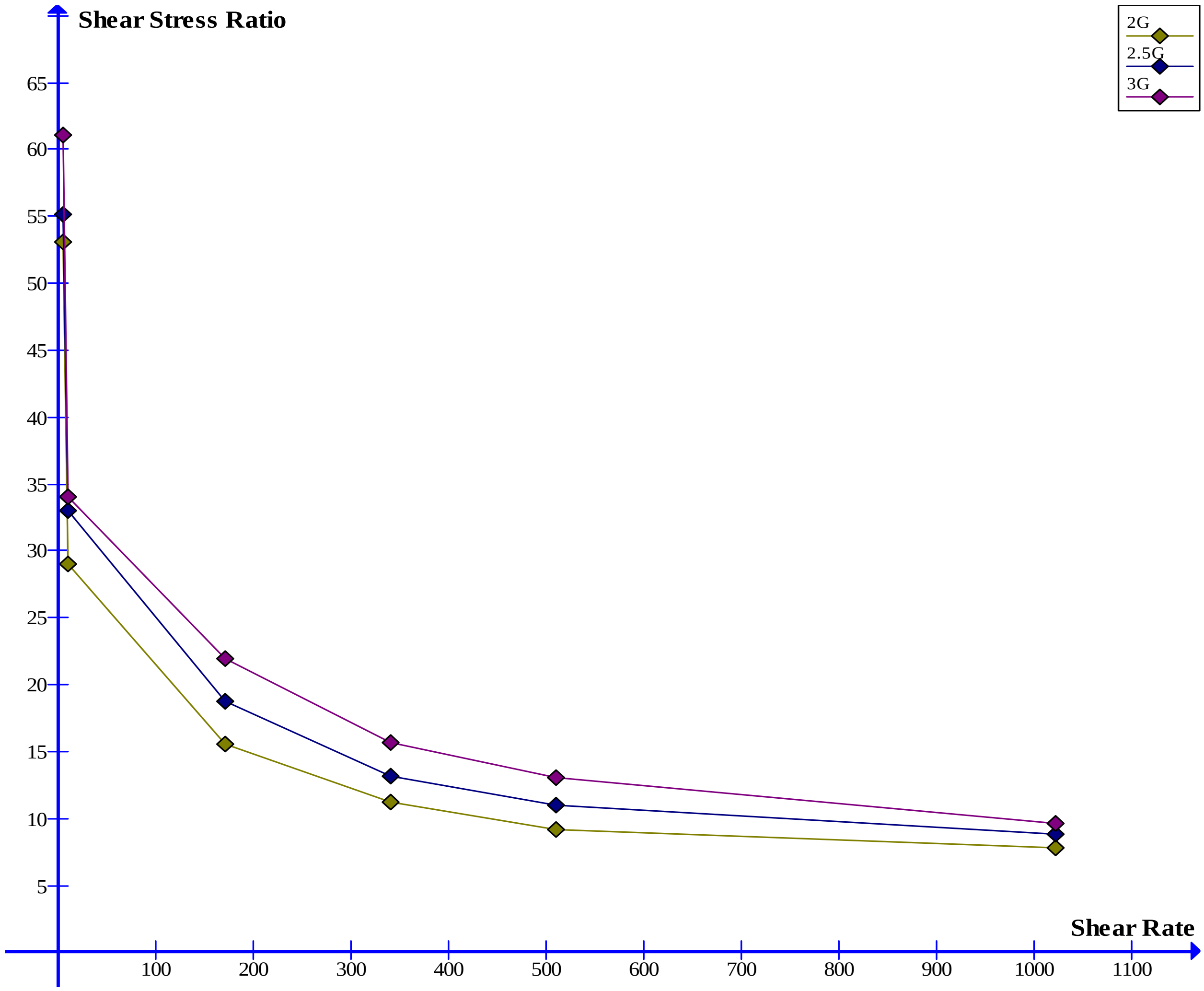


Figure 15 Graph of Shear Stress Ratio of Xanthan Gum over Basic Mud

Figure 15 show how the respond of the graph compared to the basic mud at the same shear stress ratio. All the concentration of xanthan gum will give the same shape of graph. As we can see, the ratio change at the low shear rate is very high while the change becomes linear or low at high shear rate.

3.1.3 Simulation Approach

Simulation is done using GAMBIT as modeler and FLUENT as the solver. For this simulation we are considering isothermal, laminar, fully developed flows of fluid which is air, and having constant density and viscosity. Even the flow in the annulus is supposed to be multiphase but in this simulation, we consider the flow to be in one phase only. The data below will be used for the simulation.

3.1.3.1 Data

The data below is the data used in simulating the fluid flow in GAMBIT and FLUENT.

<u>Summary of well</u>

Total depth	:5608.7 ft
Bit depth	:5608.7 ft
Temperature Gradient	:1^{o}C/100 ft
Hook load	:155439 lbs
Weight on bit	:30416 lbs
ROP	:44.8 ft/hr
Top drive torque	:0 ft lbs
Top drive torque	:0 rpm
% return flow	:34%

<u>Drill string specifications</u>

Casing	*Outer diameter*	:9.625 in
	Inner diameter	:8.681 in
	Weight	:47 lbs/ft
	Depth of set casing	:3950 ft
Drill pipe	*Outer diameter*	:5 in
	Inner diameter	:4.276 in
	Length	:36 in
	Weight	:22.6 lbs/ft

	No of joints	:166
Collar	*Outer diameter*	:6.25 in
	Inner diameter	:2.813 in
	Weight	:83 lbs/ft
	No of joints	:20

Pressures

Drill pipe pressure: 1058 psi

Casing pressure: 16 psi

Pressure loss	*Surface line*	:-37 psi
	Drill string	:141 psi
	Bit	:830 psi
	Annulus	:42 psi
Hydrostatic pressure	*Drill string*	:3059 psi
	Annulus to bit	:3043 psi
	Annulus to bottom	:3043 psi
	Annulus to shoe	:2138 psi

Pump specifications

Pump pressure: 1058 psi

Casing pressure: 16 psi

Total spm: 61

Total strokes: 1249

Pump	1	2	3
Speed (spm)	61	0	0
Pressure (psi)	1060	1058	1051

Mud data

Mud weight in	:10.5 ppg
Mud weight out	:10.5 ppg
Return flow	:34%
Active volume	:300.8 bbls
Pit gain/loss	:-0.3 bbls
Reserve volume	:200 bbls
Reserve mud weight	:10.5

From the data above, more simplified data is then produced and the fluid properties data is added:

Table 11 Summary of Simulation Data

Physical Properties	
Casing	ID: 0.22 m
Drill pipe	OD: 0.13 m Length: 0.91 m
Annulus	Diameter: 0.045 m Length: 0.91 m
Inlet Pressure	558473 Pa
Outlet Pressure	268895 Pa
Operating Temperature	341 K
Flow Properties	
Mud A	
Consistency Index	21.29
Flow Behavior Index	0.135
Density	1042.48 kg /m^3
Mud B	
Consistency Index	22.60
Flow Behavior Index	0.151
Density	1036.49 kg /m^3
Mud C	
Consistency Index	23.76
Flow Behavior Index	0.167
Density	1012.59 kg /m^3

3.1.3.2 Procedure

The procedures in carry out the simulation can be divided into two parts, the procedure for modeling using GAMBIT and the procedure for solver FLUENT.

