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Study of Cuttings Transport Using Water-Based and Oil-Based Drilling Fluids

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Thesis for the degree of Philosophiae Doctor

Trondheim, April 2018

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Abstract

Cuttings transport is a topic of great interest in the oil and gas drilling industry. Insufficient cuttings transport leads to several expensive problems. Knowledge and selection of the drilling fluids is one of the important factor for efficient hole cleaning. The present work reports pure hydraulic and cutting transport behavior of various oil-based and water-based drilling fluids. Flow loop experiments were conducted on a purpose-built flow loop close to realistic field conditions.

It has been observed, however, that the hole cleaning performance of drilling fluids can be different even if the fluid rheological properties are similar as measured in accordance with API specifications. The reasons for stated difference in the behavior of drilling fluids are not well understood. The objective of the present work was to compare hole cleaning performance of an oil-based drilling fluid and a water-based drilling fluid with similar density and viscosity measured as per API specifications. Also, to identify the reasons for differences in their hole cleaning behaviour. Limited studies are available in the literature which studied the same and conclusions differ.

Hole cleaning efficiency of an oil-based drilling fluid and a water-based drilling fluid whose viscosity profiles are similar was investigated. The fluids tested were industrial fluids used in the field and were sent to us after reconditioning. Experimental studies were performed on an advanced purpose-built flow-loop by varying flow velocities and drill string rotation rates. The flow loop had a 10 m long annulus section with 4" inner diameter wellbore and 2" outer diameter fully eccentric drill string. Pressure drop and sand holdup measurements were reported. Rheological investigations of the same fluids were used to understand the difference in the behavior of the drilling fluids tested. In case of no drill string rotation, better hole cleaning performance was observed with the oil-based fluid compared to the water-based fluid. With the presence of drill string rotation, hole cleaning performance of both the fluids was nearly the same.

Foreword

The current project focused mainly on the understanding of hole cleaning behavior of oil-based and water-based muds. This project was carried out at SINTEF and NTNU. The research work was supported by the Research Council of Norway, Aker BP, and Statoil. The project involved work of two PhDs who both performed rheological and flow loop investigations of oil-based and water-based muds. A detail rheological investigation formed the main part of the PhD study by the other PhD candidate, Benjamin Werner. The current thesis presents in detail the flow loop investigations. My main contributions to this study was:

- Conducted hydraulic and cuttings transport flow loop experiments utilizing the flow loop setup at SINTEF
- Assembled, reworked and modified the flow loop as per our research needs
- Data analysis of the results of the flow loop experiments
- Significant contribution in understanding the results, writing and publishing scientific articles
- Computational fluid dynamics(CFD) model development to simulate flow loop conditions

List of Papers

The thesis contains the following research articles. Following research articles were presented at different conferences or published in conference proceedings and journals during the course of this thesis.

Paper I
Sayindla, Sneha; Lund, Bjørnar; Taghipour, Ali; Werner, Benjamin; Saasen, Arild; Gyland, Knud Richard; Ibragimova, Zalpato; and Ytrehus, Jan David. 2016. Experimental Investigation of Cuttings Transport With Oil Based Drilling Fluids. OMAE2016-54047. In: Proceedings of the 35th International Conference on Ocean, Offshore and Arctic Engineering, June 19–24, Busan, South Korea.

Paper II
Sayindla, Sneha; Lund, Bjørnar; Ytrehus, Jan David; Saasen, Arild. 2017. Hole-cleaning performance comparison of oil-based and water-based drilling fluids. Journal of Petroleum Science and Engineering, 159: 49-57.

Paper III
Sayindla, Sneha; Lund, Bjørnar; Ytrehus, Jan David; Saasen, Arild. CFD Modeling of Hydraulic Behavior of Oil-based and Water-based Drilling Fluids.
The paper was submitted to SPE Drilling and Completion journal and it is under revision.

Additional publications

Ytrehus, Jan David; Taghipour, Ali; Sayindla, Sneha; Lund, Bjørnar; Werner, Benjamin; Saasen, Arild; 2015. Full Scale Flow Loop Experiments of Hole Cleaning Performances of Drilling Fluids. OMAE2015-41901. In: Proceedings of the 34th International Conference on Ocean, Offshore and Arctic Engineering, May 31– June 5, St. John’s, Newfoundland, Canada.

Ytrehus, Jan David; Taghipour, Ali; Gyland, Knud Richard; Lund, Bjørnar; Sayindla, Sneha; Saasen, Arild; Hermansson, Lasse. 2016. Flow Loop Investigation of Lubricant Concentration Effect on Mechanical Friction in Drilling Fluids. OMAE2016-54048. In: Proceedings of the 35th International Conference on Ocean, Offshore and Arctic Engineering, June 19–24, Busan, South Korea.

Sayindla, Sneha; Lund, Bjørnar; Ytrehus, Jan David; Saasen, Arild. 2017. CFD Modelling of Observed Cuttings Transport in Oil-based and Water-based Drilling Fluids. SPE-184660-MS. In: Proceedings of the SPE/IADC Drilling Conference and Exhibition, 14–16 March, The Hague, The Netherlands.

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I especially thank Jan David Ytrehus, Ali Taghipour, and Bjørnar Lund for giving me an opportunity to use their laboratory facilities at SINTEF and also for allowing me to be a part of their research group. Many thanks for their interest, time, and commitment to support my work. I had a great learning experience working with them under their guidance.

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I would like to thank my colleagues at NTNU especially Benjamin Werner for his support and for the good time we had together. His positive attitude always served as a source of motivation for me. I would also like to thank Nur Suriani Mamat for the good discussions on our daily life experiences.

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Table of Contents

Nomenclature

ω	Angular velocity of inner cylinder (rad/s)
U	Bulk axial velocity [m/s]
K	Consistency index (Pa s^n)
δ	Hydraulic radius (m)
ρ	Liquid density [kgm^{-3}]
R_i	Outer radius of drill pipe (m)
G_b	Sand mass transport rate
R_o	Inner radius of annulus (m)
τ_b	Shear stress on bed (Pa)
θ	Shields number
ξ	Velocity ratio
q	Volumetric transport rate
S_b	Width of cuttings bed
d_o	Inner diameter of annulus (m)
d_i	Outer radius of drill pipe (m)
$\dot{\gamma}$	Shear rate
n	Flow behavior index
A	Area of annulus section
τ_w	Wall shear stress (Pa)
τ_y	Yield stress (Pa)

1 Introduction

1.1 Background

An oil well is drilled into the earth or seabed for extraction of hydrocarbons to the surface. It acts as a passage for the flow of petroleum to the surface. The Drilling rig has several parts, e.g., derrick, drill bit, collar, and drill pipe. The derrick is the visible part of the drilling rig and is used to vertically hoist and introduce the drill strings down the hole. The drill string is rotated by either rotary table or top drive. Rotation of the drill bit, and weight at the end of the drill string, causes it to penetrate the rock. An oil rig setup is presented in Figure 1. As drilling progresses, new sections of drill strings are connected to drill to the required depth. During the drilling process, cuttings or rock fragments are generated by the drill bit.

