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Candidate: Prabin Basnyat

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Telemark University College
Faculty of Technology
Kjølnes
3914 Porsgrunn
Norway
Lower Degree Programmes – M.Sc. Programmes – Ph.D. Programmes

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2nd Supervisor:	Bernt Lie sign.: . . . .
Censor:	<name> sign.: . . . .
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Abstract:

Advancement in oil drilling technology, particularly managed pressure drilling requires better knowledge of return drill mud flow. Since the mud outflow is in an open channel, it is proposed to use flume with constriction that is based on Venturi principle for flow rate measurements. Rheological study of bentonite-base fluids as a non-Newtonian drilling fluid has been performed as well as CFD simulation of these fluids has been done for analysis of non-Newtonian fluid flow behavior.

Rheology is termed as 'rheallycomplicatedology' by Steve Devereux[1]. It is tried to keep this study as simple as possible, and this report is focused on bentonite-base fluid only. Rheograms are based on Herschel-Bukley model. Rheogram of bentonite-base fluids without yield stress show Newtonian fluid characteristics i.e. shear stress vs. shear rate being linear and passing through the origin. Rheogram of bentonite-base fluids with yield stress as non-Newtonian fluid is similar to log plot.

The geometry used for CFD simulation are the flume from the manufacturer BAMO and bachelor of science group 2013. ANSYS FLUENT is used to analyze the fluid flow behavior and liquid levels, using multiphase volume of the fluid model for bentonite-base fluid both as Newtonian and non-Newtonian. Bentonite-base fluids as Newtonian exhibit similar results as simulation conducted on water by master group project fall 2013 while, as non Newtonian, inlet surface profile gets steeper and steeper with the increase in concentration of bentonite. This is due to increase in viscosity of the fluid by the increase in concentration. It can be said that viscosity plays a vital role on defining the characteristics of the drilling fluid.

Fluid flow along the flume at different time step shows a bit different properties for different concentration of bentonite base fluids due to change in viscosity, but the flow pattern is same. First, level of fluid reaches higher elevation due to fluid jump and finally, reaches steady state. This behavior should be considered during level measurement because it is expected to measure the level at steady state.

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Preface

This report presents the result of Master's thesis, carried out in spring 2014, at Telemark University College, Porsgrunn with Statoil as project partner. This thesis is carried out in fulfillment of Master of Science degree at Telemark University College during the final semester of study.

The objective of this thesis is to develop a model for the rheology of the drilling fluid to use in an open channel venture flume and study the flow behavior in 3-D CFD models for open channel venture flume using FLUENT. It was interesting and challenging to study the flow behavior of non-Newtonian fluid.

It is with great pleasure that I would like to thank Prof. Knut Vågsæther, thesis supervisor who guided me throughout the thesis. I would also like to thank master group project fall 2013 for their valuable work in this field. The staff of TUC is also thanked for providing valuable research articles, required software and helping to print this report. Finally, I would like to thank everyone who made even a slight contribution towards the thesis that made it possible to come this far.

Porsgrunn June 4, 2014

Prabin Basnyat

1 Introduction

Advancement in oil drilling includes better control of the bottom hole pressure during drilling, and specially managed pressure drilling (MPD) require accurate measurements of drilling mud flow rate for control purposes. Currently, this flow rate is measured using large Coriolis based sensors or other extremely expensive set-ups. Statoil has an ongoing project aiming to control bottom hole pressure by means of model based control. The important parameter for better control of bottom hole pressure is the better knowledge of the return drill mud flow rate.

The goal is to study for alternatives, to replace these large and expensive equipments. One of the proposed way to measure mud outflow is by means of an open channel with Venturi type constriction since the mud is already flowing in an open channel. For decades, weirs and different contraction geometries are being used to measure open channel flows, especially in rivers, sewage channels, etc. [2]

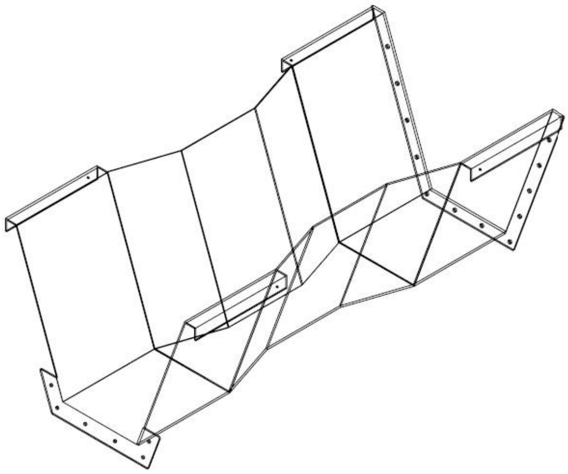


Figure 1-1Iso-metric view of experimental flume [3]

The aim of this M.Sc. thesis is to continue the initial work done in the master group project fall 2013, focused with the developed method in ANSYS FLUENT for simulating open channel flow with the non-Newtonian drilling fluid. Furthermore, different characteristics of bentonite suspensions (non-Newtonian drilling fluid) are selected for CFD simulation to provide the basis for further work on an experimental rig developed by a bachelor of science group 2013 at Telemark University College with Statoil as a project partner. The rehological study of drilling mud, i.e. bentonite suspension is done to simplify the process of developing CFD models.

The geometry studied in this report are the flume developed by bachelor of science group 2013 and ISO 4395 standard rectangular critical flow venturi flume made by the company BAMO used by master group project fall 2013. The flow rate chosen for simulation is 500 l/m3. The channel was simulated with non- Newtonian fluid (bentonite suspension) as well as bentonite-base fluid as Newtonian fluid for rheological study.

2 Literature review

2.1 Introduction to flumes

Flumes are fixed hydraulic structures which are shaped in such a way to know the relationship between the level of liquid at specified position and the flow rate[4]. It is based on a similar principle of venturi effect i.e. constriction in fluid flow regime, increases velocity and liquid level changes. Apparently, different types of flumes are being used for open-channel flow measurement of water[5].

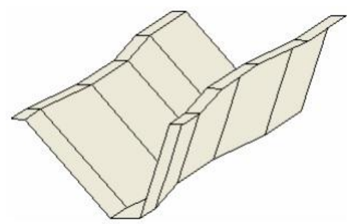
Parshall Flume	Cutthroat flumes	Trapezoidal flumes	RBC flumes
			

Figure 2-1 Some of the types of flumes being used for water flow measurement [4, 5]

Flume is divided into three sections; converging section, throat and diverging section. Throat is the constriction in fluid flow regime, and the flow is governed by the conservation of mass and momentum. Parshall flume being earliest design that is out of favor due to design complexity while other are simpler to construct and easily fit existing channel. The advantages and disadvantages as well as, design calculation of different type of flumes can be found in [4].

2.2 Introduction to rheology

Rheology is the study of deformation and flow of matter[1]. Newtonian fluid has shear stress linearly proportional with strain rates where the viscosity being constant. Non-Newtonian fluids being inadequate to describe only depending on concept of viscosity, relationship between stress and strain tensors under different flow conditions are studied to classify them into non-Newtonian behavior[6];

Table 2-1Types of non-Newtonian behaviour[6]

Viscoelastic		Materials that behave as Newtonian at time invariant conditions, but as a plastic if shear stress is changed suddenly.
Time-dependent viscosity	Rheopecty	As long as fluid undergoes shearing force, the viscosity becomes high.
	Thixotropic	The dynamic viscosity decrease with the time shear is applied.
Time-independent viscosity	Dilatant	It is termed as shear thickening property. Viscosity in dilatants material increases with the rate of shear strain.
	Pseudo plastic	It shows shear thinning property. The dynamic viscosity decreases as the rate of shear stress increases.
	General Newtonian fluids	Viscosity is constant. Stress depends on shear strain rates and viscosity is constant.

Drilling muds are composed of the multitude of additives, making them complex fluid. Generally, these fluids are classified based on their major components as Water based mud(WBM), Oil based mud (OBM), Gas based mud, Synthetic based mud, Emulsion drilling muds, foam fluids, etc.[7]. In the oil industry, WBM is commonly being used than other muds due to price and environment. The types of drilling muds being commonly used in oil industries can be classified as[7, 8];

1. Water base muds: It consists of water as a base fluid. This mud is added with different additives and further classified into clear water mud, Native mud, Calcium mud, Lignosulphonate mud, polymer muds, salt saturated mud. The composition of these muds is illustrated by Darley in [8].
2. Oil-base muds: Oil is used as a base fluid. Different kind of oil is used, like diesel, palm oil, etc.
3. Synthetic base muds: It is similar to oil base muds, but the oil is replaced by synthetic materials like poypha-olefins, esters or ethers, linear alpha olefins, linear paraffins, etc.

4. Emulsion drilling muds : It contains water as an external phase and oil/synthetic as an internal phase.
5. Invert emulsion muds : It contains oil/synthetic as external phase and water as an internal phase. Surfactant are added for fluid stability.
6. Air drilling fluids: It is only used for underbalanced drilling, where the contact with reservoir hydrocarbons or water is not observed.
7. Foam fluids: It contains fresh water or brines, inert gas, surfactant and dense brines to weight up the fluid system.
8. Development in drilling fluids toward the cost effective and environment friendly has lead to customizing the mud in many different ways like adding nanoparticles, biomass, etc. and the research is still going on.

A plot between shear stress and shear rate (rheogram) is used to depict rheology graphically but again, it is hard to describe rheological characteristics of drilling fluid with commonly used models over entire shear-rate change. Knowledge of rheological models, as well as practical experience, is necessary to understand fluid performance. Generally, the model given below is used for characterizing the fluid flow[7];

Bingham Plastic	$\tau = \tau_\circ + \mu_p \dot{\gamma}$
Casson Model	$\tau^{\frac{1}{2}} = \tau_\circ^{\frac{1}{2}} + (\mu_\circ \dot{\gamma})^{\frac{1}{2}}$
Herschel-Bulkley	$\tau = \tau_\circ + \kappa(\dot{\gamma})^n$
Robertson-Stiff Model	$\tau = \kappa(\dot{\gamma} + \gamma_\circ)^n$

where, $\tau = shear\ stress$

$$\tau_\circ = yield\ stress$$

$$\kappa = consistency\ factor$$

$$n = flow\ index$$

$$\dot{\gamma} = Shear\ rate$$

$$\mu_p = Plastic\ Viscosity$$

$$\mu_\circ = Zero\ shear\ rate\ viscosity$$

Bingham plastic model is used for the fluid whose shear-stress/shear-rate ratio is linear[9]. It contains two parameters i.e. plastic viscosity and yield point. On the other hand, Herschel-Bulkley model can describe the flow of pseudoplastic muds that require yield stress to initiate the flow. Davison et. al[10] with the comparison between Herschel-Bulkely model and casson model in figure 15 and 16 shows that Herschel-Bulkely gives the best fit for salt/polymer based mud while Casson model gives the best fit for weighted water based mud[7].

2.3 Bentonite base muds as drilling fluid

Bentonite base muds are used due to their property of stabilizing the wall of the hole by forming a cake and to clean the hole by evacuating the cuttings well as to decrease the wear on tools[11]. Ahmed et. al[12] has presented the experimental data of bentonite drill mud ranging concentration upto14% to find apparent viscosity, plastic viscosity and yield point of bentonite base muds. Similar study by Pantet et. al[13] concludes that the rheological properties are influenced by concentration of bentonite and granulometric distribution of bentonite. Herschel-Bulkley model was used and rheograms were modeled correctly ranging from 4% to 6%.

2.4 Overview of CFD simulation

With the development in computing technology, Computational Fluid dynamics (CFD) has become the basis for analysis of fluid flow in every sector of industries. In short, Tu et. al[14] states, "CFD make it possible to achieve new paths of theoretical development. It complements experimental and analytical approaches and provides an alternative cost-effective method of modeling real fluid flows". CFD simulation with appropriate physical and mathematical model can simulate flow conditions that are difficult to test experimentally. FLUENT is one of the CFD solver, solves the conservative form of Navier-stokes equations using the finite volume method on unstructured, non-orthogonal, curvilinear co-ordinate grid system[15, 16]. Turbulence is simulated using standard k-ε, standard k-w, etc. The model allows users to utilize various discretization scheme for optimization of the computational scheme. Similarly, free space problems are solved in FLUENT using volume of fluid (VOF) method.

Since open channel flumes is commonly being used for water flow measurement, it is obvious to have more research on CFD simulation of water. The result based on Burnham work[17] is quite impressive as well as CFD simulation of water flow through open channels with a sudden expansion using k-ε turbulence model is also promising with small relative error[18]. On the other hand, CFD simulation of non-Newtonian fluids are very minimum. The result obtained by Dular et. al [19] on simulation of mixing of non-Newtonian fluid using power law model and experiment is with discrepancy of 20%. It is possible to simulate non-Newtonian fluid using rheological models, but it is also crucial to validate them with experimental data.