Start GAMBIT

1. Operation Toolpad > Geometry Command Button> Vertex Command Button> Create Vertex

a) Create the vertex at the lower-left corner of the rectangle.

b) Enter the following:

X = 0, Y = 0, Z = 0

c) Click APPLY

d) Repeat step (a) and (c) for the following:

X = 0, Y = 0.045, Z = 0	X = 0.91, Y = 0.045, Z = 0
X = 0.91, Y = 0, Z = 0	X = 0, Y = 0.175, Z = 0
X = 0.91, Y = 0.175, Z = 0	X = 0.91, Y = 0.22, Z = 0
X = 0, Y = 0.22, Z = 0	

2. Operation Toolpad > Geometry Command Button > Edge Command Button > Create Edge

a) Click on the up-arrow next to Vertices.

b) Click on All-> to select all of the vertices at once. Close the Vertex List window.

c) Click Apply.

3. Operation Toolpad > Geometry Command Button > Face Command Button > Form Face

a) Click on the up arrow next to Edges.

b) Click on All-> to select all of the edges at once. Click Close

c) Click Apply.

4. Operation Toolpad > Mesh Command Button > Edge Command Button > Mesh Edges

a) Bring up the *Edge List* window and select both the vertical lines.

b) Select Interval Count from the drop down box that says Interval Size in the *Mesh Edges Window*. Then, in the box to the left of this combo box, enter 10 for the interval count.

c) Click Apply.

d) Repeat step (a) and (b) for the horizontal lines. Use 100 for interval count.

5. Operation Toolpad > Mesh Command Button > Face Command Button > Mesh Faces

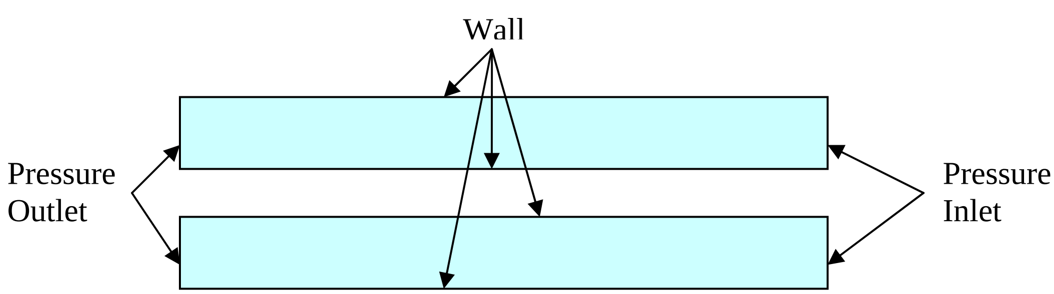
a) Click up arrow next to Faces to select the face. Click Apply.

6. Operation Toolpad > Zones Command Button > Specify Boundary Types Command Button

a) Under Entity; pick Edges. Click up arrow next to Edges to select the edge Pick ,both, left vertical edges.

b) Next to Name:, enter inlet. For Type:, select VELOCITY_INLET.

c) Repeat the process for the other three edges according to the following figure:



7. Main Menu > File > Save

8. Main Menu > File > Export > Mesh

a) Type in simulation.msh for the File Name. Select Export 2d Mesh since this is a 2 dimensional mesh. Click Accept.

Start FLUENT

9. Main Menu > File > Read > Case

a) Pick the simulation.msh file.

10. Main Menu > Grid > Check

a) Any errors in the grid would be reported at this time. Check the output and make sure that there are no errors reported.

11. Main Menu > Grid > Info > Size

12. Main Menu > Display > Grid

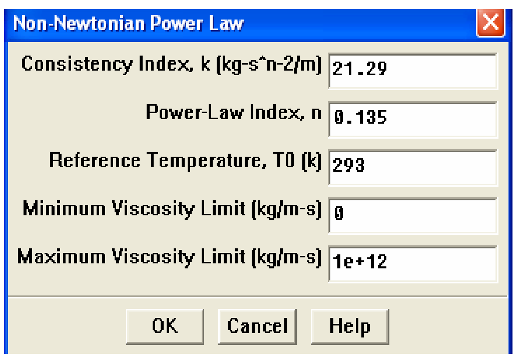
13. Main Menu > Define > Models > Solver

a) Click OK

14. Main Menu > Define > Materials

a) Change the density to 1042.48 kg/m^3.

b) Change the viscosity from constant to Non-Newtonian Power Law. Insert the data using the properties of Mud A.



c) Click Change/Create. Close the window.

15. Main Menu > Define > Operating Conditions

a) Use the default value of 1 atm (101,325 Pa) as the Operating Pressure.

b) Tick the Gravity option. Insert -10m/s^2 in Y-direction box as the gravity acceleration.

c) Click OK.

16. Main Menu > Define > Boundary Conditions

a) Select inlet under Zone.

b) Click on Set. Enter 81 psi for Pressure Magnitude. Click OK.

c) Select outlet under Zone.

d) Click on Set. Enter 268895 Pa for Gauge Pressure. Click OK.

17. Main Menu > Solve > Controls > Solution

a) Change Momentum to Second Order Upwind. Click OK

18. Main Menu > Solve > Initialize > Initialize

a) Choose inlet under Compute From.

b) Click Init. Close the window.

19. Main Menu > Solve > Monitors > Residual

a) Change the residual under Convergence Criterion for continuity, x-velocity, and y-velocity, all to 1e-6.

b) Under Options, select Plot. This will plot the residuals in the graphics window as they are calculated. Click OK

20. Main Menu > File > Write > Case

21. Main Menu > Solve > Iterate

a) In the Iterate Window that comes up, change the Number of Iterations to 1000.

b) Click Iterate.

22. Main Menu > File > Write > Data

23. Main Menu > Plot > XY Plot

a) Under Y Axis Function, pick Velocity. In the box under that, pick Axial Velocity.

b) Select centerline under Surfaces. Click Plot.

24. File > Hardcopy

a) Under Format, choose JPG. Click Save.

25. Main Menu > Display > Vectors

a) Choose Velocity Magnitude. Click Display.

26. File > Hardcopy

a) Under Format, choose JPG. Click Save.

27. Main Menu > Display > Contours

a) Choose Total Pressure. Click Display. Repeat Step 26 to save the file.

b) Choose Dynamic Pressure. Click Display. Repeat Step 26 to save the file.