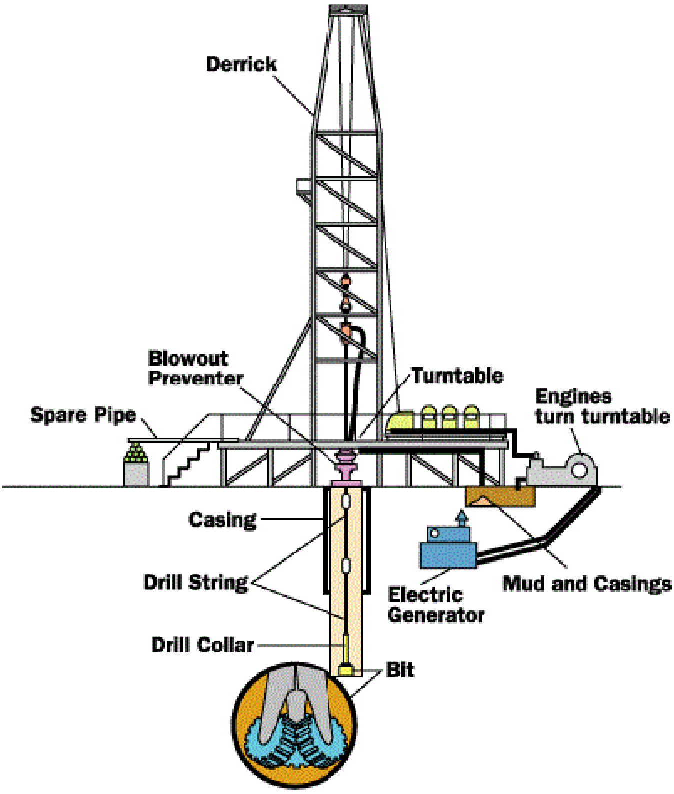

Figure 1. Oil Rig Systems (science.howstuffworks.com)

Drilling fluid is circulated through the drill string and back up the annulus in order to transport cuttings to the surface, enabling drilling operation to progress. Moreover, high dense weighing materials such as barite, ilmenite or hematite are added to the drilling fluid to increase the bulk density of the same. This makes the drilling fluid exert a hydrostatic pressure greater than the downhole pressure hindering influx of gas, oil or water. Cuttings collected at the surface are separated from the drilling fluid using sieves/screens put on shale shakers. Cuttings are discarded, and the drilling fluid is reconditioned for further use. Also, during the drilling operation, the borehole walls are cased intermittently to stabilize them and to prevent them from collapsing or fracturing.

Significant resources are spent by oil and gas companies annually on drilling, out of which a large fraction is lost due to various drilling problems, e.g., equipment failure and loss of drilling fluid. Such failures need to be repaired, during loss of time, termed as non-productive time. It is vital for the drilling engineer to choose parameters properly to minimize the cost of operation and to prevent failures. One such drilling problem, which has been in focus for many researchers for several decades, is inadequate cuttings transport. Insufficient hole cleaning may lead to operational problems such as stuck pipe, increased pump pressures, lost circulation, excessive drill string torque and drag. The drilling fluids ability to transport cuttings is considered one of the most important task for performing safe and efficient drilling operations.

Cuttings are transported to the surface by several different mechanisms. The specific mechanism depends on the wellbore angle (Clark and Bickham, 1994). Good hole cleaning occurs is unproblematic in vertical wells, whereas in an inclined well, the fluid velocity has a reduced vertical component and the direction of cuttings settling is still vertical. This, in turn, reduces the suspension capability of the drilling fluid. At a high angle of inclination the generated cuttings has a short distance to the borehole wall. After reaching the borehole wall, local fluid velocities near the wall are very low and maybe insufficient to re-entrain the particle into the flow.

Drilling fluids are classified based on its primary components like water, oil/gas. It consists of two phases, the continuous phase, which is the base fluid, and a discontinuous phase comprising solids. Viscofiers are added to increase the viscosity of the drilling fluids and barite or salt is added to increase the density. In addition to cuttings transport, the drilling fluid serves many other functions: lubricate the well string, transmit hydraulic energy to tool and bit, avoid formation damage, facilitate cementing and completion, control erosion of the borehole, minimize the potential for lost circulation, and maintaining wellbore stability.

Water-based and oil-based fluids are the most commonly used drilling fluids. Each of these two fluid types have their own advantages and disadvantages, as shown in the review by Apaleke et al. (2012). Oil-based drilling fluids are widely used to overcome problems in HPHT conditions. Oil-based drilling fluids also provide superb shale stability, faster penetration rates, and high lubricity especially in high deviated and horizontal wells. Latter parameter reduces the risk of differential sticking. Also, oil-based drilling fluids offers exceptional corrosion protection. However, oil-based drilling fluids are not always feasible because of its higher cost. They are less environmentally friendly fluids. Water-based drilling fluids are cheaper; they are more environmentally friendly. Cuttings from drilling with water-based drilling fluids can be disposed of, while oil contaminated cuttings need to be treated at site before disposed of or sent onshore for disposal.

Oil-based drilling fluids have been claimed to be superior to water-based drilling fluids when it comes to hole cleaning, even if the fluid rheological properties are equal as measured in accordance with API specifications. The reasons for this difference is not completely understood (Saasen and Løklingholm, 2002). Field studies show that drilling ROP improves by using OBM, whereas laboratory evaluations have indicated that it is not obvious that drilling ROP improves with OBM. Field engineers strongly believe that OBMs perform better compared to WBMs, but no laboratory investigations were made to verify this belief. In addition, it was not clear whether the superior performance of OBMs was because of the hole cleaning ability of the fluids or its interaction with the formation.

Very limited research studies are available where OBMs and WBMs with similar rheological properties were tested. Also, there are no standards available which suggest which drilling fluid to be used for a particular well. Proper selection of the drilling fluid for a well is very important concerning cost of operation and efficient hole cleaning. According to industrialists, water-based drilling fluids are used wherever possible, and oil-based drilling fluids are used where needed.

In recent years, drilling fluids also have become more complex in nature. Investigations at controlled flow loop conditions representing realistic field parameters will definitely improve the understanding of drilling fluids. In addition, the identification of the differences in performance of OBM and WBM will enable the development of improved drilling fluids, both operationally and environmentally, for both oil based and water based fluids.

1.2 Cuttings Transport Experimental Studies

Cuttings transport has been a topic of theoretical and experimental studies for many investigators. Cuttings transport is essential for successful drilling operation, which can affect the cost of operation, the time, and the quality of the well and its completion. It is a major issue especially in highly deviated oil well drilling design.

The ability of drilling fluid to transport cuttings is known as the carrying capacity of the drilling fluid. The process of transporting cuttings from well to the surface is called hole-cleaning. Transportation of cuttings in the annulus is a complex process. Based on laboratory investigations available in the literature, cuttings transport is influenced by many parameters and are classified into three categories: Cuttings parameters, fluid parameters, and operational parameters. Cutting parameters include cutting density, cutting shape and size, and cutting concentration. Fluid parameters include fluid rheology, fluid density, and fluid flow rate. Operational parameters include inclination, drill pipe rotation speed, annuli size, eccentricity, and rate of penetration (ROP) (Chien, 1994; Duan et al., 2009; Ford et al., 1990; Gavignet and Sobey, 1989; Hussaini and Azar, 1983; Peden et al., 1990; Piroozian et al., 2012; Sifferman and Becker, 1992; Sifferman et al., 1974; Tomren et al., 1986; Yu et al., 2004; Zeidler, 1972).