3 Models and methods

Computational fluid dynamics (CFD) utilizes Volume of fluid (VOF) method for mathematical model analysis to track and locate the free surface. Basically, this method revolves around the idea of volume fraction (C) of a phase in the cell. If the value of C is 1 then it is completely filled with that phase. Cells having a fraction value of zero are filled with the other phase, and cells which have a fraction value between zero and one contain the interface. The VOF method is well known for conservation of the mass of the traced fluid even when the topology of fluid interfaces is subjected to any changes. The fluid interface change can be tracked [6].

Similarly, standard k-ε model was used to simulate turbulent conditions of fluid flow along the flume. This model basically assumes turbulent viscosity is isotropic where k is turbulent kinetic energy and ε is rate of dissipation of the turbulent kinetic energy[20].

4 CFD simulations of Flume

In order to develop three dimensional CFD models, ANSYS FLUENT is used. Here we are focused in analyzing height-discharge relationship of non-Newtonian fluid i.e. bentonite suspension at the flow rate of 30.3 m^3/hr. Similarly, bentonite suspension is also analyzed as a Newtonian fluid to compare the results of the simulations. The simulation domain is from experimental rig developed by bachelor of science group as well as the simulation is also done in the domain developed by master group project fall 2013[21]. General CFD simulation procedure can be illustrated as;

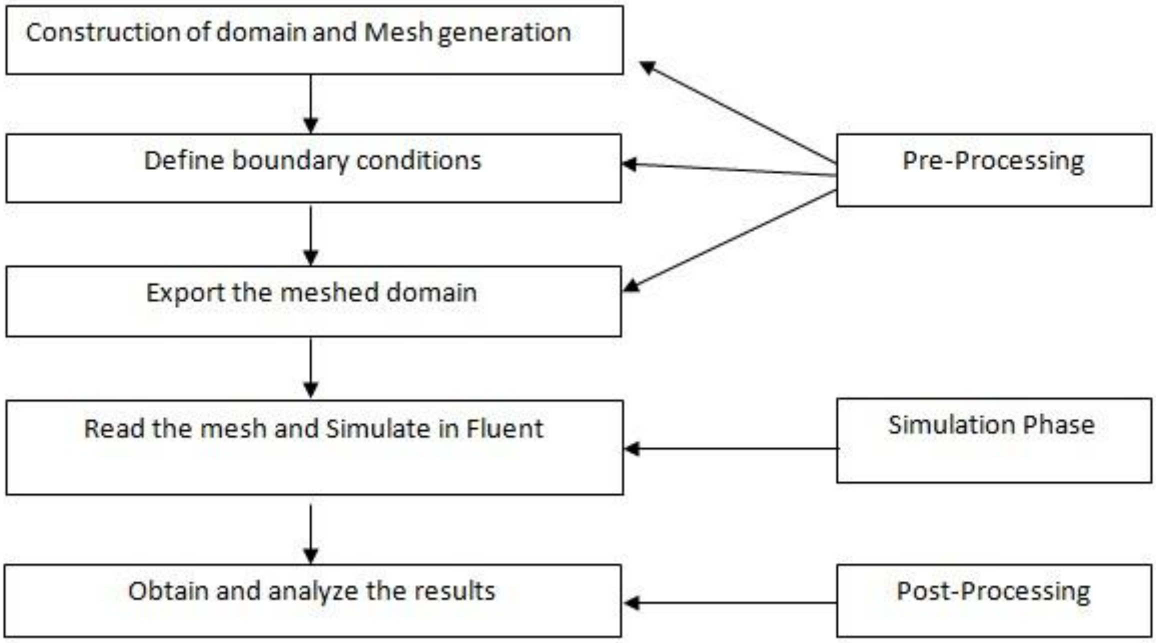


Figure 4-1 CFD simulation procedure

4.1 Pre-processing

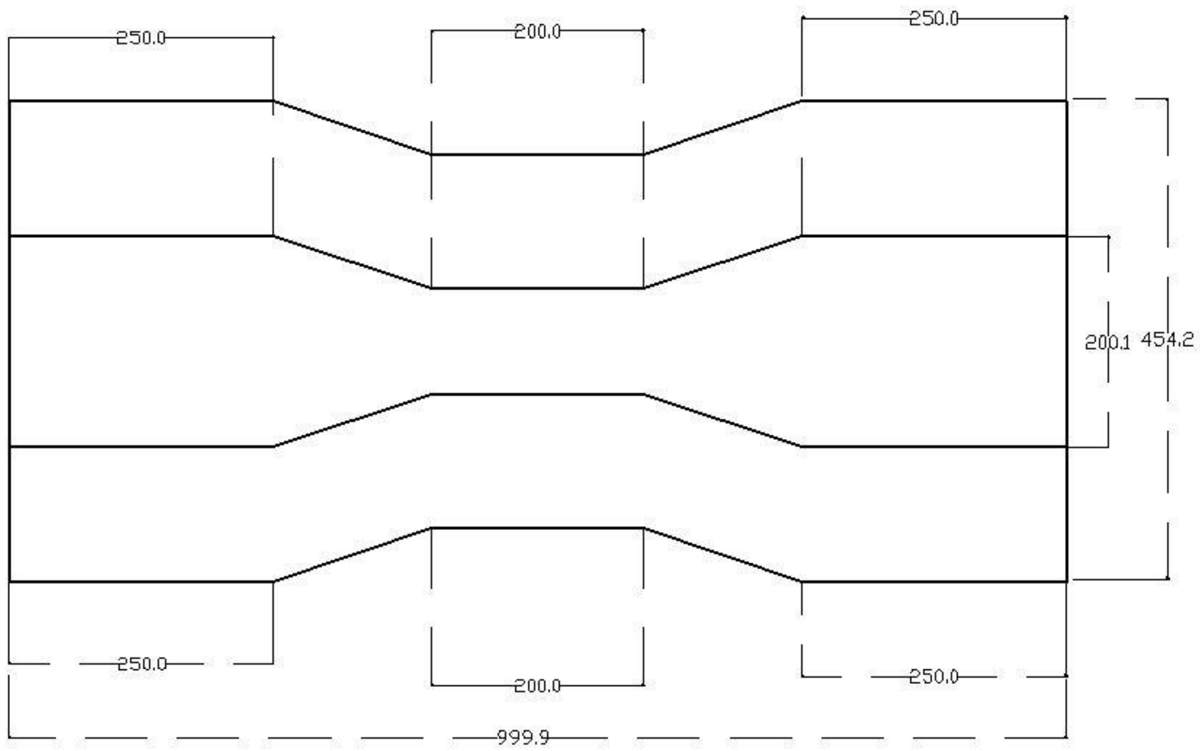


Figure 4-2 Flume dimensions

The geometrical drawing for meshing and simulation purpose was developed in Gambit 2.4.6. Only the symmetric half portion of the flume was used as well as meshing was kept simple.

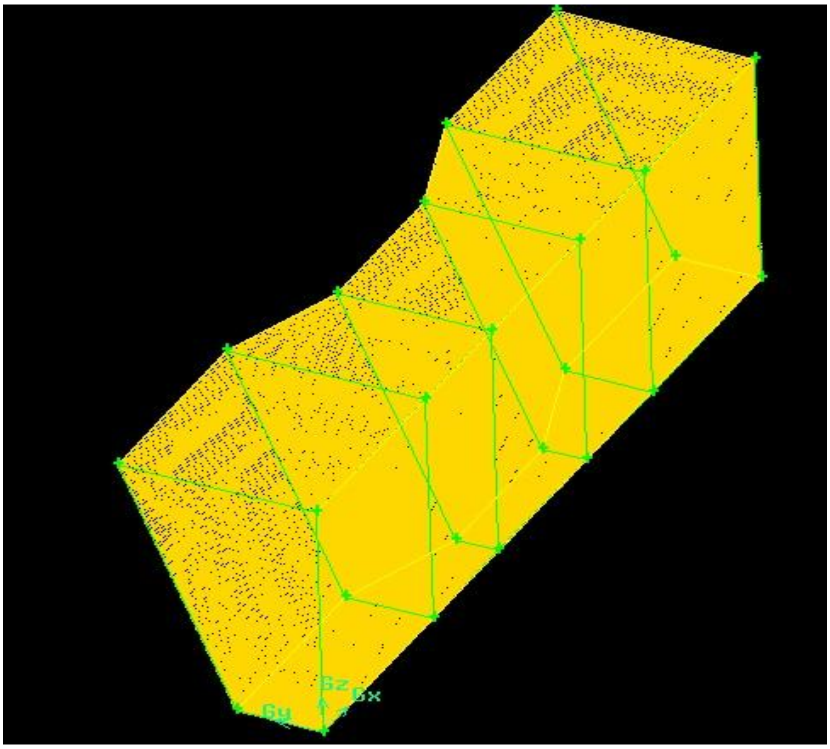


Figure 4-3 Half of the flume with mesh developed in Gambit

The flume was divided into multiple segments, and the meshing was done accordingly by sweeping face mesh along the volume. Finer mesh was provided along the critical parts i.e. neck, converging section and wall of the flume while concentration of mesh was reduced on the other geometry to avoid having many elements.

Now, the mesh is examined so that they are not skewed. Skewed is referring to mesh whose skew size ratio is greater than 0.97. FLUENT does not accept meshes with elements higher than 0.97 skew ratio, as well as transport equations of higher skew ratios, are solved have a higher error i.e. the difference between the calculated results of equations at each iteration and the correct value. It leads to more time demanding convergence.

4.2 Read the mesh and Simulation

Mesh is read by ANSYS FLUENT, and a further assumption was made that the flow is isothermal, so energy equation was not activated. There are two solvers; Density based solver and Pressure based solver. Usually, density based solver is used to solve the problem with compressible flow while pressure based solver is used for incompressible flow. In an open channel flow, the governing equations are momentum and continuity equations while they are solved in order to get the flow field. The flow of the liquid in open channel flow is an incompressible fluid. So, the pressure based solver was used in the simulations.

For simulation, further steps are completed which are presented below;

4.2.1 Models

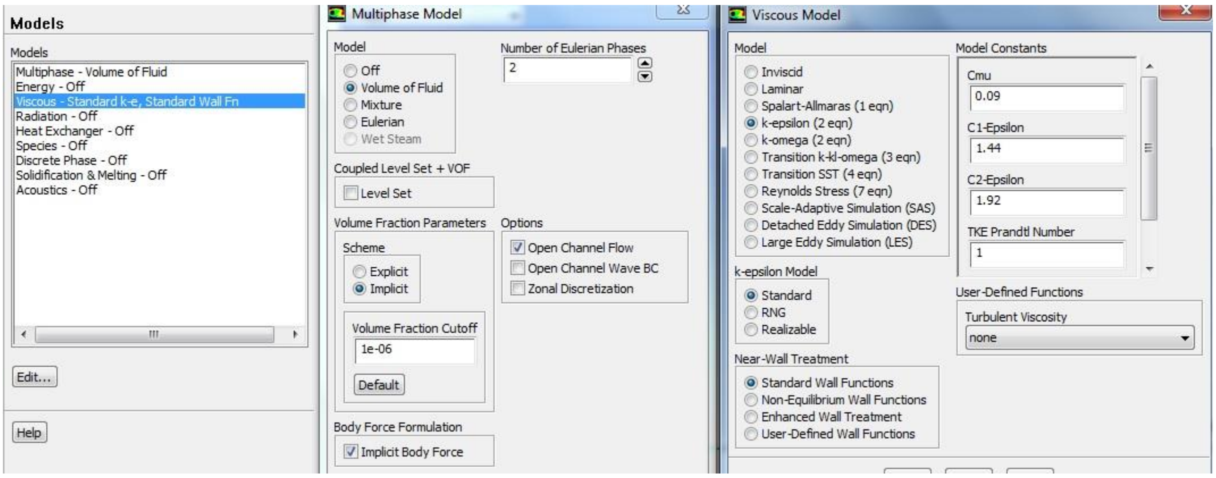


Figure 4-4Model used in FLUENT simulations

Volume of fluid (VOF) model was used as the multiphase model. Similarly, the implicit scheme was used in developing the model considering both the computational time and final solution as well as implicit body force and open channel flow options were enabled. For the Viscous model, standard k-epsilon model was used with standard wall functions.