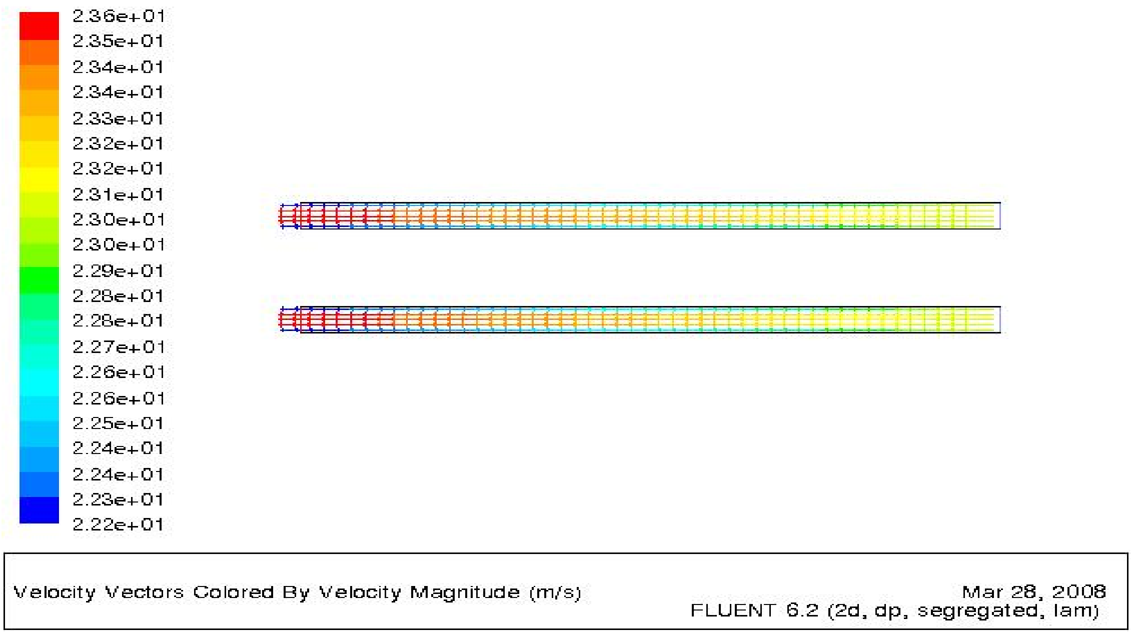
c) Choose Static Pressure. Click Display. Repeat Step 26 to save the file.

Repeat the simulation for Mud B and Mud C.

3.1.3.3 Result and Discussion

FLUENT and GAMBIT

Mud A



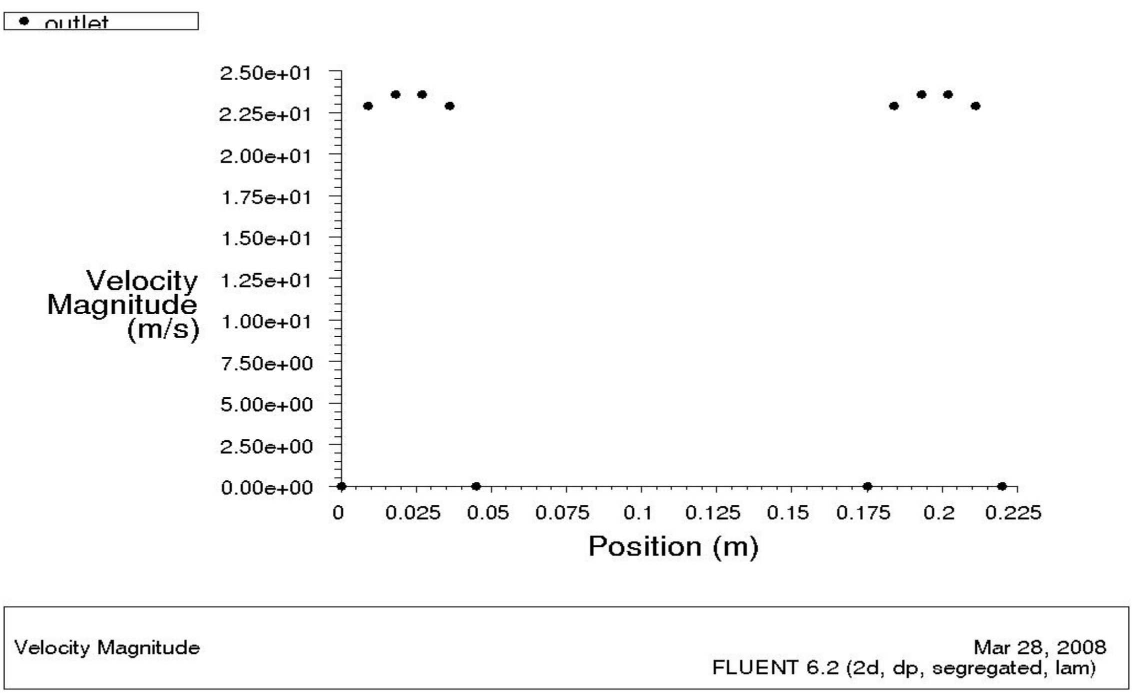
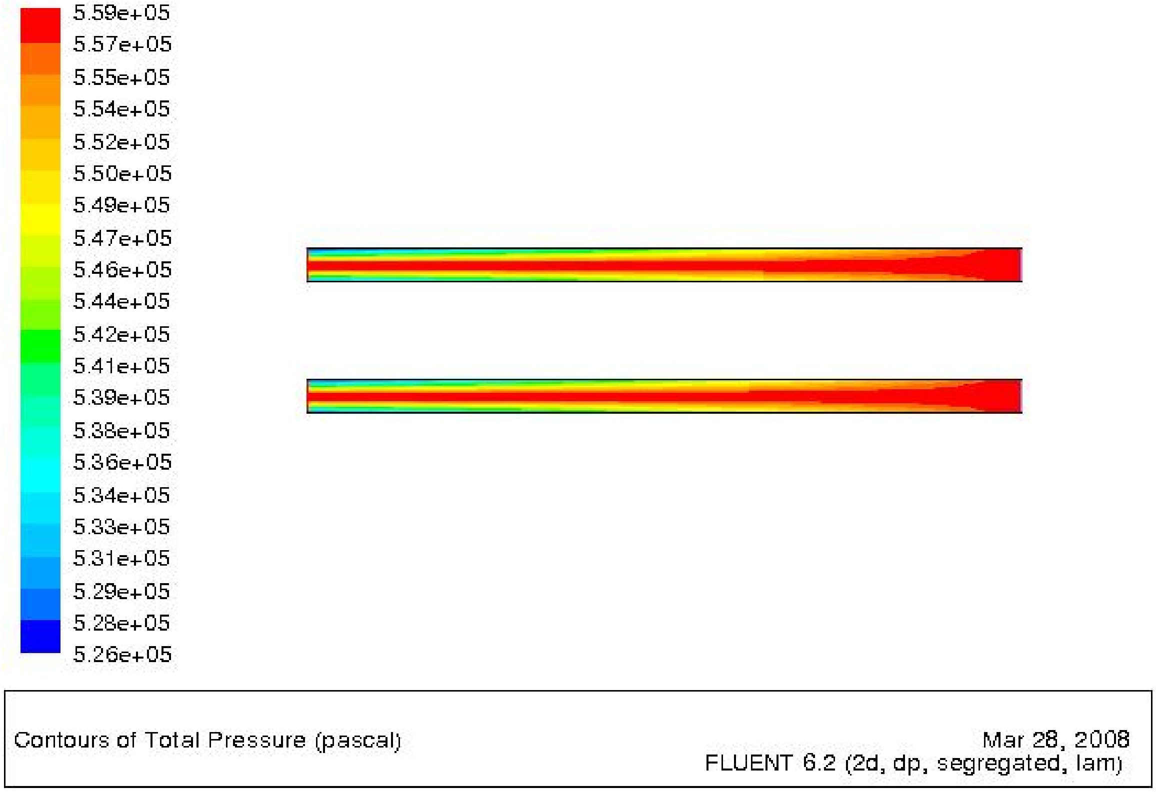