Among all the parameters which influence hole cleaning, undoubtedly flow rate has a significant positive effect. Cuttings bed height is significantly reduced by increased flow rate (Cho et al., 2001; Hussaini and Azar, 1983; Li and Walker, 2001; Okrajni and Azar, 1986; Tomren et al., 1986). However, higher fluid flow rate will also increase the annular pressure drop, which in turn increases the equivalent circulation density of the drilling fluid system. This may result in well fracture. Therefore, the optimized flow rate should be used to avoid well stability issues.

Cuttings size is another important parameter that effects cuttings transport, but it is very difficult to control cuttings size. Several studies were conducted with various cuttings sizes, but conclusions differ. Studies by Bilgesu et al. (2007); Duan et al. (2008); Yu et al. (2007) conclude that smaller particles are difficult to be removed, and study by (Sanchez et al., 1999) conclude that smaller particles are easier to be cleaned with pipe rotation than larger particles. Duan et al. (2008) from their experiments conclude that behavior of particles depends on the drilling fluid. Smaller particles are difficult to clean with water, but they are easy to clean with

0.25 lbm/bbl PAC solution in the presence of drill string rotation. Size and shape of the cuttings effect their dynamic behavior in the system.

Rheological properties of drilling fluids also have a significant effect on cuttings transport. Rheological properties include yield values (YP), plastic viscosity (PV), viscosity, fluid behavior index (n), and consistency index (K). Experimental observations by Okrajni and Azar (1986) show that lower viscosity drilling fluid is more effective than higher viscosity drilling fluid at a particular flow rate. Higher drilling yield values and higher YP/PV provide better cuttings transport in laminar flow. However, cuttings transport is not effected by drilling fluid rheology in turbulent flow. In horizontal/near horizontal wellbore hole cleaning is more efficient with a low viscosity fluid in turbulent flow. Whereas in vertical/near vertical wellbore hole cleaning is more efficient with a high viscosity fluid in laminar flow (Walker and Li, 2000). Seeberger et al. (1989) emphasized on evaluating low shear viscosity to obtain good hole cleaning. YP and PV values are often derived from the data produced at far higher shear rates than occurring in the realistic drilling conditions (Werner et al., 2017). The influence of rheological properties on hole cleaning cannot be generalized. It depends on the inclination, flow regime, and flow rate.

Wellbore inclination may vary from vertical to horizontal and cuttings transport mechanism is different in different ranges of inclination. Most of the investigations conclude that cuttings transport is most difficult in the wellbore with intermediate angles of inclination. A study by Brown et al. (1989) concludes that region ranging from 50^o to 60^o have the poorest cutting removal rates. A study by Piroozian et al. (2012) demonstrate cutting transport mechanisms in different angles of inclination. In high angle or near horizontal regions, a stationery cuttings bed can form and transport is dominated by rolling mechanism. In intermediate angles, moving cuttings bed can form and transport is dominated by lifting mechanism, and at lower angles or near-vertical angles, cuttings transport is determined by the particle slip velocity. As the hole angle increases from 0^o to 90^o, hydraulic requirements to achieve sufficient cuttings transport also increases.

The rate of penetration (ROP) has a negative effect on cuttings transport. With the increase of ROP, cuttings concentration in the drilling fluid increases and also the accumulation in the annulus increases (Sanchez et al., 1999; Tomren et al., 1986).

Drill pipe rotation positively influences cuttings transport. Drill pipe whirling agitates the flow around it, which brings the particles in the cuttings bed back into the flow. This improves cuttings transport. Pressure drop might increase or decrease with drill pipe rotation, based on the drill pipe position in the annulus. In eccentric annulus, pressure drop increases with the increase of drill pipe rotation. Increased pressure drop increases the shear stress acting on the cuttings bed, which enhances cuttings transport. For optimal hole cleaning, it is recommended to use as high drill pipe rotation as possible. However, there is no much effect on the cuttings transport beyond a certain drill pipe RPM. Haige et al. (1994) concludes that cuttings bed is significantly reduced with drill pipe rotation at low flow rate, but the pipe rotation has no significant effect on cuttings transport at higher flow rates. Study by Ozbayoglu et al. (2008) shows that the orbital motion by drill pipe reduces the critical velocity required to remove stationary cuttings bed. However, contribution by drill pipe rotation to improve cuttings transport reduces at higher flow rates. Effect of drill pipe rotation on cuttings transport is more significant in smaller annulus than larger annulus (Peden et al., 1990). Drill string rotation produces centrifugal action that may cause flow instabilities, such as Taylor vortices. This phenomenon is complex and highly unstable.

In deviated and high angle wells, the drill string is seldom concentric. Due to gravity, the drill string mostly lies on the lower side of the annulus. Due to eccentricity, the annulus is divided into a narrow and a wider region. In the narrow part of the annulus, fluid velocity is low, which causes the formation of cuttings bed. Experiments by Walker and Li (2000) showed that cuttings transport is difficult with eccentric string annulus and the velocities in the narrow region are low, causing settling of particles. As the viscosity increases, this effect further increases, as the drag forces on the liquid will reduce the velocity in the narrow gap. Also, the effect of drill pipe eccentricity is more prominent as the angle of inclination increases.

Cuttings Transport Comparison of Oil-based and Water-based Drilling fluids

Many researchers have been working with oil-based and water-based drilling fluids to understand and identify differences in their behaviour, but conclusions differ. Most of the conclusions were drawn from experimental investigations. Results from some studies contradict results from other studies. Some researchers have reported that oil-based drilling fluids with similar rheological properties as water-based drilling fluids behave similarly regarding hole cleaning, while other researchers have reported that hole cleaning performance of oil-based fluids and water-based fluids differ in spite of similar rheological properties.

Hareland et al. (1993) experimentally compared the cuttings transport performance of invert emulsion mineral-oil-based mud systems and water-base mud systems with similar rheological properties. Experiments were performed at various inclinations ranging from 0^o to 90^o on a 50% eccentric annulus of 40 ft. having 5 in. outer pipe and 2.125 in. inner pipe. The author reported that at higher inclinations, cuttings transport performance of oil-based and water-based drilling fluids were similar at lower yield point and plastic viscosity. At 40^o to 50^o inclinations, higher cuttings accumulation was observed with oil-based drilling fluids. They concluded that increased yield point and plastic viscosity results in decreased cuttings transport. They attributed higher yield point and plastic viscosity for the increase in the cuttings accumulation to the OBMs. Furthermore, severe bed sliding along the flow loop wall with OBMs leading to clumping of OBM cuttings contributed to reduced cuttings transport rate.

Hemphill and Larsen (1996) investigated hole cleaning capabilities of water-based and oil-based drilling fluids experimentally with similar rheological properties in the inclined annulus at varying fluid velocities. They compared cuttings transport capabilities of OBM and WBM with similar API YP value and yield-power law (τ) and found that both the fluids performed similarly across the angle spectrum 0^o to 90^o. They concluded that OBMs and WBMs with similar rheological properties and flow velocity profiles would clean similarly. In another test, they compared an OBM and a WBM with nearly equivalent densities, but with different yield-power law viscosity characteristics at intermediate angles. OBMs required slightly higher fluid velocities to clean similarly as WBMs at intermediate angles. They attributed bed sliding for the reduced hole cleaning performance of OBMs compared to WBMs. In their experiments with base oil and water, it was observed that water prevented the formation of cuttings bed at 45^o, 65^o and 85^o and the base oil required about 20 to 25 % more fluid velocity than water at the higher angles to achieve critical flow rates. Differences in the densities of water and base-oil could account for some of the difference in their performance.