4.2.2 Materials and Phases

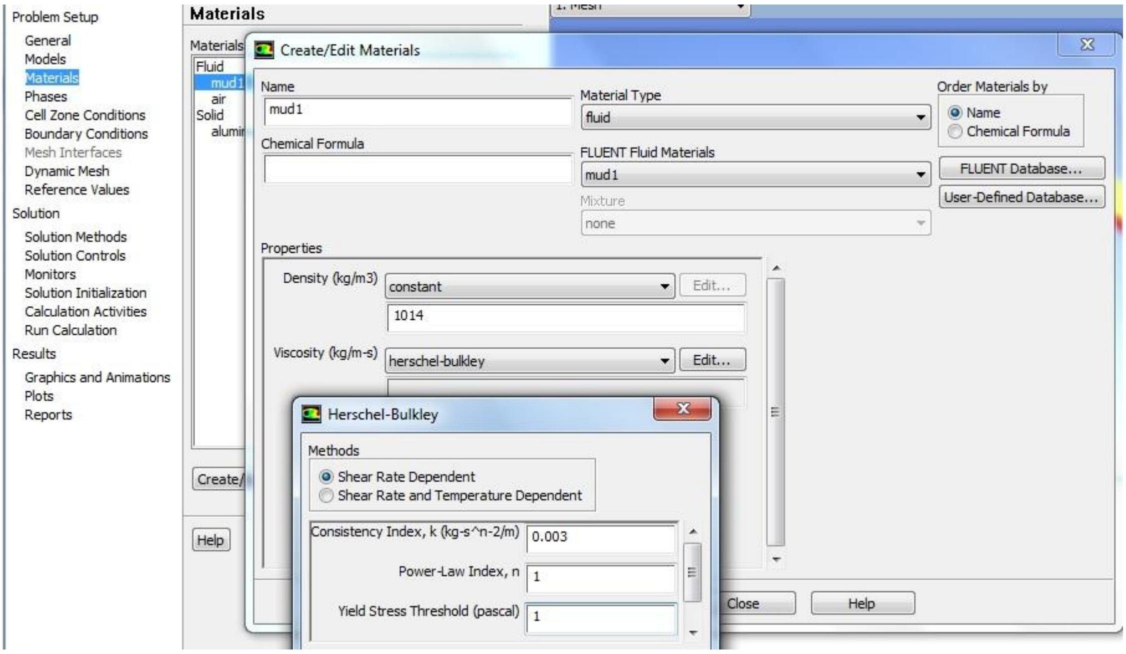


Figure 4-5 Materials used in FLUENT

In FLUENT, while developing CFD models, several non-Newtonian flow models are available such as non-Newtonian power law, Sutherland law, Cross model, Herschel- Bulkley model and Carreau model. Moreover, piecewise polynomial or user defined function is also available for user. These models need to be activated, and the command mentioned below is typed in the user interface.

difine/models/viscous/turbulence-expert/turb-non-Newtonian>

Enable turbulence for non-Newtonian fluids? [no] yes

Herschel-Bulkley model was used as the viscosity model of the drilling mud and the parameters used during simulations are presented in the Table below;

4-1 Properties of Muds used for simulation[22]

Fluid	Density, ρ (kgm^{-3})	Consistency index, k (kgs^{n-2}/m)	Power law index, n	Yield stress threshold, τ_y (Pa)	Critical shear rate , (1/s)
3% bentonite suspension	1014	0.003	1	1	0.1
4.5% bentonite suspension	1025	0.006	1	4.4	0.1
6% bentonite suspension	1,33	0.006	1	12.70	0.1

The critical shear rate provided here, should be close to zero but too small value used for calculation makes relatively unstable so, values chosen for the critical shear rate are after conducting several trails.

Air being lighter, selected as primary phase and mud are selected, as a secondary phase.

4.2.3 Boundary and Operation conditions

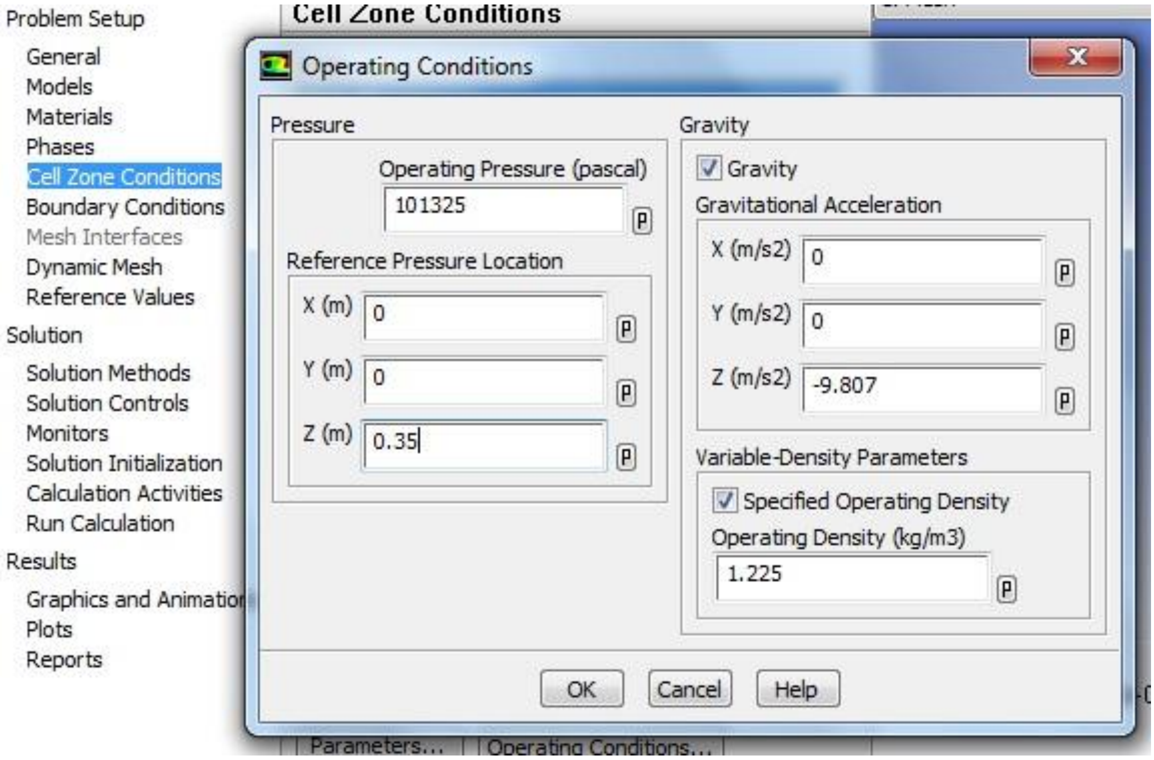


Figure 4-6 Operating conditions in FLUENT

The flume here is considered to be perfectly horizontal. Hence, the gravity is defined as minus 9.807 ms-^{2} in the z direction. If flume is inclined than the gravity has to be defined accordingly. The pressure reference point is chosen where the pressure does not change with time[15]. So, top of the inlet is used as a reference point i.e. (0,0,0.35).

The mesh used for the simulation includes six boundaries similar to the domain developed by master group project fall 2013 [21]; inlet, outlet, top, bottom, side wall and symmetry.

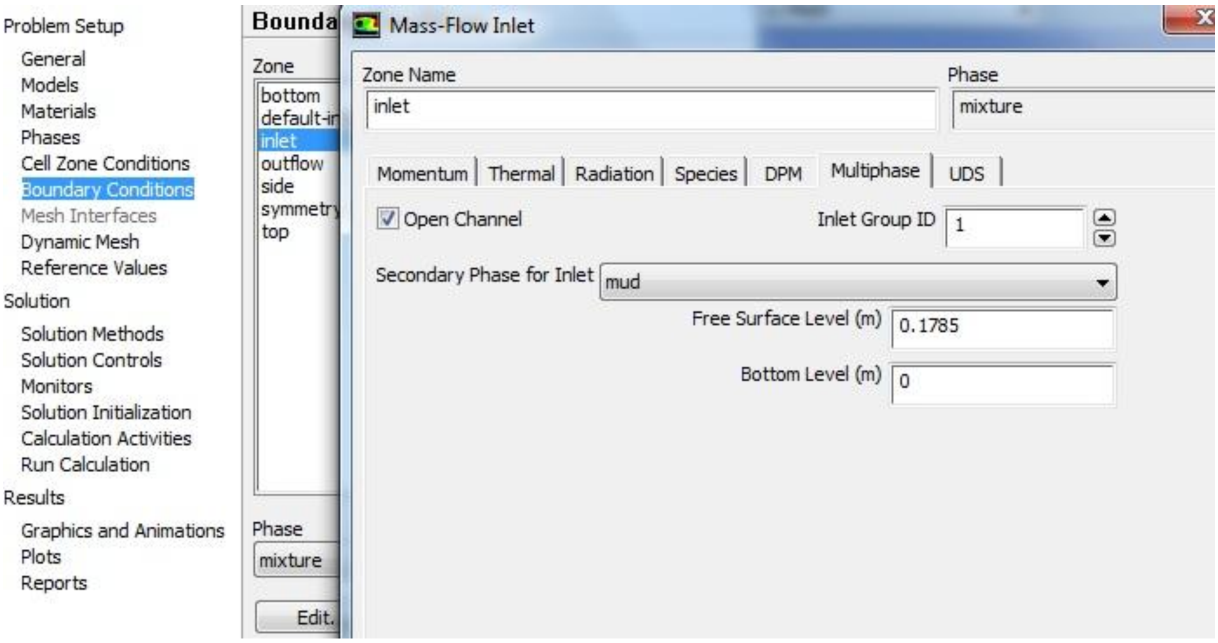


Figure 4-7Boundary condition of Inlet in FLUENT

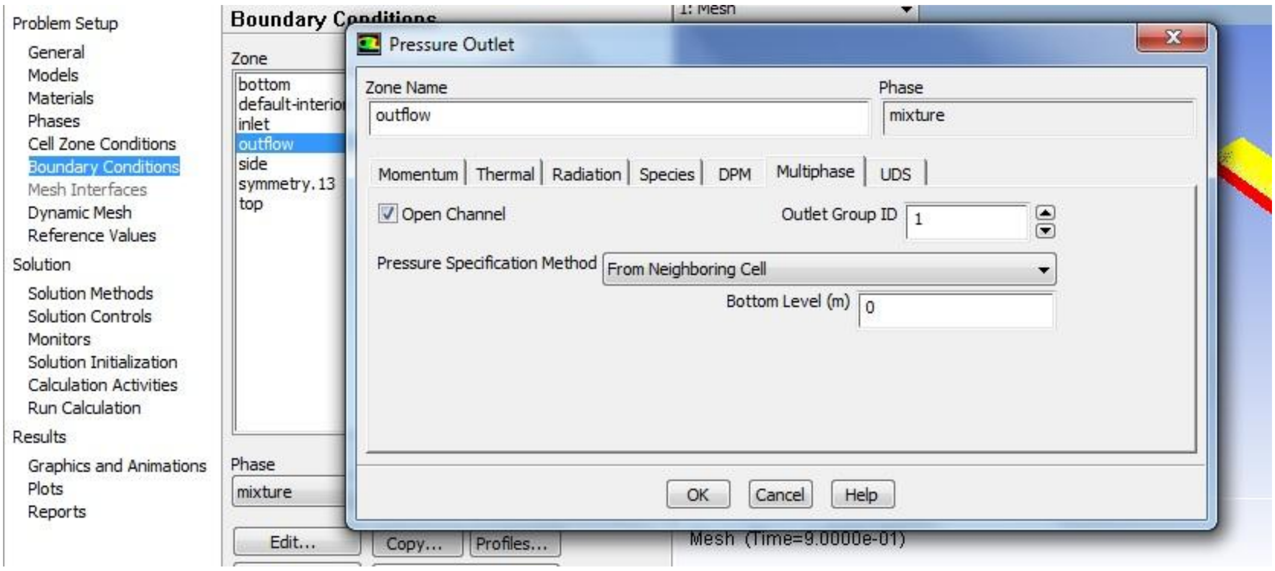


Figure 4-8Boundary Condition of Outlet in FLUENT

Mass-flow inlet was used with open channel flow in multiphase tab. The fluid flow (mixture) was set from the bbottom level and free surface level at 0.178 m. Mass flow of air is set to 0 whereas mud flow is 9.2499 kg/sec (i.e. ca.500 L/min).

Similarly, pressure outlet is used with pressure specification method from neighboring cell for open channel.

For others, the boundary condition is same as the default.