Figure 16 Vector Plot and Velocity Profile for Mud A



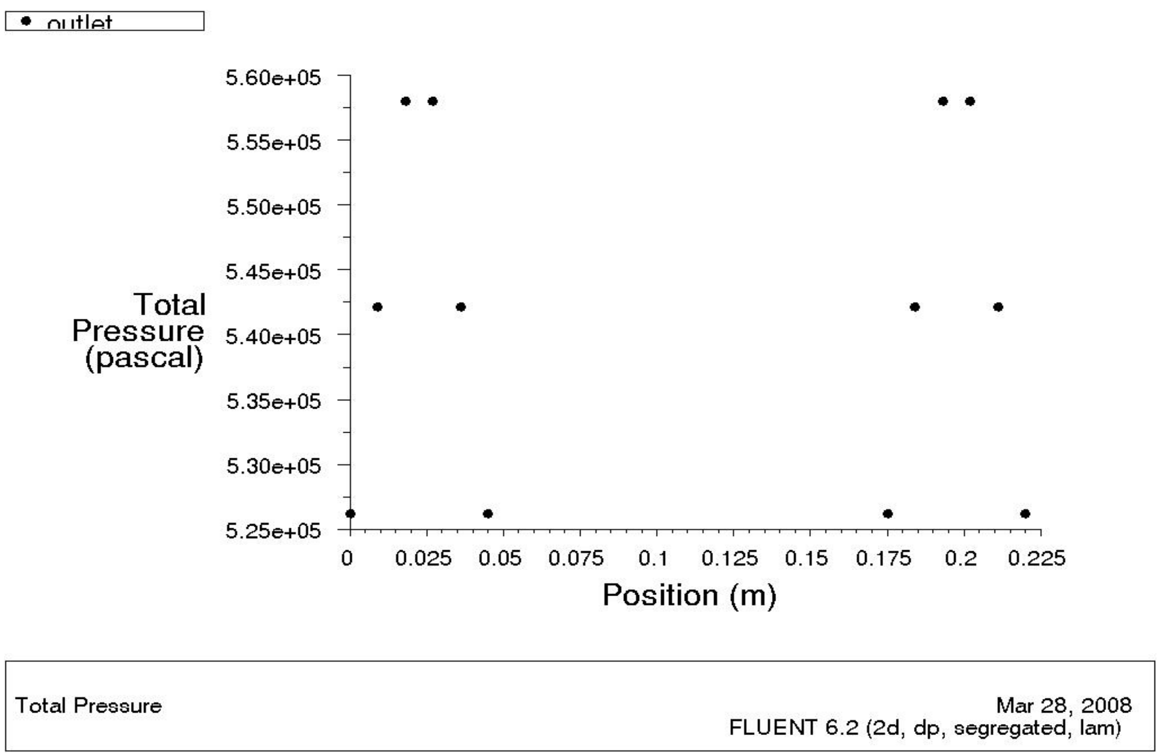


Figure 17 Total Pressure Plot and Pressure Profile for Mud A

Mud B