Another experimental study by Seeberger et al. (1989) concluded that WBMs and OBMs having similar rheological properties are equally efficient at cuttings transport. They observed that the fluid viscosity at low shear rates and its initial gel strength are critical parameters to determine its hole cleaning ability. Their field study also concludes that OBMs are deficient in cleaning large diameter, high angle holes.

In contrast to the above studies, study by Saasen and Løklingholm (2002) shows that OBMs have better performance when compared to the WBMs in spite of having similar viscosity profiles. They claimed that the method of constructing the drilling fluids cause the difference in their behavior. This was especially true for cuttings bed properties. WBM formed a more consolidated bed as compared to OBM. This is because of the use of polymers in the construction of WBMs. In WBM, water can react with the cuttings and form a gel in the cuttings bed. For better hole cleaning the gel formed should not resist a large strain and it should be broken easily. Certain large polymers are added to the WBM during its construction, which creates strong resistive gels and are difficult to shear degrade. Whereas in OBM, the continuous phase is oil and there is no contact between the cuttings and the emulsified water. They suggest the use of high molecular weight polymers only for preventing barite sag and use of shorter polymers for further viscosification of drilling fluid to prevent the formation of a strong cuttings bed gel.

1.3 Objective

Limited studies are available where oil-based drilling fluids and water-based drilling fluids with similar viscosity profiles are tested under identical conditions, in order to understand the difference in their hole cleaning behavior. Field experience shows that drilling ROP improves with the use of oil-based drilling fluids. It is believed that oil-based drilling fluids provide superior hole cleaning performance to water-based drilling fluids. There are very few studies performed to understand this, and conclusions from the investigations differ. It is also not understood if the superior performance of oil-based drilling fluids to water-based drilling fluids is because of fluids hole-cleaning ability or because of other reasons like fluid's interaction with the formation.

The main objective of this project has been to contribute to the optimal planning of drilling operations with respect to choice and use of drilling fluids, and in particular with respect to hole cleaning performance. The objective of this PhD study was to investigate hole cleaning performance of oil-based and water-based drilling fluids. This was done by a systematic study of oil-based and water-based drilling fluids under controlled conditions. A study includes:

- Systematic investigations in flow loop of water-based and oil-based muds (WBM and OBM) under identical conditions
- Rheological characterization of oil-based and water-based muds

This project tested fluids under conditions close to realistic field conditions, like eccentric annulus, realistic drilling fluids, realistic flow velocities, and drill string rotation. Also, in this project, hydraulic and cutting transport studies at various fluid and operational parameters were performed, those which have the most influence on its behavior. Also, knowledge from rheological investigations of fluids has been combined with the flow loop investigations for better understanding of the hole cleaning behavior of the fluids. Wherever applicable, analytical methods have been used for better understanding of the phenomena observed in the flow loop experiments. In addition, a CFD model of the flow loop has also been modeled. Results from the flow loop experiments were compared with the results from the CFD simulations. Clearly, the identification of the differences in performance of OBM and WBM determined at controlled flow loop conditions will increase the understanding of the fluids behavior and enable the development of improved drilling fluids, both operationally and environmentally, for both oil-based and water-based fluids.

2 Experimental

This chapter presents a detail description of the experimental setup, experimental procedures and details of the drilling fluids used in our investigations.

Experiments were conducted in two parts. The first part included testing of OBMs and the second part included testing of WBMs with nearly similar viscosity profiles as the OBMs. Three oil-based muds and one water-based mud were tested in our experiments. More experiments with water-based muds could not be performed due to practical difficulties with our lab setup. Testing of one OBM and one WBM with similar viscosity profile was considered sufficient for testing hypothesis as described in the Chapter 1.

2.1 Fluids Tested

Fluids tested in the flow loop included three oil-based drilling fluids named OBMA, OBMB and OBMC and one inhibitive water-based drilling fluid named KCl. These fluids are industrial fluids used in Norwegian offshore fields. These fluids were then cleaned, conditioned and provided to us by MI-Swaco for our research activities. The three OBMs are variations of an industrial fluid Versatec of density 1.28 g/cm^3 and 1.5 g/cm^3. OBMA with density 1.11 g/cm^3 is Versatec 1.28 g/cm^3 fluid diluted with base oil EDC 95/11. OBMB with density 1.27 g/ cm^3 is OBMA fluid mixed with Versatec 1.5 g/cm^3. In order to create a have high viscosity fluid, the organophilic clay Bentone 128 was added to OBMB, which is named as OBMC. These adjustments to the drilling fluids were made to deal with certain practical issues related to the fluid handling and filtration system. Water-based fluid KCl is an industrial fluid Glydril which was also provided by MI-Swaco. For our research purpose, KCl fluid was adjusted to match viscosity profile of OBMB fluid within the shear rate ranges occurring in the flow loop. However, the viscosity could not be matched at all shear rates measured following the API 13D/ISO standard 10414. Here, τ and τ_y are shear stress and yield stress respectively, γ is shear rate, *K* and *n* are viscosity consistency index and flow behavior index respectively

Table 1 presents composition and oil-water ratio of all drilling fluids. The Herschel- Bulkley parameters of the drilling fluids were obtained by a least squares fit to Anton Paar rheometry data and are listed in Table 2 along with resulting Herschel-Bulkley parameters.

The rheology of the non-Newtonian drilling fluids is described by the Herschel–Bulkley model,

$$\tau = \tau_y + K\gamma^n \qquad (1)$$

Here, τ and τ_y are shear stress and yield stress respectively, γ is shear rate, *K* and *n* are viscosity consistency index and flow behavior index respectively

Table 1. Composition of OBMA, OBMB, OBMC, and KCl

Composition			
OBMA	**OBMB**	**OBMC**	**WBM (KCl)**
Base oil EDC 95-11 Barite Organophilic clay (Bentonite) Salt ($CaCl_2$) Lime ($Ca(OH)_2$) Emulsifier Fluid loss agent Oil-water ratio 80/20	Base oil EDC 95-11 Barite Organophilic clay (Bentonite) Salt ($CaCl_2$) Lime ($Ca(OH)_2$) Emulsifier Fluid loss agent Oil-water ratio 80/20	Base oil EDC 95-11 Barite Organophilic clay (Bentonite) Salt ($CaCl_2$) Lime ($Ca(OH)_2$) Emulsifier Fluid loss agent Bentone 128 Oil-water ratio 95/5	Fresh water KCl Xanthum gum Polyanionic cellulose Glycol Starch Soda ash Barite Not applicable

Table 2. Properties of OBMA, OBMB, OBMC, and KCl

Property	**K [Pa*s]**	**n [-]**	**τ_y [pa]**	**Density [kgm^{-3}]**
OBM A	0.038828	0.88	1.6155	1113
OBM B	0.062122	0.8759	1.73073	1270
OBM C	0.144892	0.8285	2.83713	1270
KCl	1.0362	0.42975	0	1188

Flow curves of the tested fluids OBMA, OBMB, OBMC and KCl are shown in Figure 2 and Figure 3. The shear rates encountered in the flow loop and in field conditions are below about 400 $\frac{1}{s}$. Within that shear rate range, viscosity profiles of the drilling fluids OBMB and KCl are similar as seen from the Figure 4. Vertical lines in the Figure 4 indicate the maximum shear rates occurring in typical boreholes with $5\frac{1}{2}$" drill pipe and $12\frac{1}{4}$" and $8\frac{1}{2}$" bit. These shear rates are included to show what flow velocities and shear rates are commonly found at relevant hole sizes, pump rates, and drill pipe size. It is included so that results from flow loop campaign and fluid lab, presented later for various annular velocities and shear rates, can be related to relevant drilling conditions.