4.2.4 Solution Methods

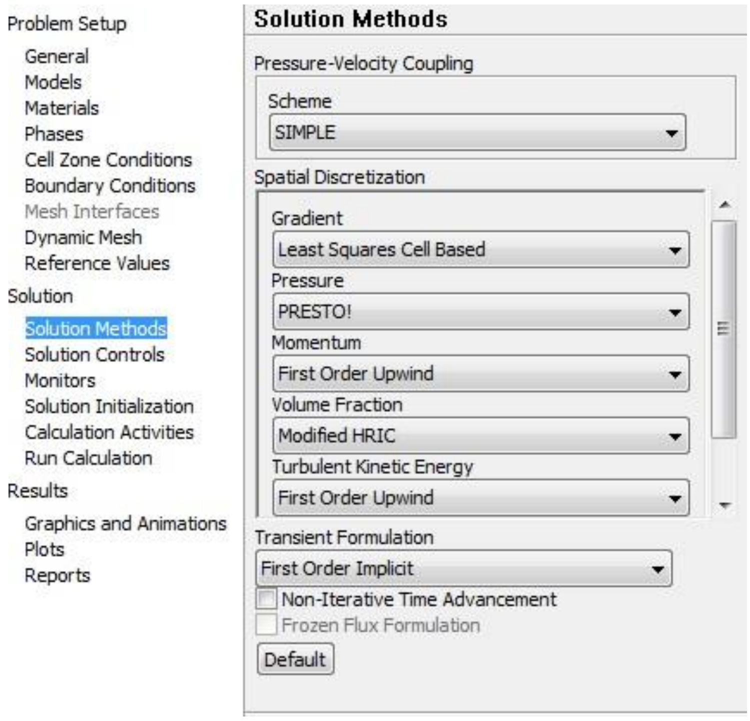


Figure 4-9 Solution Methods used in FLUENT

The SIMPLE scheme was selected in Pressure-Velocity Coupling. All other schemes were used default schemes except for volume fraction that was changed to Modified HRIC from first order upwind scheme. First order upwind scheme is overly diffusive nature, and it is not suitable for tracking the interface of free surface[15].

4.2.5 Solution controls and Monitors

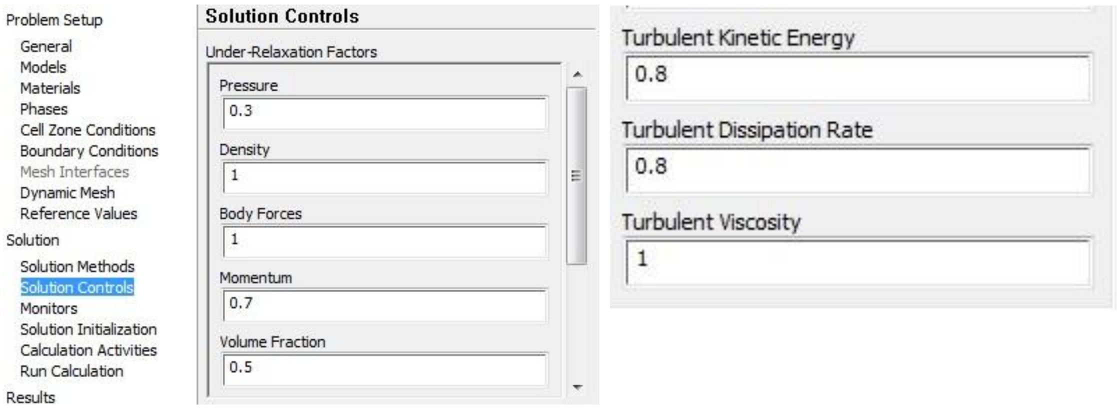


Figure 4-10 Solution Controls used in FLUENT simulations

The values used Under-Relaxation Factors for simulation were default.

4.2.6 Solution initialization and Calculation

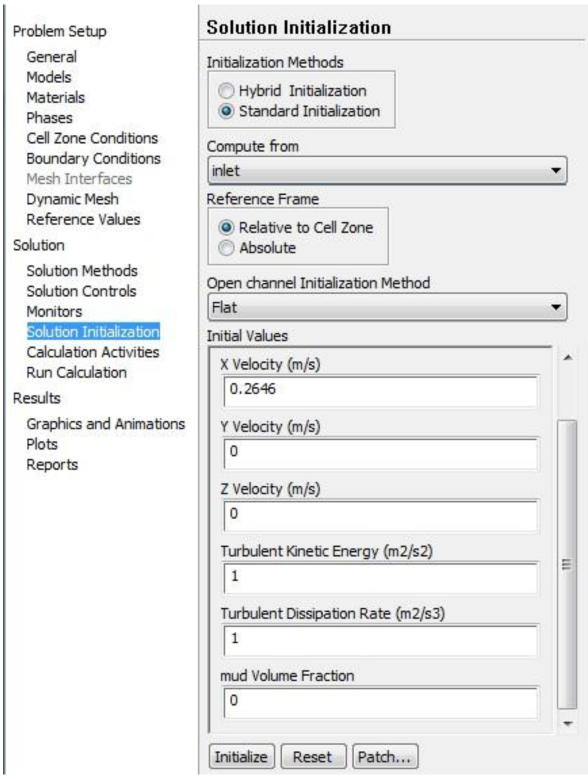


Figure 4-11 Solution initialization used in FLUENT simulations

The flow is along x-direction, hence was defined while other two velocity components were considered as zero. The velocity in the x-direction is calculated based on the inlet level and the volumetric flow rate. The fluid zone was patched with full of air in order to analyze the transient flow pattern of the flume.

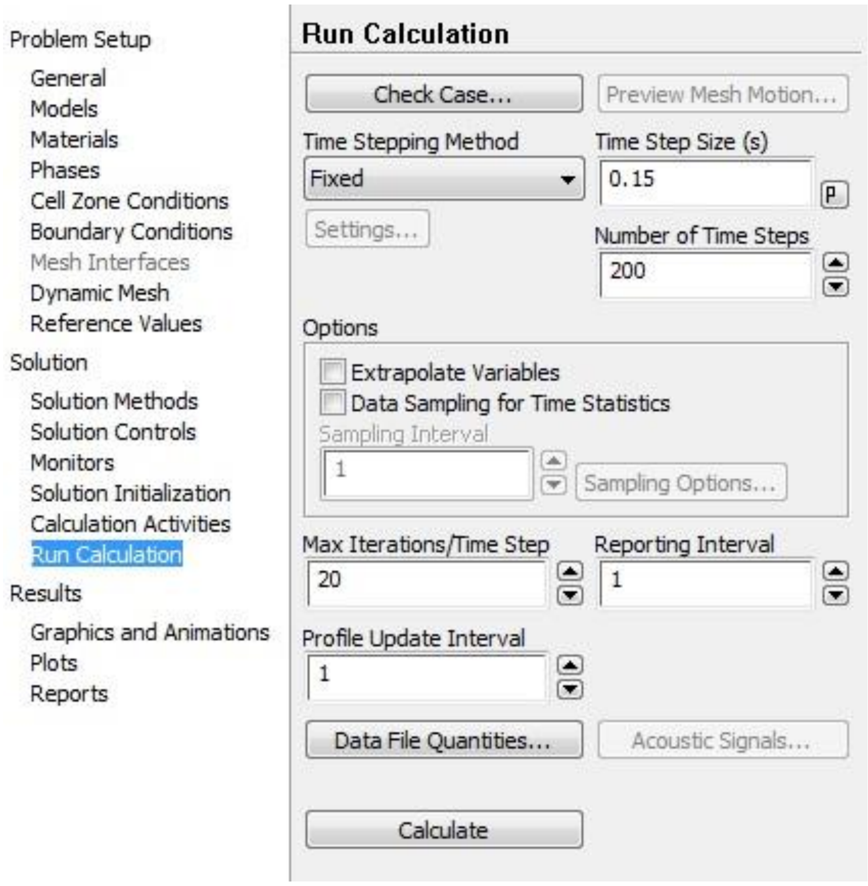


Figure 4-12 Calculation activities used in FLUENT simulations

The simulation time step of 0.15 second was used. Maximum iterations per time step were set as 20 whereas the number of time steps is 200. The solution are obtained solving conservation equations iteratively with a numerical solver. The solver calculates the conservation equation successively until the change of the calculated values of the variable are negligible from one iteration to the next.

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5 Results

The rheology of different non-Newtonian drilling muds is studied, particularly focused on 3% bentonite suspension, 4.5% bentonite suspension and 6% bentonite suspension. These muds are further discussed without yield stress as well as rheograms are postulated based on the Herschel-Bulkely rheological model. The characteristics of muds are extracted from the experimental data presented in [22].

Moreover, this chapter presents the results obtained by simulating these muds using FLUENT at the flow rate of 500 l/min. Herschel-Bulkely rheological model is used for non-Newtonian fluid simulation as well as these fluids are further simulated as Newtonian fluid at constant viscosity.

5.1 Rheograms obtained from Herschel-Bulkely rheological model

Rheograms are obtained in MATLAB by varying shear rate in Herschel- Bulkely rheological model. Figure 1 is obtained by shear rate from 0 to 1600 (1/s) for the general analysis of different characteristic of muds. Figure 2 and figure 3 are obtained by shear rate from 0 to 200 (1/s) for analysis of different concentration of bentonite suspension as both Newtonian and non-Newtonian fluid. Shear rate for bentonite suspension is only considered up to 200 (1/s) because the data obtained from FLUENT simulation shows the maximum strain rate obtained is 200 (1/s).

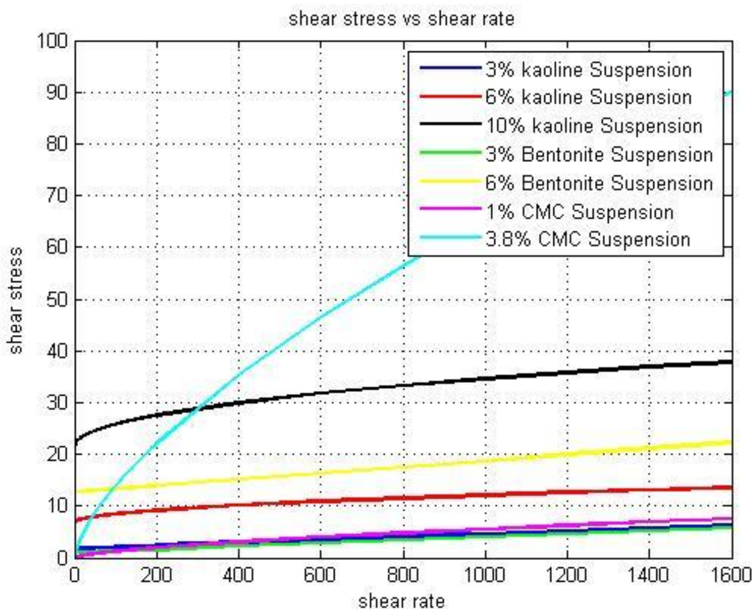


Figure 5-1Rehogram obtained for diffferent concentration of kaoline suspension, bentonite suspension and CMC suspension

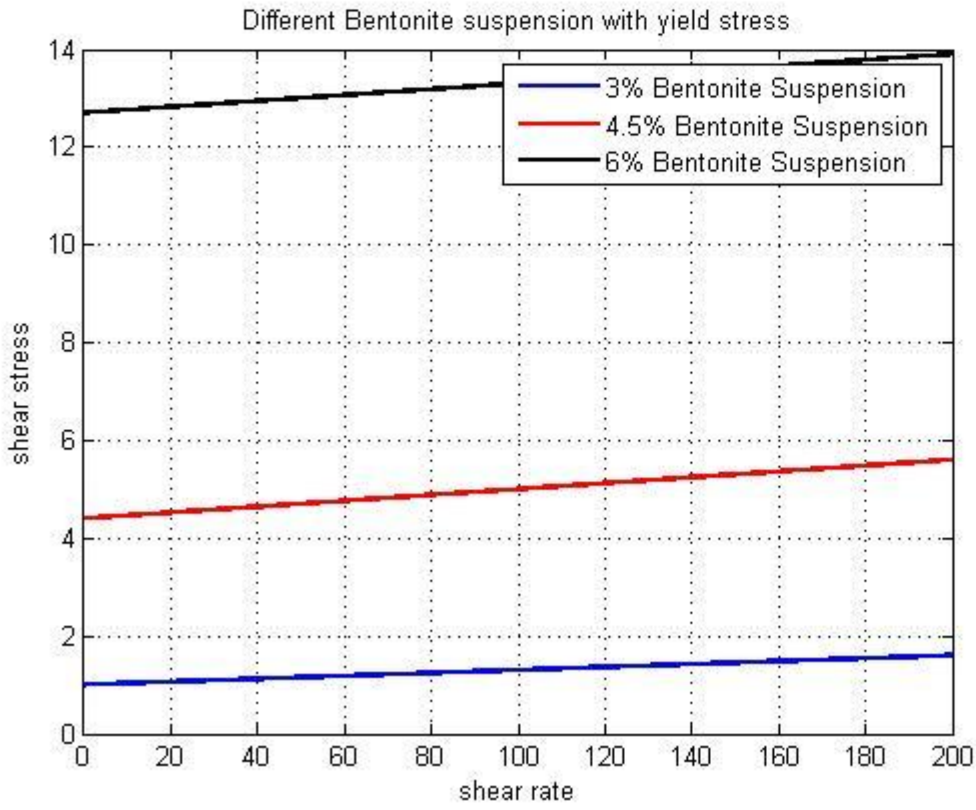


Figure 5-2Rheogram obtained for different concentration of Bentonite Suspension as non-Newtonian fluid