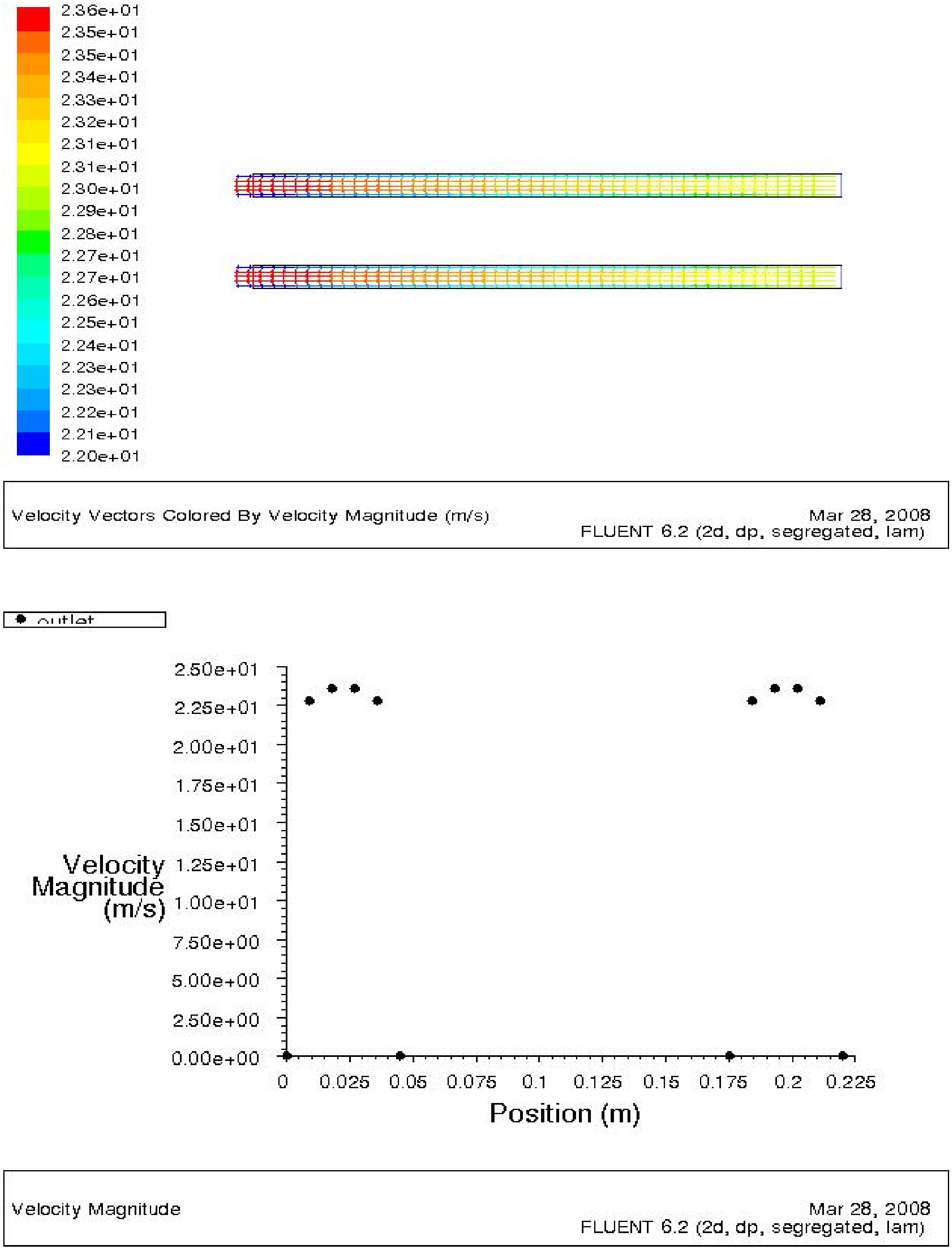


Figure 18 Vector Plot and Velocity Profile for Mud B

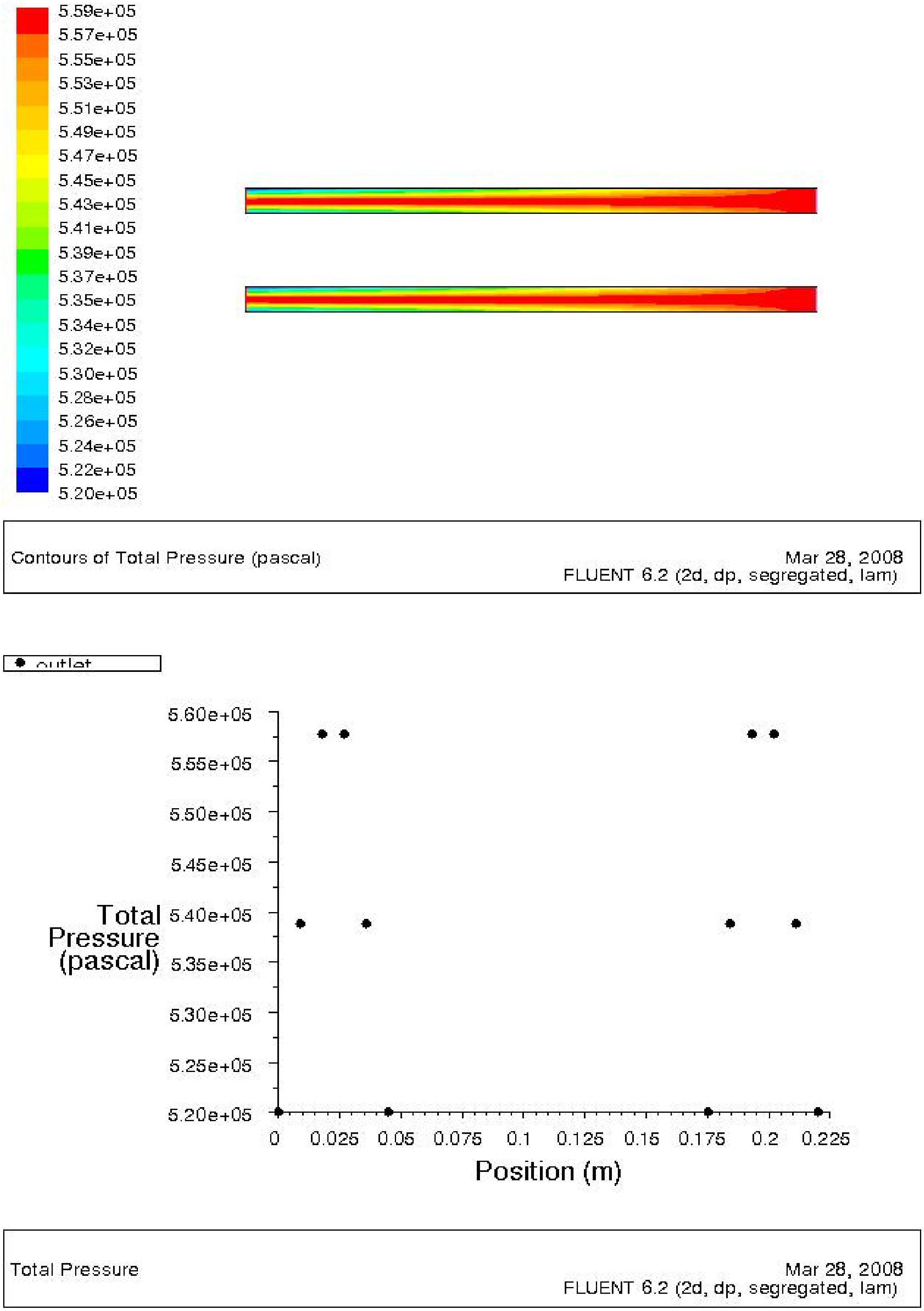
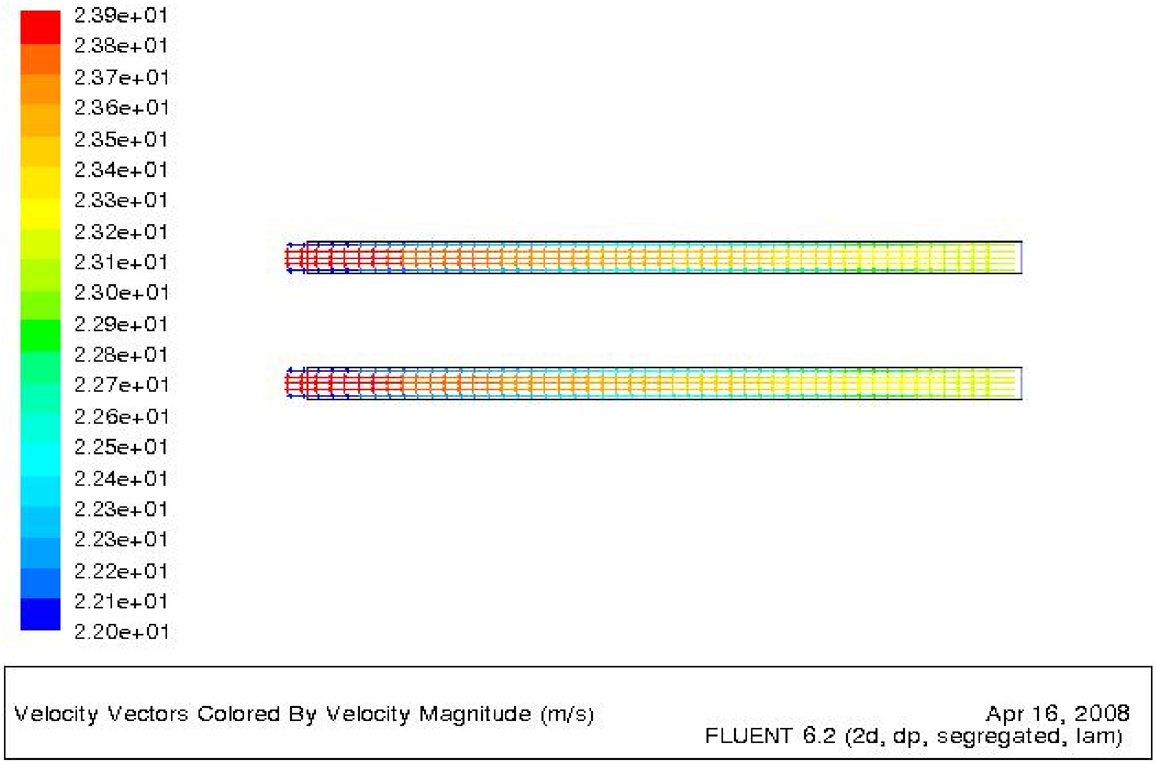