The wall shear rates for laminar flow in a concentric annulus (narrow slot approximation) can be calculated using equation 2 that was used by for example by (Saasen, 2014). This equation holds true for power law fluids but are not valid for yield stress fluids and eccentricity. However, as the contribution of drill pipe rotation to the shear rate is much smaller than the contribution from the axial flow, the values shown in Figure 3 were calculated using $\omega = 0$.

$$\dot{\gamma} = \left[\left(\frac{12U}{(\mathrm{d}_o - \mathrm{d}_i)} \frac{2n+1}{3n} \right)^2 + \left(\frac{\omega R_i}{(\mathrm{R}_o - \mathrm{R}_i)} \right)^2 \right]^{\frac{1}{2}} \tag{2}$$

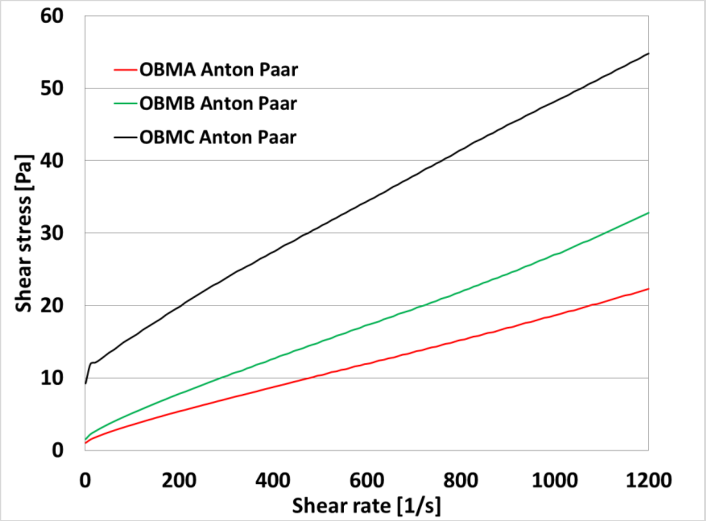

Figure 2. Flow curves of OBMA, OBMB and OBMC fluids for full shear rate range covered by measurements performed in accordance with API 13D/ISO standard at 28°C

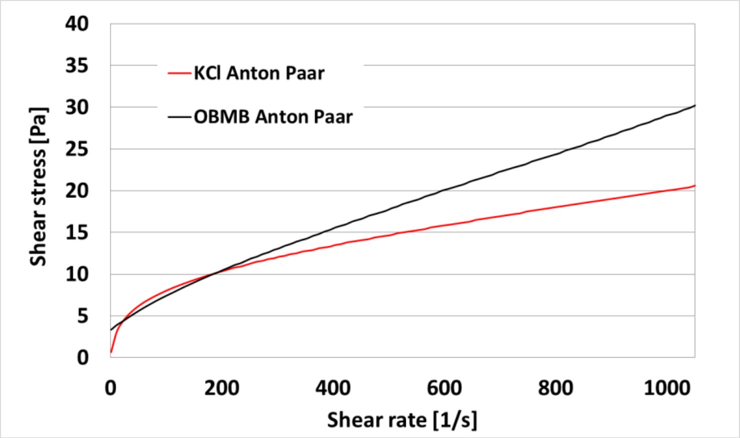

Figure 3. Flow curves of OBMB and KCl fluids for full shear rate range covered by measurements performed in accordance with API 13D/ISO standard at 28°C

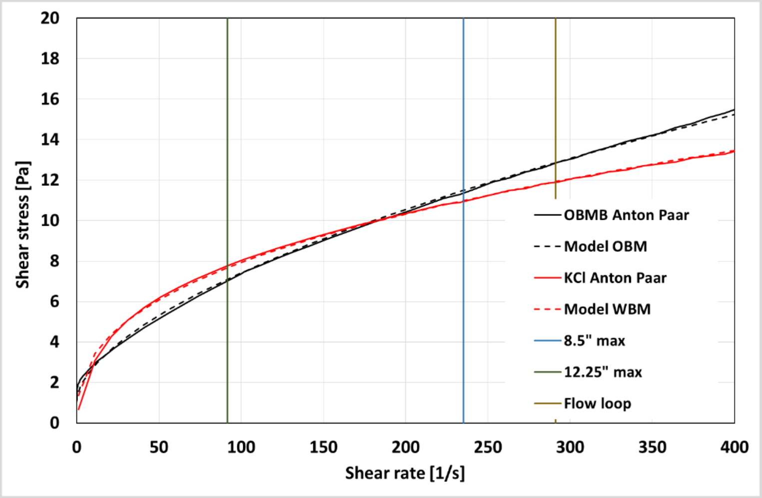

Figure 4. Measured (at 28 °C) and calculated flow curves of KCl and OBMB. Vertical lines indicate corresponding wall shear rates for OBMB flow in our flow loop (at 1 m/s), in an 5.5" by 8.5" annulus at 1.41 m/s (1800 lpm), and in an 5.5" by 12.25" annulus at 1.24 m/s (4500 lpm).

2.2 Experimental Setup

Experiments to study hydraulic behaviour and hole cleaning behaviour of various drilling fluids are performed on an advanced purpose-built flow rig. A schematic diagram of the experimental facility along with the circular concrete sections used inside the test section is presented in Figure 5. The experimental drilling rig was constructed for testing and comparing circular and non-circular wellbore geometries with respect to hydraulics, cuttings transport and friction (Taghipour et al., 2014). The flow rig consists of a 10 m long test section, a processing unit (sand injection, sand separation, fluid storage tanks and pumps), connecting hoses, valves, and instrumentation (see Figure 6).