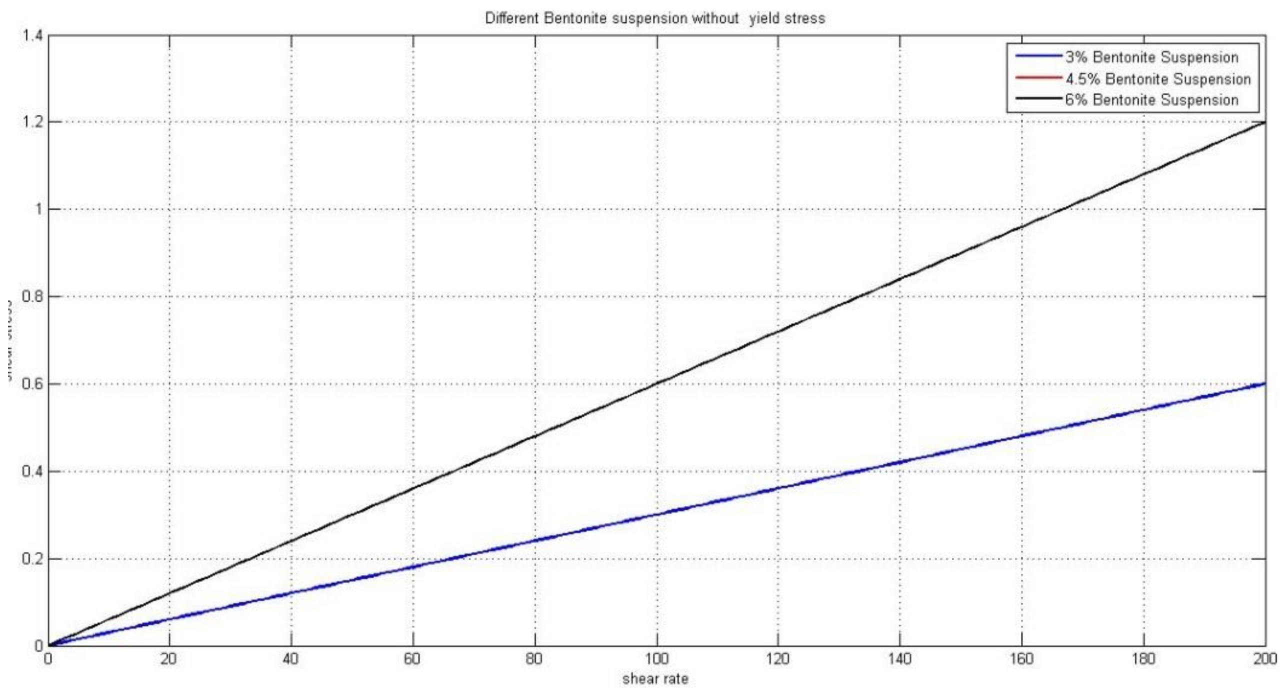


Figure 5-3Rheogram obtained for different concentration of Bentonite Suspension as Newtonian fluid

As we discussed, non -Newtonian rheology, it can be observed in Figure 5-1, kaolin suspension and CMC solution exhibit pseudoplastic fluid characteristics whereas bentonite suspension shows Bingham plastic fluid characteristic.

Figure *5-2* shows the change in shear stress of 3%, 4.5% and 6% bentonite suspension with the change in shear rate. The non-Newtonian plot of bentonite suspension looks like log- plot of Newtonian flow due to yield stress. Figure 5-3 is plotted without yield stress of bentonite suspension whose rehogram is same as Newtonian flow as well as 4.5% and 6% bentonite suspension exhibit same inclination.

5.2 Results obtained by CFD simulations I

These simulation results are obtained from simulation domain by master project group 2013 [21].

5.2.1 CFD simulations of different bentonite suspension as Newtonian fluid

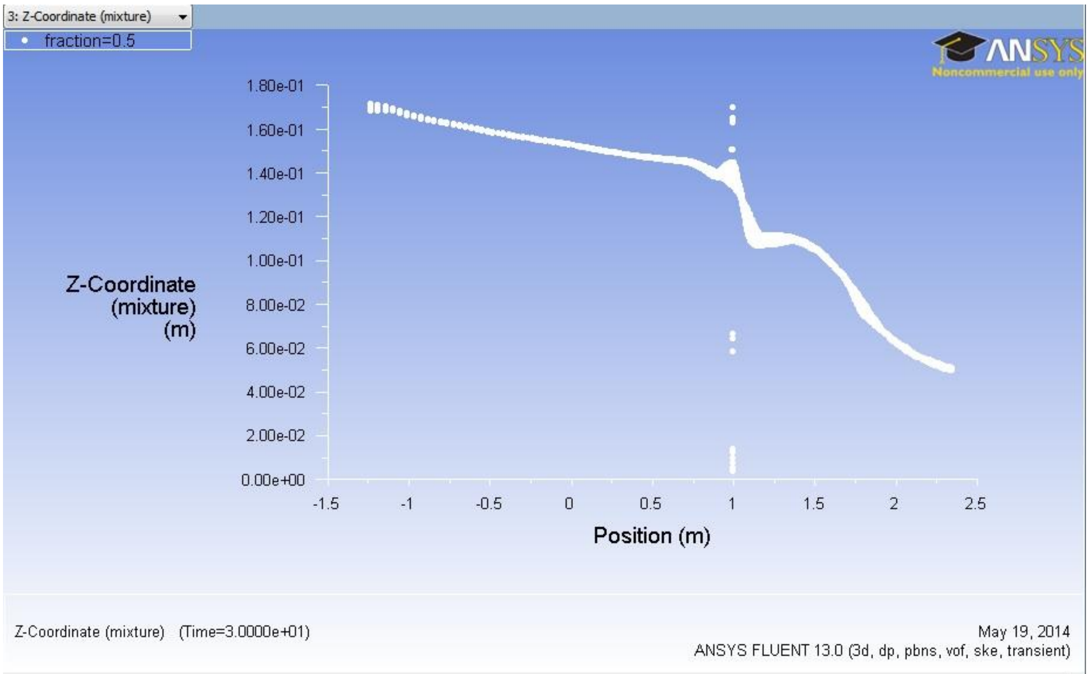


Figure 5-4Position of the free surface at the flow rate of 500 l/min of 3% bentonite suspension

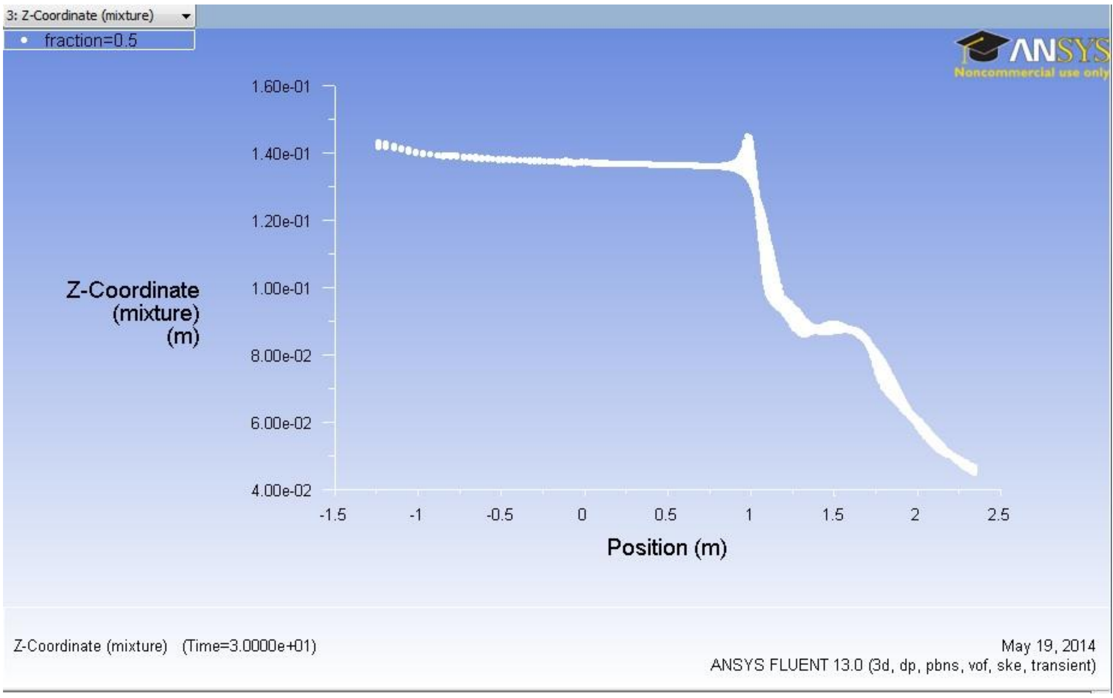


Figure 5-5Position of the free surface at the flow rate of 500 l/min of 4.5% bentonite suspension

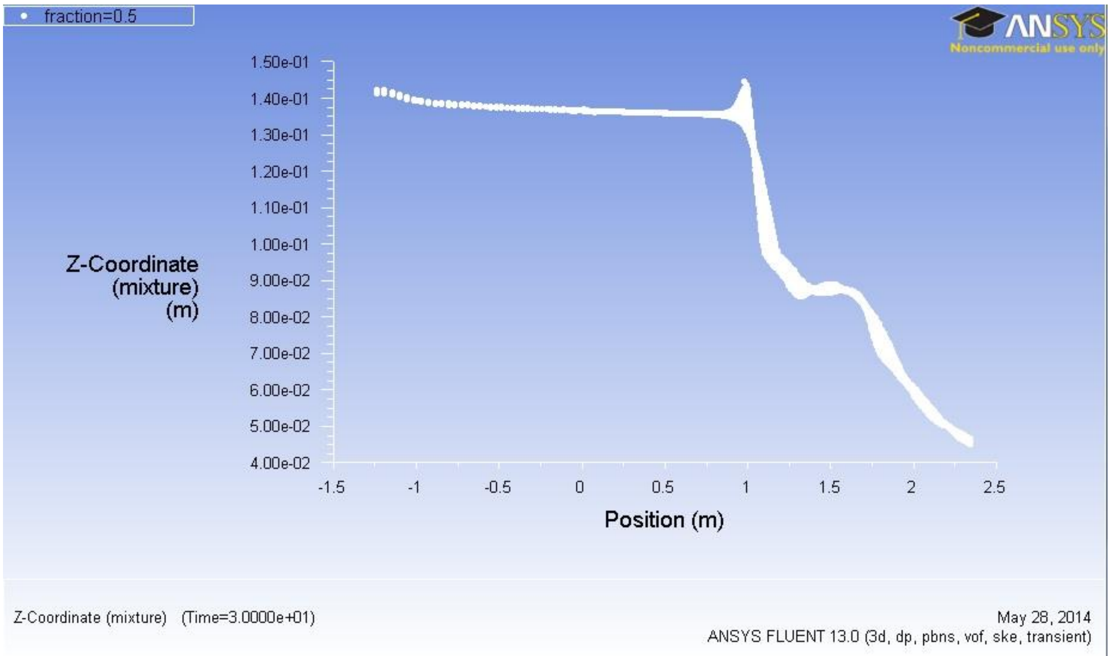


Figure 5-6 Position of the free surface at the flow rate of 500 l/min of 6% bentonite suspension

As expected from rehogram in Figure 5-3, 4.5% and 6% bentonite suspension shows same level gradient as well as a constant level in the inlet section whereas the level gradient in the inlet section of 3% bentonite suspension is steeper.