Figure 19 Total Pressure Plot and Pressure Profile for Mud B

Mud C



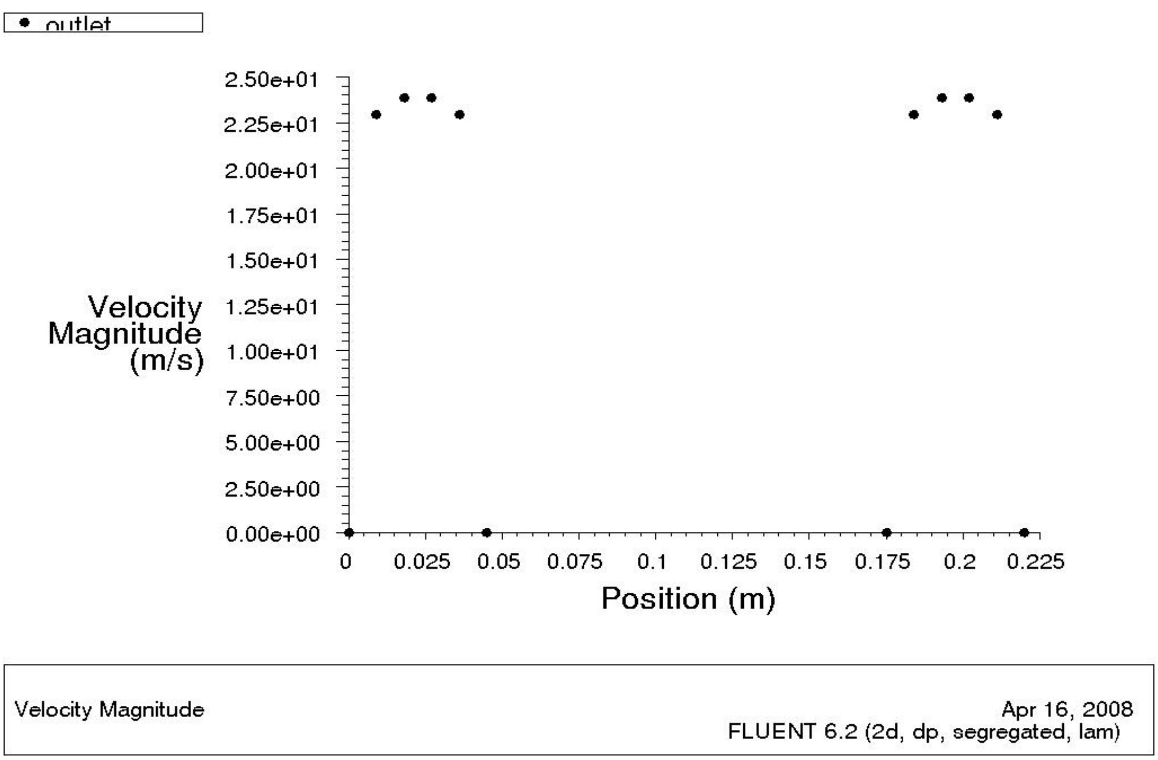


Figure 20 Vector Plot and Velocity Profile for Mud C

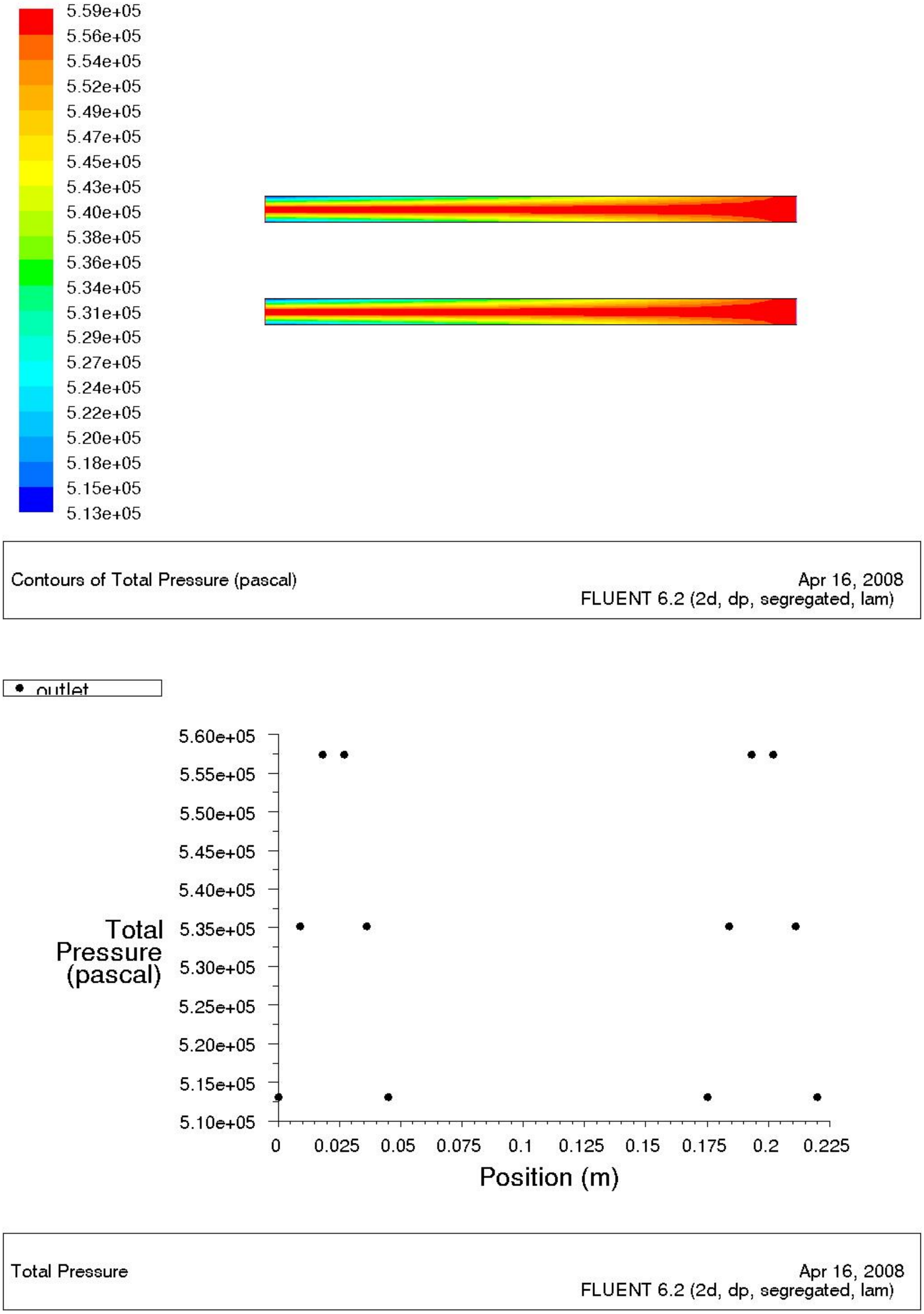


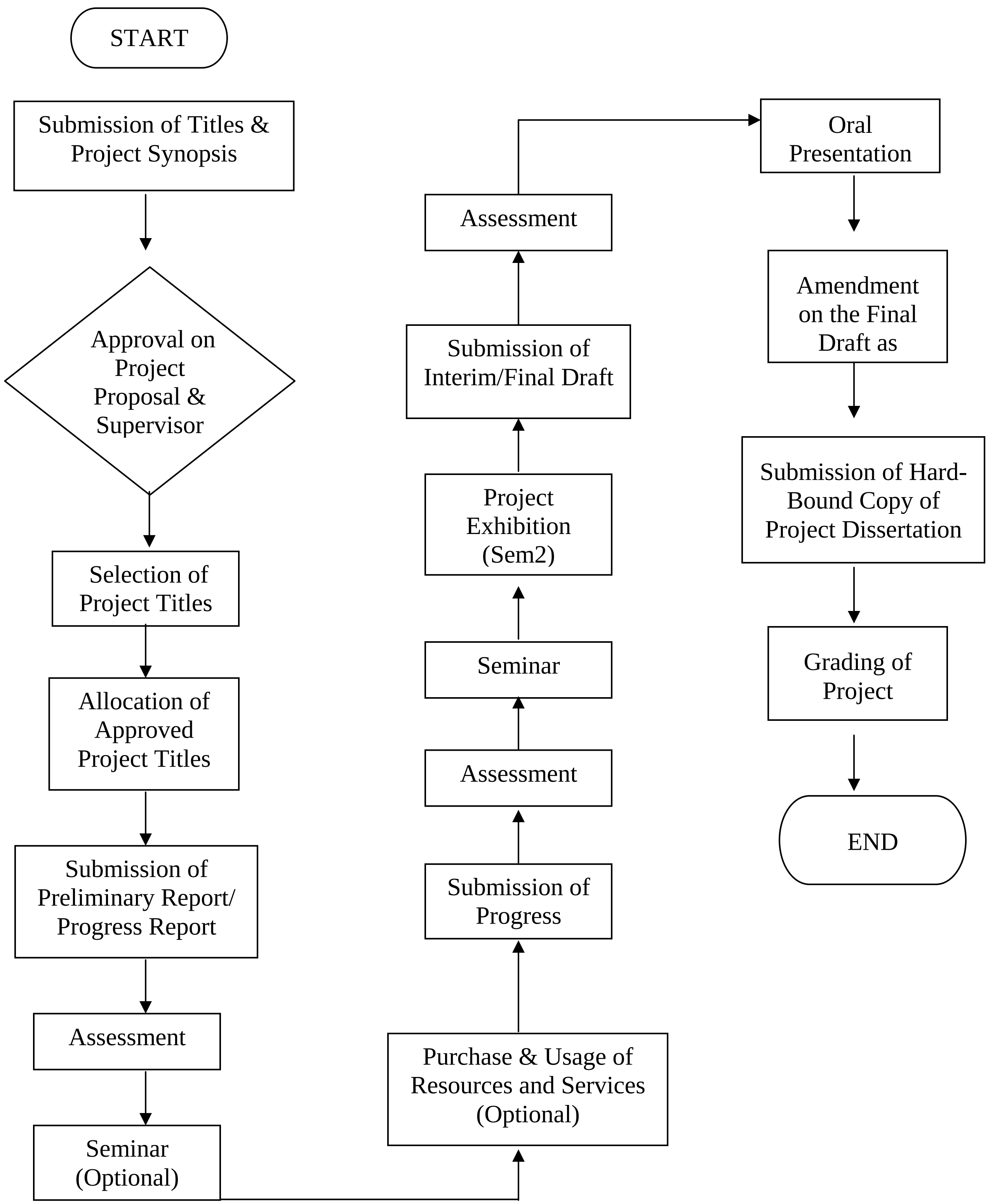
Figure 21 Total Pressure Plot and Pressure Profile for Mud C

Table 12 Summary of Simulation Result

Properties	Maximum Value	Minimum Value
Mud A		
Velocity (m/s)	23.6	22.2
Total Pressure (Pa)	5.59×10^5	5.26×10^5
Mud B		
Velocity (m/s)	23.6	22.0
Total Pressure (Pa)	5.59×10^5	5.20×10^5
Mud C		
Velocity (m/s)	23.9	22.0
Total Pressure (Pa)	5.59×10^5	5.13×10^5

The results from simulation of Mud A, Mud B, and Mud C does not show much difference in both pressure and velocity. This maybe happen as the density and the dflow behavior index does not vary much. But by observing vector plot for Mud A and Mud B, which both mud have very little difference in density, Mud B show more developed flow than Mud A. Instead of having only one line of highest velocity, as in Mud A, Mud B has more. Thus the velocity profile for Mud B seems to be more stable at the center. Mud C show much different in velocity and pressure. The velocity profile developed at higher velocity but quite stable at the center.

3.2 Flow Chart



3.3 Gantt Chart

Milestone for the first semester of Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic								MID SEMESTER BREAK							
2	Preliminary Research Work															
3	Submission of Preliminary Report															
4	Modeling and analyzing for simple fluid															