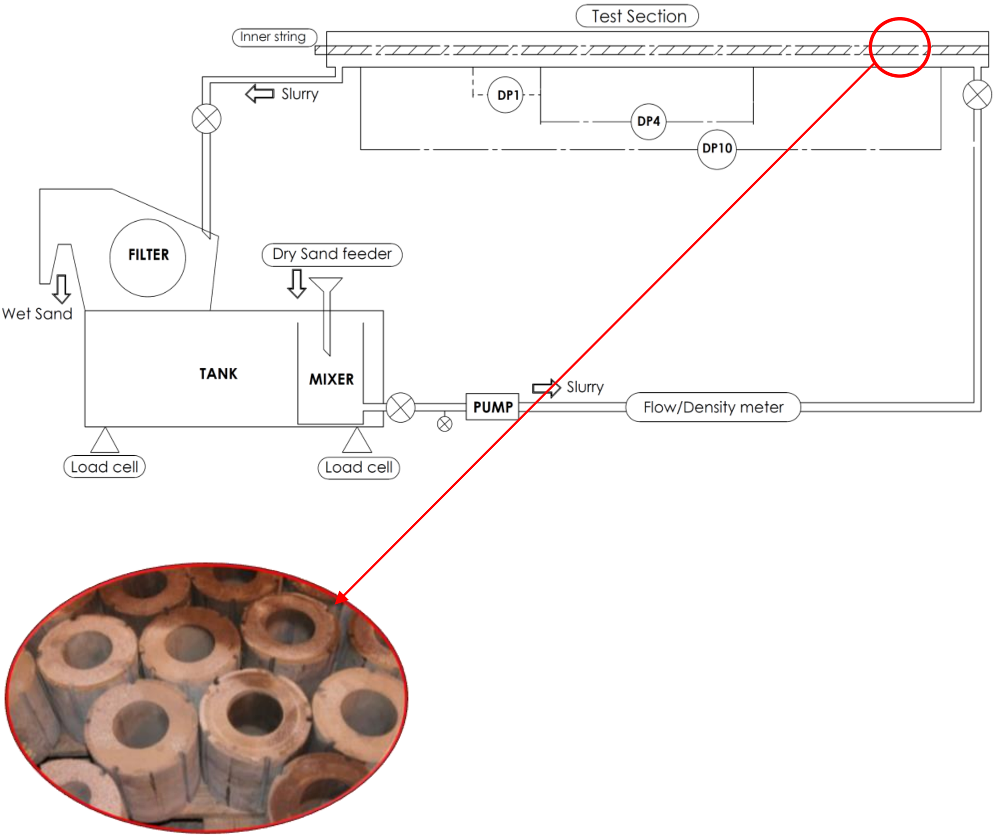

Figure 5. Schematic of the flow loop system (top) and concrete elements (bottom)

The 10 m long test section consists of replaceable hollow cylindrical elements of concrete with an inner diameter of 100 mm representing the wellbore (see Figure 5) and a steel rod of 50 mm diameter, representing a drill string. One end of the rod is connected to a drive motor to simulate a variable speed system. The rod is supported laterally at both ends using universal flexible joints allowing free whirling (lateral) motion within the constraints of the wellbore. Movement of the drill string in the axial direction is constrained. Thus, the drill string is fully eccentric due to the gravity of the drill string. The flow loop is supported by a metal structure which can be tilted to an angle of 30^{o} from horizontal. A transparent section is placed in the middle of the test section to visualize the formation of the cuttings bed. However, drilling fluids used in our study are opaque, which makes visual measurements difficult.

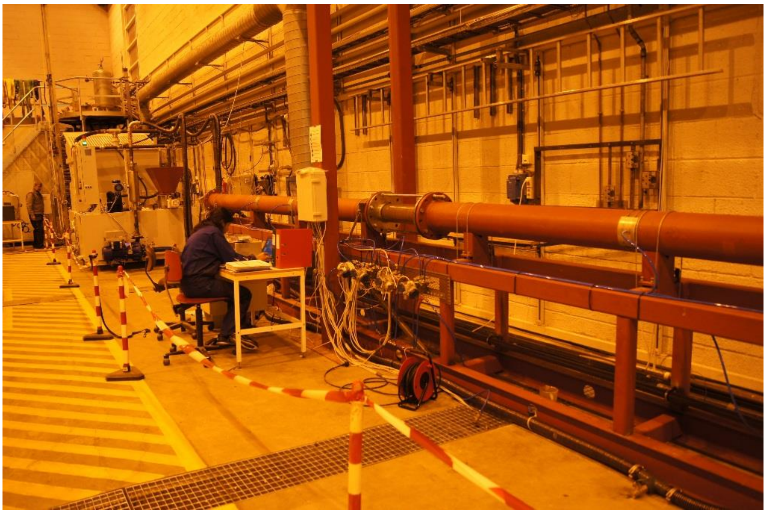

Figure 6. Purpose-built flow rig

Instrumentation includes a Coriolis flow meter and two differential pressure (DP) transducers connected to the logging system. The flow rate and the density are monitored with the Coriolis flow meter. The temperature is maintained using the heating elements in the fluid tank and is monitored continuously. Differential pressure cells measure differential pressure between pressure ports which are located at positions 3 m, 7 m and 8 m from the inlet. DP cell measurements (DP1815) which measure the pressure difference between ports at 3 m and 7 m location are reported in the thesis. The DP transducers are flushed regularly before each experiment to ensure that there are no air bubbles in the test section. Test parameters like flow rate, rotation rate, temperature, density and frictional pressure loss are displayed and recorded by a data acquisition and control system Labview. A sand injection system is calibrated to a preset sand rate. The outlet of the test section is connected to a sand separator unit, where the fluid and sand gets separated. The fluid storage system is capable of holding 5 m^3 of drilling fluid (see Figure 7). Load cells under the processing unit are used to measure the variation in weight due to the corresponding variation in the amount of sand in the test section. Thus, the cuttings holdup in the system could be calculated versus time. The loop is designed for ambient pressure and temperature conditions, which was considered sufficient for the purpose of this investigation, and is much less expensive than performing experiments at reservoir conditions.

Figure 7. Fluid storage unit, filtration unit and sand unit

2.3 Experimental Procedure

The experimental procedure of the flow loop study is as follows:

Hydraulic study:

- The fluid to be tested is circulated by the pump through the flow loop at a desired flow rate
- Pressure drop measurements are made at steady state conditions using the available pressure transducers
- To observe the effect of rotation on pressure drop, the drill string is rotated at a desired rotational speed. Rotational speed is maintained until steady state flow conditions are established. Pressure drop measurements at a particular drill string rotational speed are made at steady state conditions
- Test procedure is repeated at various flow rates and drill string rotational speeds and pressure drop measurements are made

Cuttings transport study:

- The fluid to be tested is circulated by the pump through the flow loop at a desired flow rate

- Cuttings are then injected at a calibrated rate into the flow upstream of the test section using a dry sand feeder and are separated from the recirculating fluid in the processing unit
- Experiment is run until steady state condition is reached. Weight of the sand in the test section is continuously measured. Initially, the amount of sand entering the test section will be greater than the amount of sand leaving the system. After a certain time, the amount of sand entering and leaving the test section will be the same. This is considered as a steady state condition. The amount of sand left in the test section indicates formation of the cuttings bed
- To study the effect of rotation, a desired drill string rotational speed is set and experiment is run till a steady state condition is reached
- At the end of the experiment, cuttings injection is stopped and the flow rate along with the rotation is continued till the hole is clean
- Experiments are repeated with another set of operational parameters
- Throughout the experiment pressure drop measurements using available pressure transducers are made. Weight of the fluid storage system along with the sand injection unit is continuously monitored, to be able to calculate the amount of sand in the test section
- Sand bed formation could not be visualized due to the opacity of the fluids. In this study, sand holdup is used to compare the hole cleaning efficiencies of fluids. Sand bed holdup is defined as the average amount of the sand left in the test section over the length of the section, at the end of the experiment. The weight of the fluid and sand handling system is measured throughout the experiment and the difference of the weight before and after experiments indicates the amount of sand left in the flow loop. The sand bed holdup was determined by averaging the mass of sand in the flow loop over the length of the section, assuming all sand to be in a bed with an assumed constant porosity. However, it is not possible to distinguish between a stationary cuttings bed and transported cuttings with this measurement

During a particular test case with OBMA at 0.75 m/s flow velocity, plot showing variation of tank weight and pressure drop with time is shown in the Figure 8 and plot showing variation of tank weight and drill string rotational speed with time is shown in Figure 9.