5.2.2 CFD simulations of bentonite suspensions as non-newtonian fluid

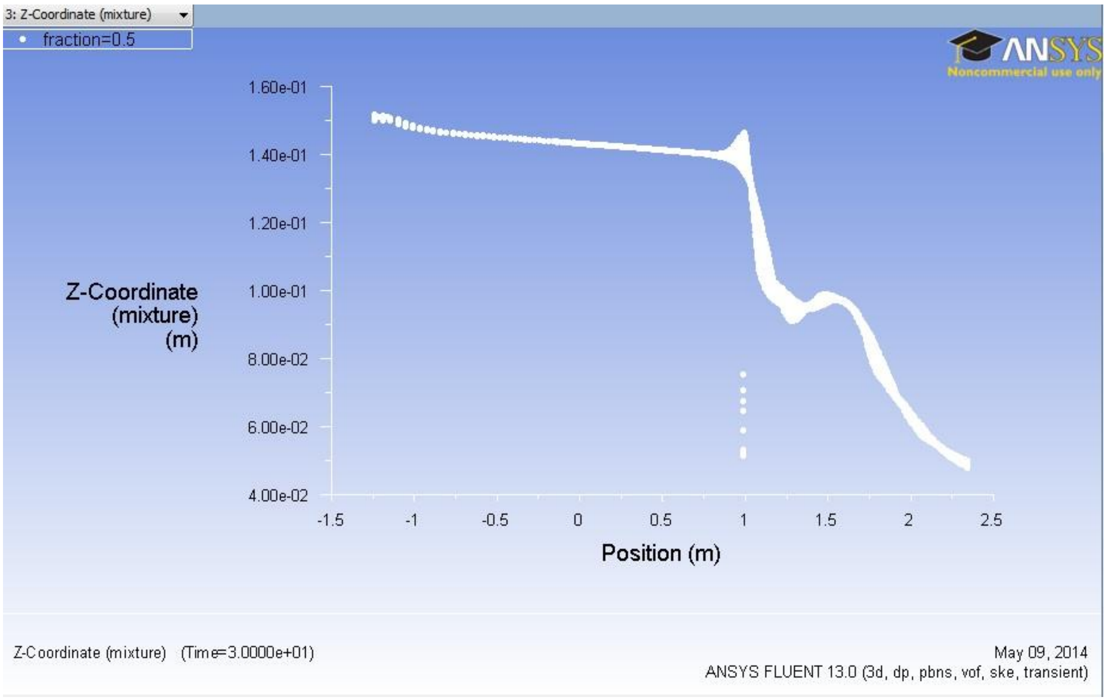


Figure 5-7 Free surface profile of 3% bentonite suspension at the flow rate 500 l/min

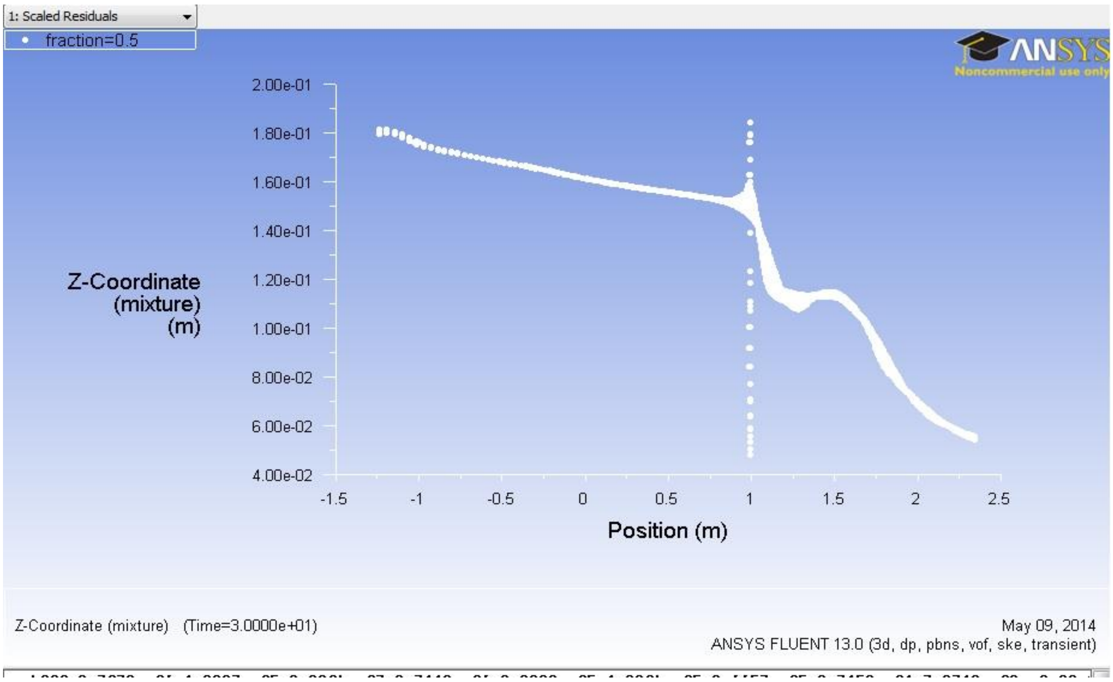


Figure 5-8Free surface profile of 4.5% bentonite suspension at the flow rate 500 l/min

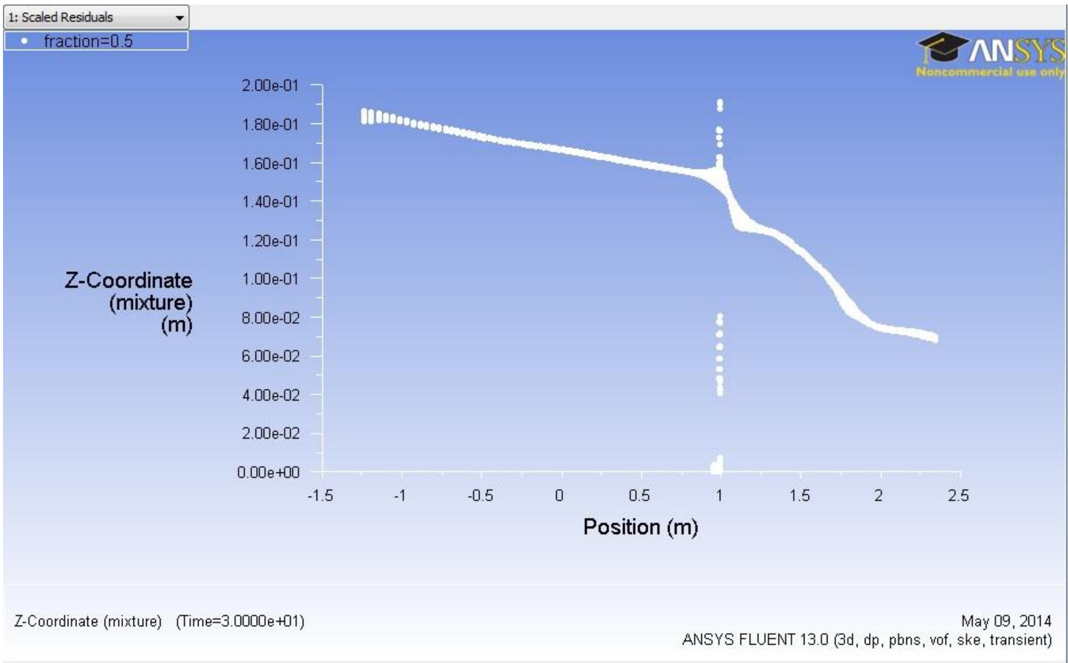


Figure 5-9 Free surface profile of 6% bentonite suspension at the flow rate 500 l/min

We can observe in Figure 5-7, Figure 5-8, Figure 5-9 that the level gradient in the inlet section is getting steeper and steeper. Unlike the Newtonian characteristics, the non-Newtonian flow has significant level gradient. It can be said that yield stress and viscosity of the material plays a significant role.

5.3 Results obtained by CFD simulations II

These simulation results are obtained using the geometry of bachelor of science project group 2013 [3]

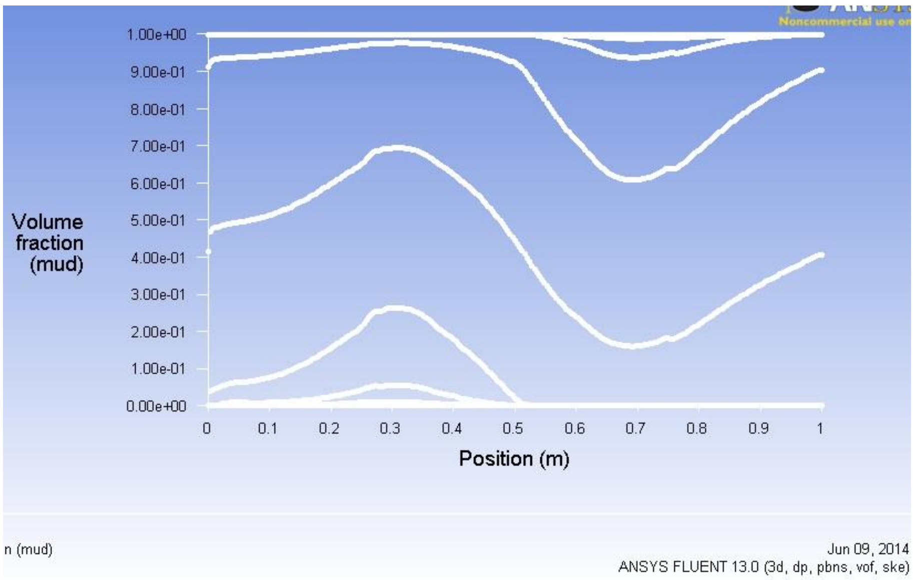


Figure 5-10 Varying mud volume fraction of 3%bentonite-suspension along the flow direction

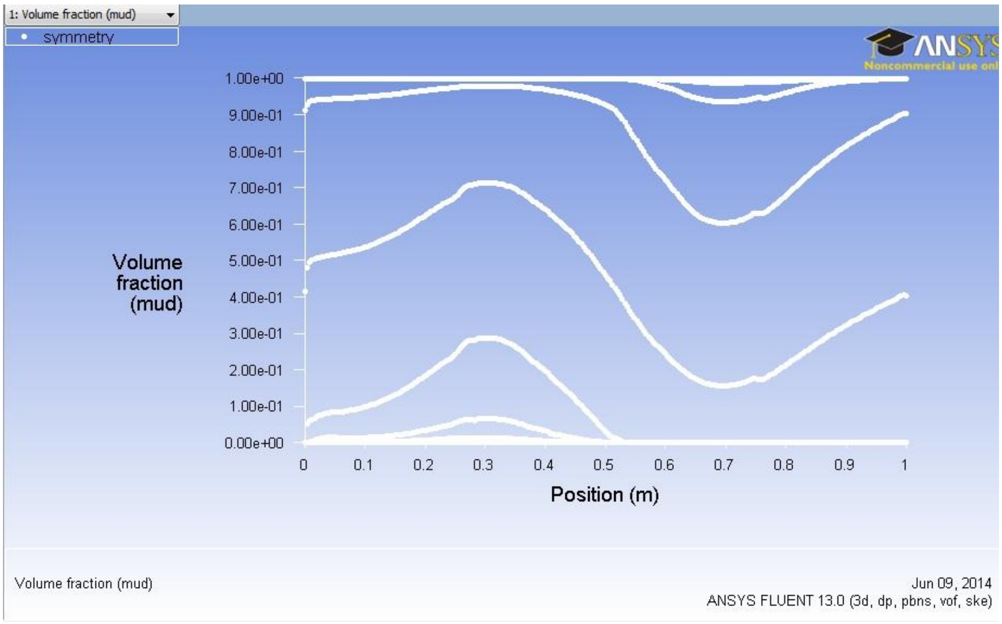


Figure 5-11Varying mud volume fraction of 4.5%bentonite-suspension along the flow direction

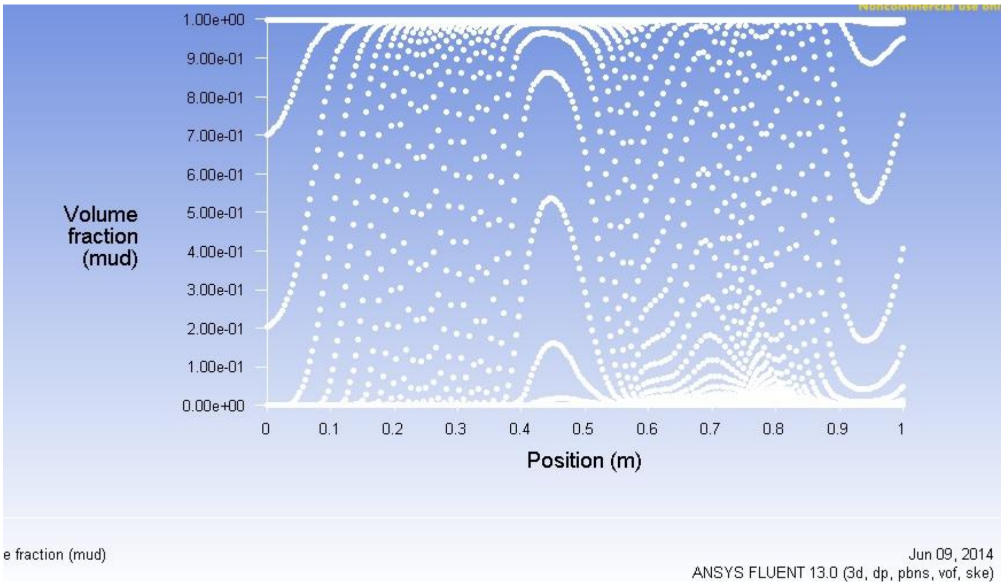


Figure 5-12Varying mud volume fraction of 6%bentonite-suspension along the flow direction

5.4 Non-Newtonian fluid flow along the flume

These results are obtained by using simulation domain of master of science project group 2013[21].