5	Research for viscous fluid properties															
6	Submission of Progress Report															
7	Seminar 2 (compulsory)															
8	Modeling and analyzing for viscous fluid															
9	Submission of Interim Report Final Draft															
10	Oral Presentation															

Suggested milestone

Process

Milestone for the second semester of Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Research for viscoelastic fluid	■	■	■					MID SEMESTER BREAK							
2	Submission of Progress Report 1				●											
3	Modeling and analyzing for viscoelastic fluid				■	■	■	■								
4	Submission of Progress Report 2									●						
5	Seminar (compulsory)										■	■	■			
5	Analyzing all the result									■	■	■	■			
6	Poster Exhibition											●				
7	Submission of Dissertation (soft bound)													●		
8	Oral Presentation														●	
9	Submission of Project Dissertation															●

● Suggested milestone

■ Process

CHAPTER 4

THEORY AND ANALYSIS

4.1 Viscosity Model

As the fluid act differently when stress is apply, then the relation between stress and strain rate of the fluid vary also. The general equation for shear stress and strain rate is:

$$\tau = K\gamma^{n} \text{ [2]}$$

K respond to the consistency index while *n* is the flow behavior index. When value of *n* is equal to 1, *K* will be the viscosity of the Newtonian fluid. For shear thinning fluid, *n* is less than 1 and if *n* more than 1, it will show the dilatant fluid. For non Newtonian fluid, the function become complex as the viscosity is dependant on the strain rate.