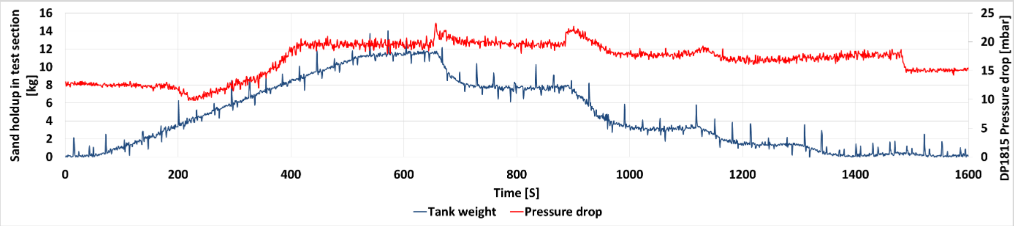

Figure 8. Variation of tank weight and pressure drop with time in a test case with OBMA at 0.75 m/s

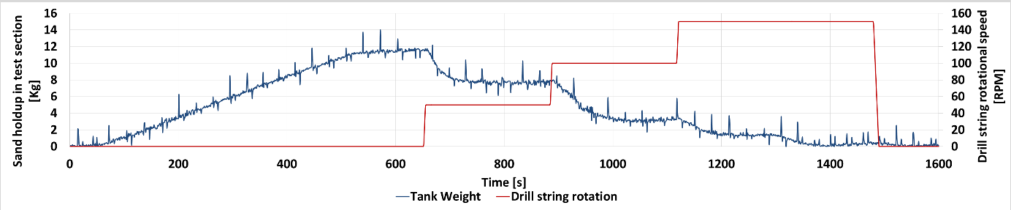

Figure 9. Variation of tank weight and drill string rotational speed with time in a test case with OBMA at 0.75 m/s

To ensure that the fluids are stable over time and that the measurements made are reliable, Fann viscometer measurements and emulsion stability (ES) measurements (for the OBM) were done on a daily basis. The stable readings from the ES meter confirmed that the emulsions of the OBM were stable throughout the tests. To confirm the reliability of the results, some experiments were also repeated. A stable temperature of 28°C was maintained throughout the tests and all the experiments were made at this temperature. Viscometric measurements were conducted both with Anton Paar and with Fann 35 viscometers, at the same temperature as the flow loop experiments.

2.4 Test Parameters for Flow-Loop Experiments

The chosen sand rate represents a typical averaged ROP value in the field. The flow rates and drill string rotation rates were chosen to cover typical operational ranges.

- Flow velocities of 0.55/0.5, 0.75/0.7, 1.0 and 1.2/1.1 m/s for OBM/WBM
- Drill string rotational speeds of 0, 50, 100 and 150 RPM
- Sand rate of 43 g/s and 86 g/s corresponding to a ROP of 8 m/hr and 16 m/hr
- Quartz sand particles from Dansand A/S were used in the experiments with their size ranging from 0.9 to 1.6 mm to represent cuttings

3 Hole-Cleaning Behavior Comparison of Oil-Based Muds

The effect of various parameters on hole cleaning are presented in this chapter. Flow loop experiments are performed with three OBM's with varying viscosity and density and the results from the investigations are discussed in this chapter. These experiments are conducted to study hydraulic behavior and cuttings transport behaviour of fluids and the influence of various parameters on its behaviour. Hydraulic results are from the experiments in the absence of sand whereas cuttings transport results are from the studies with sand injection. Composition, flow curves of the three fluids were presented and Herschel-Bulkley parameters of fluids tested were presented in chapter 2. Herschel-Bulkley parameters of OBMS' are presented again in Table 3 for reference. Among the three-tested OBM's, OBMC fluid has the highest viscosity and OBMA has the lowest viscosity. OBMA also has the least density among the three OBM's. The densities of OBMB and OBMC are nearly the same.

Table 3. Herschel-Bulkley parameters of OBMA, OBMB, OBMC

Property	**K [Pa*s]**	**n [-]**	**τ_y [pa]**	**Density [kgm^{-3}]**
OBM A	0.038828	0.88	1.6155	1113
OBM B	0.062122	0.8759	1.73073	1270
OBM C	0.144892	0.8285	2.83713	1270

Hydraulics results and cuttings transport results from the flow loop studies are presented in section 3.1. All the presented values are time averaged values over a time period of 30 s of steady state conditions.

3.1 Hydraulics

Figure 10 presents a comparison of pressure drop over a length of 4 m for the three oil-based drilling fluids OBMA, OBMB and OBMC for non-rotating and rotating string. Pressure gradient values of OBMC are higher than for OBMB and OBMA at all flow rates, mainly because of its higher yield stress. Pressure gradient increases with string rotation speed and flow rate. This effect can be seen for all the three OBM's.

The effect of drill string rotation is seen to be greatest for OBM A, see Figure 11, but for all fluids, the pressure gradient increases with rotation. For all the fluids the power-law index is relatively large, i.e. the shear-thinning effect is small. Furthermore, the string is fully eccentric with free lateral movement during rotation. Both these factors will cause an increase in pressure gradient, i.e. inertial effects will dominate over shear thinning effects. However, it is not obvious why the effect is so much larger for OBM A. Since this difference is seen for all flow rates, it cannot be explained as a result of turbulence alone.

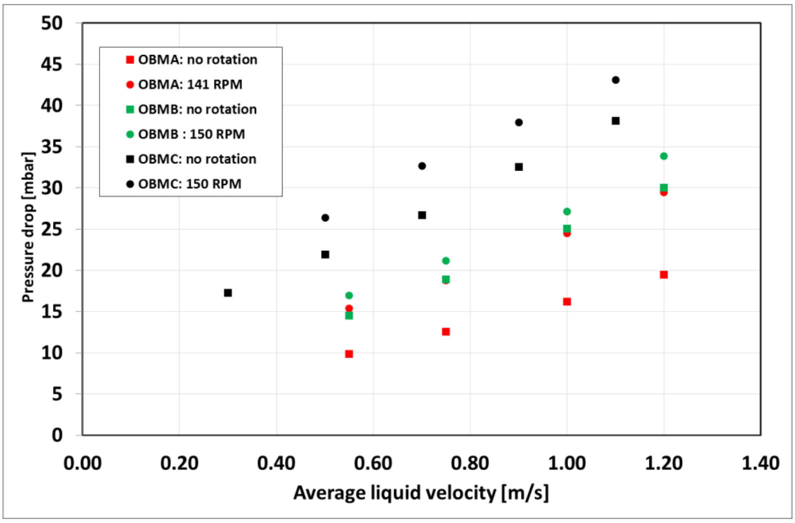

Figure 10. Pressure drop versus flow rate for OBMA, OBMB and OBMC with and without rotation