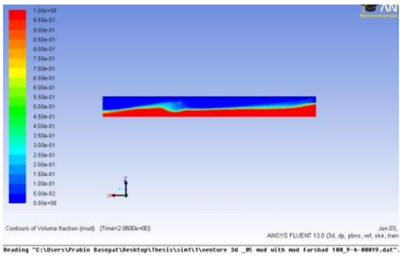
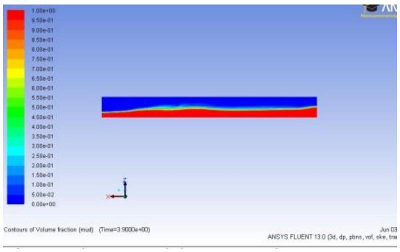
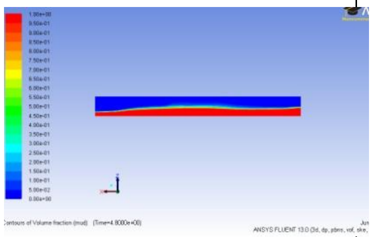
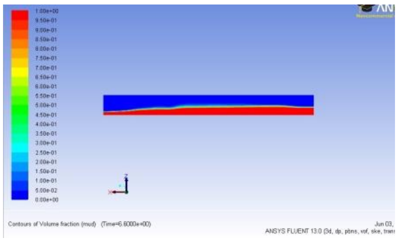
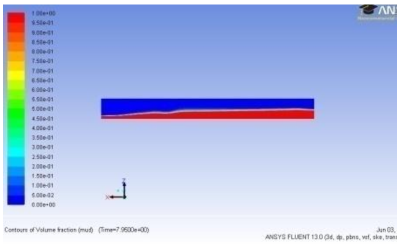
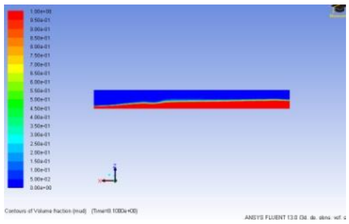
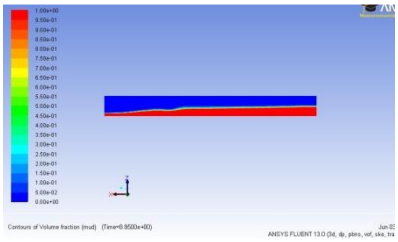
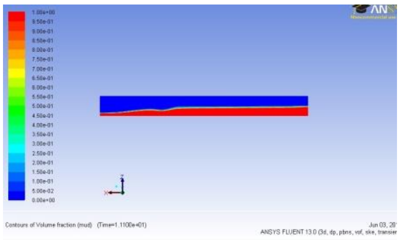
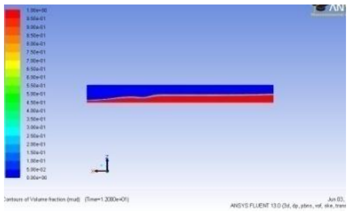
S.N.	1	2	3
A1	T=2.85 s	T=3.9 s	T=4.8
			
B1	T=6.6s	T=7.95s	T=8.1s
			
C1	T=8.85s	T=11.1s	T=12s
			

Figure 5-13 Flow behaviour of 3.5% Bentonite suspension at flow rate of 500 l/min

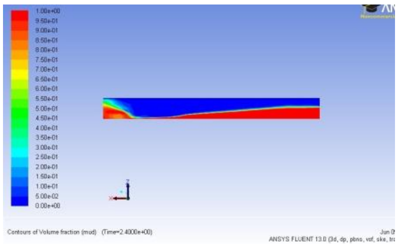
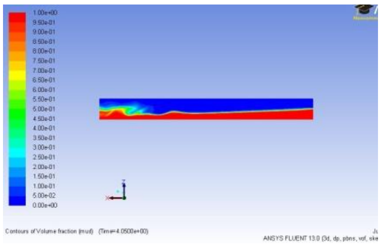
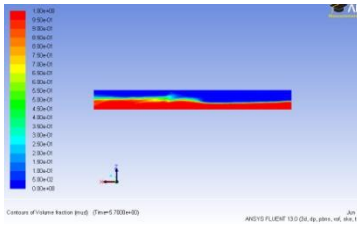
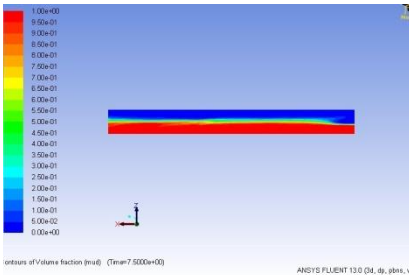
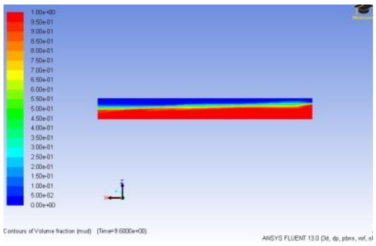
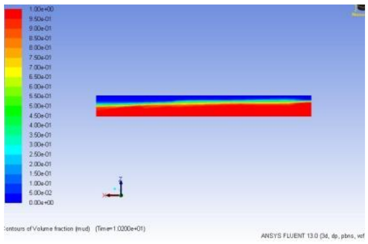
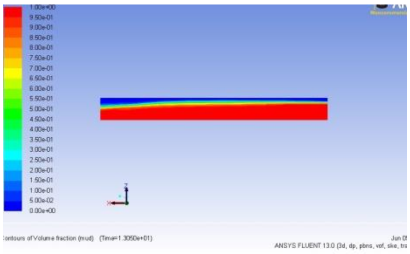
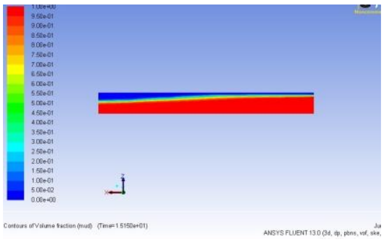
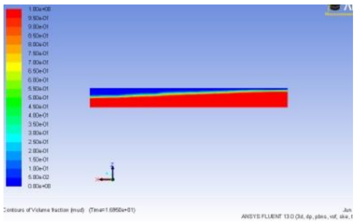
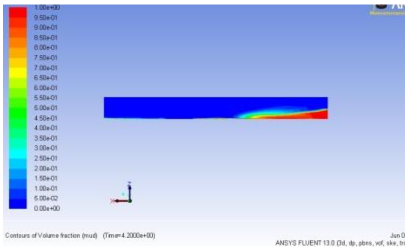
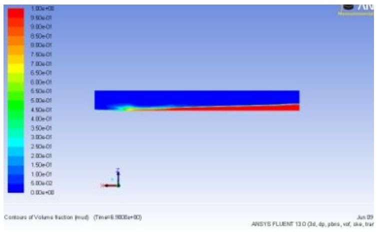
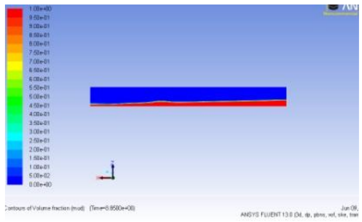
S.N.	1	2	3
A2	T=2.4s	T=4.05s	T=5.7s
			
B2	T=7.5s	T=9.6s	T=10.2s
			
C2	T=13.45s	T=15.15s	T=16.95s
			

Figure 5-14 Flow behaviour of 4.5% Bentonite suspension at flow rate of 500l/min

S.N.	1	2	3
A3	T=4.2s	T=6.9s	T=8.85s
			
B3	T=12.15s	T=15s	T=18.6

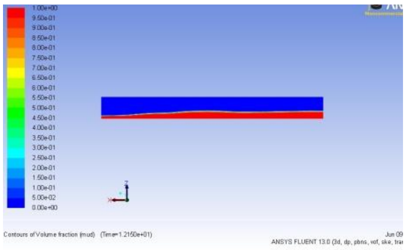
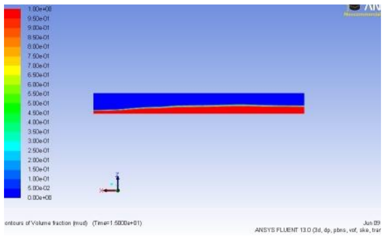
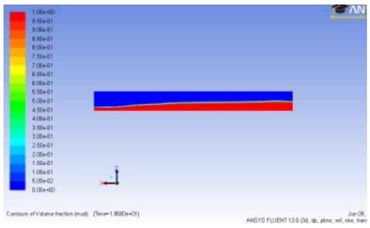
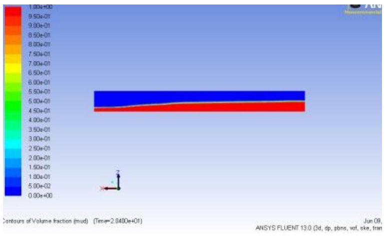
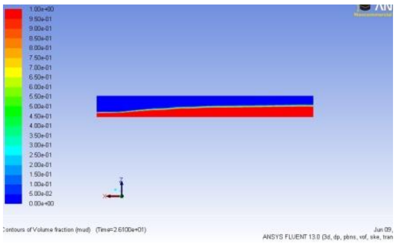
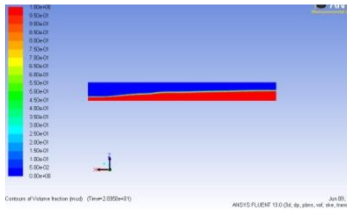
			
C3	T=20.4s	T=26.1s	T=28.35s
			

Figure 5-15Flow behaviour of 6% Bentonite suspension at flow rate of 500 l/min in simulation domain developed by master group project fall 2013

It is possible for fluid jump due to constriction in the flume. It represents turbulent transition between super- and sub- critical flows. The analysis of water flowing with varying initial flow condition changing between super-and sub-critical flows is done by master group project fall 2013[21]. Similar study by Christopher & Marshall[16] concludes that the hydraulic jump is fundamental and ubiquitous aspect of free-surface hydrodynamics.

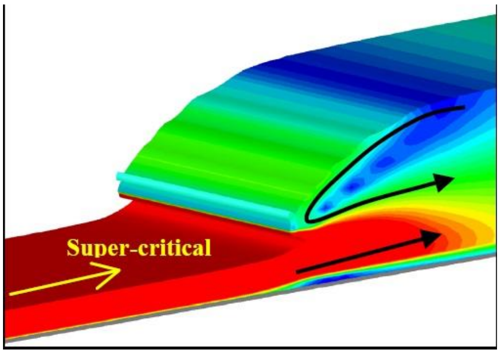


Figure 5-16 Hydraulic jump observed by Christopher & Marshall[16]

Flow behavior of different concentration of bentonite suspension is also similar with water in terms, fluid jumps to higher elevation and in the end reaches the steady state level. From Figure 5-13, Figure 5-14, Figure 5-15 of different concentration of bentonite suspension flow behavior, it is expected that fluid jump is inevitable in flume. Although the flow behavior of different concentration of bentonite shows a bit different pattern. It is due to change in viscosity of the fluid with the increase in the concentration of the bentonite.

6 Discussion

Synergetic combination of multiple experiments, as well as experimentally validated CFD solutions, is the best method for analyzing fluid flow behavior in open channel flow and to achieve the ultimate goal of achieving simplified model for accurate measurement of the drill mud flow rate.

Herschel-Bulkely model is used for analysis of rheology as well as to develop rehogram of non-Newtonian fluid. It was found by master group project fall 2013, CFD simulation with water agrees well with manufacturer's specification for ANSYS FLUENT. Similarly, 3%, 4.5% and 6% bentonite suspension as a Newtonian fluid show almost same features. Again, these fluid with non-Newtonian properties exhibit complex characteristics through the throat section. It can be postulated from the analysis of the result; viscosity of mud plays a vital role.

Analyzing the flow pattern of different concentration of bentonite suspension through the flume, it is expected that fluid jump is inevitable that is similar in water flow. Although a bit difference is observed in fluid flow due to different viscosity of the fluid but the pattern is same. First, fluid jumps to higher elevation and in the end reaches steady state level. The phenomena should be considered while measuring the level of fluid. It is expected to measure the level at steady state rather than fluctuating height.

The CFD simulations with drilling fluid provides basis for further analysis of fluid behavior but as we discussed in the start, experimental data is needed for further validation. It is difficult to judge the accuracy without correct experimental data.

7 Conclusion

Herschel-Bulkley model is used to fit for the unweighted rheological data. The rehogram for the bentonite-base fluids without yield stress represents Newtonian fluid, the relation between shear stress and shear rate being linear and passing through origin. The rehogram for the bentonite-base fluids as non-Newtonian fluids are similar to log plot.

The CFD simulation of bentonite-base fluids as Newtonian fluid agrees well with the simulation conducted on water by master group project fall 2013. The bentonite-base fluids as non-Newtonian fluid inlet surface profile get steeper and steeper with the increase in concentration of bentonite. This is due to increase in viscosity of the mud due to increase in the concentration of bentonite. The energy loss was also higher than Newtonian fluid. Viscosity plays a vital role on defining the characteristics of the drilling fluid.

Studying the fluid flow along the flume, it can be concluded that fluid jump is inevitable. It represents the turbulent transition between super-and sub-critical flows. Although fluid shows different fluid flow properties with respect to time step due to change in viscosity, but the flow pattern is similar with fluid jump to higher elevation and reaches steady state. It should be considered while measuring the level of fluid with sensor because it is expected to measure fluid flow at steady state.