Some experiment has been carried out in determining the relationship between the viscosity and the strain rate. From the experiment empirical model is developed. One of the models is called Carreau-Yasuda Model. The model is:

$$\frac{\eta - \eta_{\infty}}{\eta_{o} - \eta_{\infty}} = [1 + (\lambda\dot{\gamma})^{a}]^{(n-1)/a} \quad \text{[4]}$$

Where η_{∞} = infinite-shear-rate viscosity, η_{o} = zero-shear-rate viscosity, λ = time constant, $\dot{\gamma}$ = strain rate, a = dimensionless parameter, n = power law exponent.

The other model that has been developed is Power Law Model. This model has few parameters compared with Carreau-Yasuda Model. Power Law Model stated that:

$$\eta = m\dot{\gamma}^{n-1} \quad \text{[4]}$$

Where *m* = is a constant while *n* = dimensionless parameter.

Power Law Model has some limitations which are [4]:

- It cannot describe the viscosity for very small shear rate.
- Underestimate the low shear rate viscosity.
- A characteristic time and characteristic viscosity cannot be constructed from the *m* and *n* value alone. Thus pursuing dimensional analysis is awkward.
- Parameter of *m* and *n* cannot be related to the molecular weight and concentration.

Despite the limitation, Power Law model is used a lot in solving non Newtonian fluid flow in the industry. Compared to Carreau-Yasuda Model, Power Law Model is easier to apply and interpret as the equation is simple and only few parameters are needed to complete the model.

Beside these two models, there are also Bingham Plastic Model and Herschel-Bulkley Model. These two models also used in solving fluid flow problem.

Bingham Plastic Model is the simplest model compare to all model stated. It can be made to fit high-shear-rate viscosity data reasonably well. But this model tends to overestimate the low-shear-rate viscosity of most drilling fluid. The Power Law model tends to act different way. The model tends to underestimate the low-shear-rate viscosity.

Herschel-Bulkley Model is created to solve the problem of overestimate and underestimate value. Herschel-Bulkley Model can be said as the hybrid of both Power Law and Bingham Plastic Model.

But compare between the three models, Bingham Plastic and Herschel-Bulkley Model is more suited for Bingham plastic fluid while all commonly used drilling fluid is shear thinning fluid. Thus for this project, Power Law Model will be selected as the viscosity model.

4.2 Generalized Power Law

Most drilling fluids have consistency course that are intermediate between the ideal Bingham plastic fluid and the ideal pseudoplastic flow model [5].At low shear rate, the power law fluid mostly behave like pseudoplastic but when move to the higher shear rate, the fluid behave like Bingham fluid.

Drilling fluid flow also depend on the flow behavior index of the fluid. Figure 22 below show the dependence of the velocity profile with the flow behavior index.

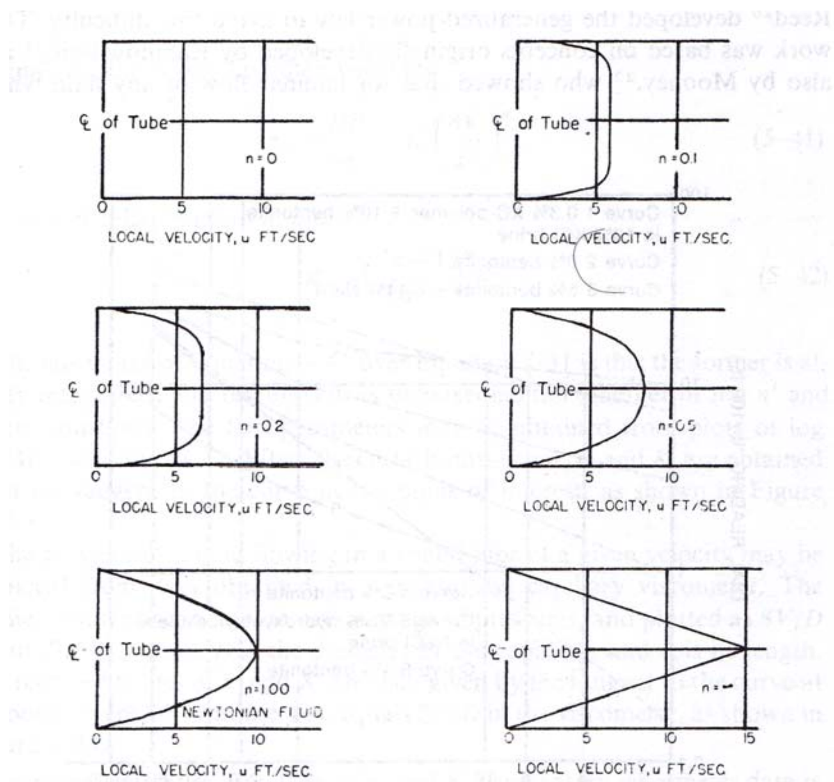


Figure 22 Dependence of Velocity Profile to the Flow Behavior Index

CHAPTER 5

CONCLUSION

5.1 Conclusion

Drilling fluids are important as the absence of it will paralyze the whole drilling process itself. Understanding the behavior of drilling fluids will help in optimizing the usage of the fluid. Hence this will make the whole drilling process easier, safer, and cheaper.

The most common type of drilling fluid is the shear thinning fluid. As stated before, this type of fluid become thinner or the viscosity decrease as more force is applied. From the experiment carried out, we can see that shear thinning fluid have high viscosity at low shear rate and low viscosity at high shear rate.

By simulation carried out using the fluid tested, we can see the variation in the velocity and pressure. From the simulation, by changing the flow behavior index and consistency index, the flow already becomes different. This can be seen in Mud A and Mud B as they differ very little in density but differ quite much in the flow behavior index. This show that the flow behavior index controlling the flow.

The simulations that have been done are under some assumptions that limit the simulation to imitate the real situation of drilling. This simulation should be, in the future to include the effect of temperature and pressure on the drilling fluid. Multiphase flow also should be carried out. This will move the simulation much more toward the real drilling situation.

Through the simulation, the behavior of the drilling fluid under some condition can be determined. How the fluid react in the simulation can predict the fluid behavior in the real world. This prediction hopefully will make the drilling process a better process.

5.2 Recommendation

Even the project have been carry out, room of improvement still exist in this project. Few recommendations can be made in order to improve the project.

As the project aim to understand better the behavior of drilling fluid or the behavior of shear thinning fluid, it is recommended to conduct experiment to obtain a lot more flow behavior index value. The value should be varying large enough to see the difference in the simulation. By doing experiment and simulation in different value of *n*, the value of consistency index, *k* and the mass should stay the same or does not vary much. By this effect of *n* can be seen clearly.

Beside value of *n*, varying value of *k* also should be done. By varying both values, one can see which of the value that is controlling the flow of the fluid.

Solving the simplified Navier-Stokes and comparing the value with the simulation must be done. This can verify the simulation data.

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