All in all, CFD simulations are very useful tool in designing flume and analyze the fluid behavior through the flume. However, experimental data is needed to validate the results.

Further work

This report provides a good basis for rheological analysis for bentonite-base fluids as well as their flow behavior through the flume, but it yet to be validated with experimental data. Further work is to conduct CFD simulations along with the experiments so that the results can be validated to each other.

Appendices

Appendix 1: Abstract

Appendix 2: Project task description

Appendix 3: Dimension of flume of BAMO measures

Appendix 4: Dimension of flume developed by B.Sc. Project Group

Telemark University College

Faculty of Technology

M.Sc. Programme

MASTER'S THESIS, COURSE CODE FMH606

Student:	**Prabin Basnyat**
Thesis title:	**Simulating open channel flow for drill mud mass flow measurement, part II**
Signature:	. . . .
Number of pages:	38
Keywords:	**Rheology, Rheogram, CFD, ANSYS, Open channel flow, non- Newtonian fluid**
Supervisor:	Knut Vågsæther sign.: . . . .
2nd Supervisor:	Bernt Lie sign.: . . . .
Censor:	<name> sign.: . . . .
External partner:	Statoil sign.: . . . .
Availability:	<Open/Secret>

Archive approval (supervisor signature)**:** sign.: . . . . **Date :** . . . .

Abstract:

Advancement in oil drilling technology, particularly managed pressure drilling requires better knowledge of return drill mud flow. Since the mud outflow is in an open channel, it is proposed to use flume with constriction that is based on Venturi principle for flow rate measurements. Rheological study of bentonite-base fluids as a non-Newtonian drilling fluid has been performed as well as CFD simulation of these fluids has been done for analysis of non-Newtonian fluid flow behavior.

Rheology is termed as 'rheallycomplicatedology' by Steve Devereux[1]. It is tried to keep this study as simple as possible, and this report is focused on bentonite-base fluid only. Rheograms are based on Herschel-Bukley model. Rheogram of bentonite-base fluids without yield stress show Newtonian fluid characteristics i.e. shear stress vs. shear rate being linear and passing through the origin. Rheogram of bentonite-base fluids with yield stress as non-Newtonian fluid is similar to log plot.

The geometry used for CFD simulation are the flume from the manufacturer BAMO and bachelor of science group 2013. ANSYS FLUENT is used to analyze the fluid flow behavior and liquid levels, using multiphase volume of the fluid model for bentonite-base fluid both as Newtonian and non-Newtonian. Bentonite-base fluids as Newtonian exhibit similar results as simulation conducted on water by master group project fall 2013 while, as non Newtonian, inlet surface profile gets steeper and steeper with the increase in concentration of bentonite. This is due to increase in viscosity of the fluid by the increase in concentration. It can be said that viscosity plays a vital role on defining the characteristics of the drilling fluid.

Fluid flow along the flume at different time step shows a bit different properties for different concentration of bentonite base fluids due to change in viscosity, but the flow pattern is same. First, level of fluid reaches higher elevation due to fluid jump and finally, reaches steady state. This behavior should be considered during level measurement because it is expected to measure the level at steady state.

Appendix 2: Project task description

Title: Simulation open channel flow for drill and mud mass flow measurement, Part II

TUC supervisors: Statoil ASA

Task description:

- The students will continue with the developed method in Fluent for simulating open channel flow with the non-Newtonian drilling fluid. the initial work was done in the master group project fall 2013.

- The simulation domain will be of the proposed experimental rig for testing the Venturi type mass flow indicator.

- Find/develop a model for the rheology of the drilling fluid that can be used in Fluent.

-Investigate the effects of transient mass flow.

-If needed: assist in the construction project (B.Sc.) for the test rig.

Task background:

Necessary advances in oil drilling includes better control of the bottom hole pressure during drilling: a too low pressure leads to blow-out, while a too high pressure may reduce permeability and thus production rate. An important part of a more intelligent drilling involves better knowledge of the return drill mud flow. Currently, this flow rate is measured using large Coriolis based sensors or other extremely expensive set-ups. It is of interest to explore the possibility of using Venturi type mass flow sensors both to reduce space requirements and to reduce the cost.

In an on-going project at Telemark University College, together with Statoil, the goal is to study this possibility of using Venturi type mass flow sensors for on-line mass flow measurements. Some literature study has been carried out, but it is now time for a more quantitative study. The future work will include developing detailed models of flow of drill mud in an open channel with a Venturi type constriction. In a B.Sc. project, the aim will be to design and instrument a rig for experiments, which will then be built by Statoil. In M.Sc. project (this), CFD models for venturi flow of drill mud in open channels will be developed. In a subsequent M.Sc. thesis, this detailed model will be compared to experimental data from a rig. Furthermore, in another M.Sc. thesis, the possibility of developing simplified models for the flow will be explored, and this simplified model will be calibrated against the more detailed model. The final aim is to used a simple, calibrated model in an on-line smart sensor for accurate measurement of the drill mud flow rate.

Thus, the CFD study of Venturi flow in an open channel forms an important first step in the development.

Student category:

PT and EET (CFD)

Practical arrangements:

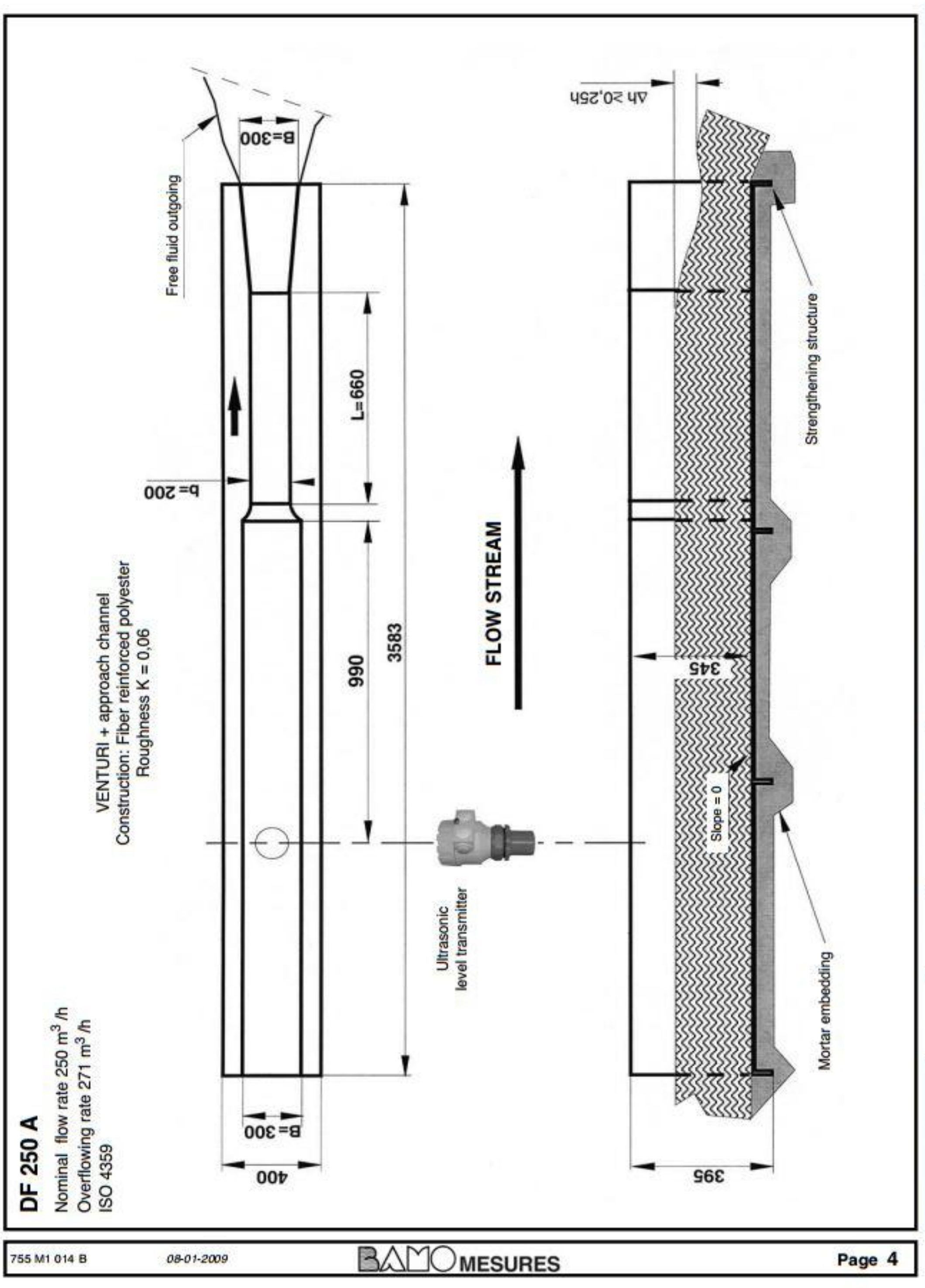
The student will work at TUC.

Signatures:

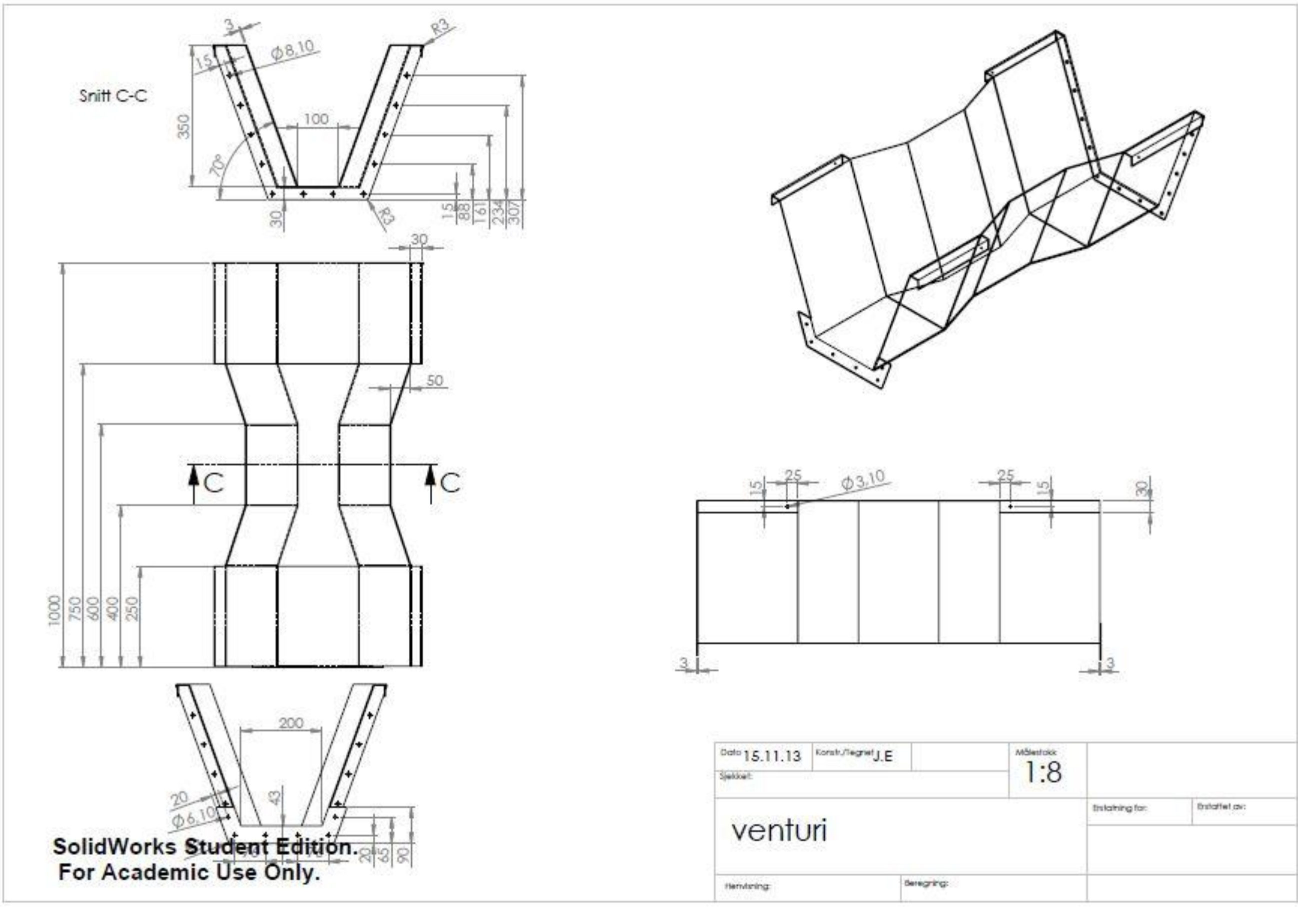
Student(date and signature):

Supervisor(date and signature):

Appendix 3: Dimension of flume of BAMO measures



Appendix 4: Dimension of flume developed by B.Sc. Project Group



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