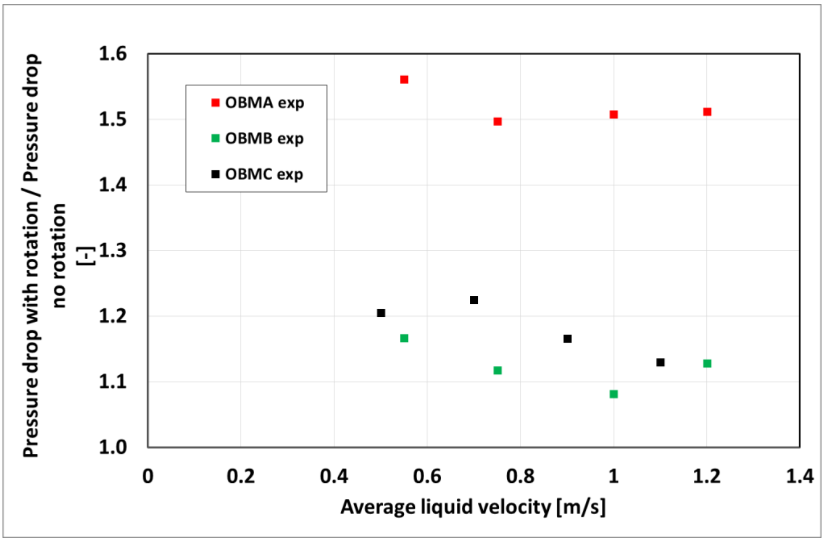

Figure 11. Effect of rotation on pressure drop versus flow rate for OBMA (141 RPM), OBMB (150 RPM) and OBMC (150 RPM)

Several researchers observed different trends of pressure loss changes with the inclusion of drill string rotation (Ahmed and Miska, 2008; Erge et al., 2014; Saasen, 2014). Hansen et al. (1999) and (Sterri et al., 2000) observed that pressure drop increases with the increase in drill string rotation while the reverse behavior was reported by Hansen and Sterri (1995). Saasen (2014) presented a comparison of several field and theoretical studies. Transverse motion of drill string increases the pressure gradient in annular flow. Wan et al. (2000) showed this for the case of laminar flow, demonstrating the competing effects of shear thinning and inertial effects with inner pipe rotation. However, in highly eccentric annuli, they found that inertial effects dominate, resulting in monotonous increase in pressure loss as the rotation speed increases. This agrees qualitatively with our experimental results. The Reynolds numbers calculated in the section below indicate that the flow is laminar, except for OBM A at the largest flow rate (1.2 m/s) where transitional or turbulent flow is indicated.

An analytical solution for eccentric annular flow is only available for Newtonian fluids, whereas analytical solutions for non-Newtonian Herschel-Bulkley type fluids are difficult to develop. In both cases i.e., for Newtonian and non-Newtonian, rotation of the drill string produces centrifugal action that may cause flow instabilities, such as Taylor vortices. Theoretical analysis of helical flow in an eccentric annulus is very challenging. To facilitate the interpretation of the experimental data, we have calculated the Reynolds number and Taylors number for a concentric annulus using the power law model with parameter values from the Fann viscometer measurements (see Table 2) (Escudier et al., 2002).

A characteristic viscosity μ_F is evaluated at a characteristic shear rate that was used by for example Escudier et al. (2002):

$$\dot{\gamma}_F = \frac{1}{2}\sqrt{\left(\frac{U}{\delta}\right)^2 + \left(\frac{\omega R_i}{\delta}\right)^2} \tag{3}$$

Where U is the bulk axial velocity, ω is the angular velocity of inner cylinder, R_i is the outer radius of drill pipe.

The Reynolds number in absence of rotation is defined as

$$\mathrm{Re}(\omega = 0) \equiv \mathrm{Re}_0 = \frac{\rho U^{2-n} D_H^n}{K} \tag{4}$$

Where D_H is the hydraulic diameter, n is the power law index and K is the corresponding consistency index.

The Taylor number in absence of axial flow is defined as

$$Ta(U=0) \equiv Ta_0 = \frac{1}{8}\left(\rho\frac{\omega^{2-n}}{K}\right)^2 D_H^{2n+1} R_i^{3-2n} \tag{5}$$

In the general case, define

$$\begin{aligned} \mathrm{Re}(\omega \neq 0) &= \left(1+\xi^2\right)^{(1-n)/2} \mathrm{Re}_0 \\ Ta(U \neq 0) &= \left(1+\xi^{-2}\right)^{1-n} Ta_0 \end{aligned} \tag{6}$$

Where

$$\xi \equiv \frac{\omega R_i}{U}$$

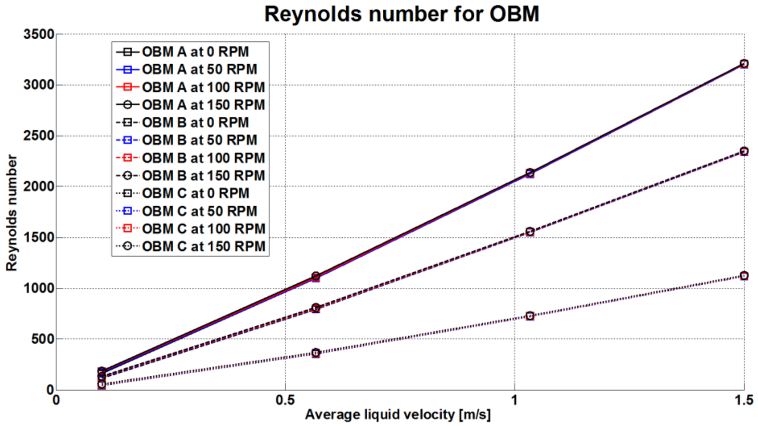

Figure 12. Reynolds number variation with average liquid velocity for OBM A (upper curves), OBM B (middle curves) and OBM C (lower curves)

From Figure 12 we notice that there is not much change in the Reynolds number when rotational effects are included. Since we observe a significant effect of rotation on pressure gradient (Figure 10) the Reynolds number as defined here is not sufficient to characterize the pressure gradient with rotation. Also, we notice that the Taylor numbers (see Figure 13) are well above the critical Taylor number for Newtonian fluids in a concentric annulus (Tac ≈ 1700). However, both axial flow and eccentricity tend to stabilize flow with respect to Taylor vortices (Koschmieder, 1976; Lockett et al., 1993). Lockett et al. (1993) presented results from computer simulations showing that the critical Taylor number increases rapidly as the eccentricity increases, at a rate which is only marginally dependent on the non-Newtonian character of the fluid. However, results were presented only for eccentricities up to 0.55 and not including the effect of axial flow. No numerical or experimental investigations of Taylor instabilities in fully eccentric annulus without or with axial flow are widely known.

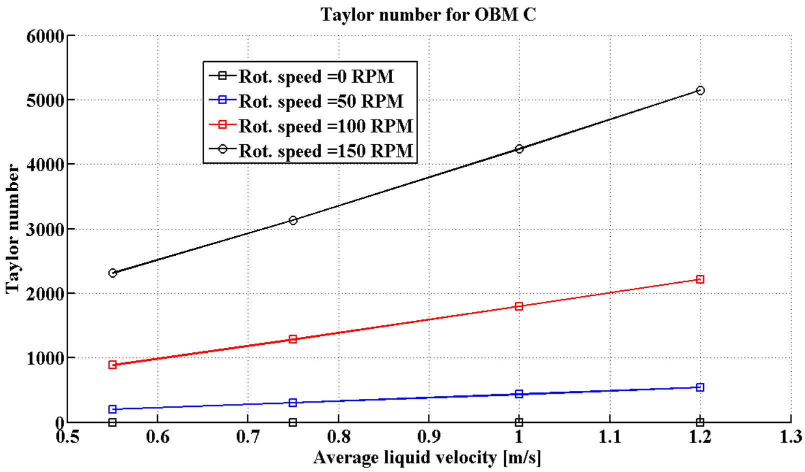

Figure 13. Taylor number variation with average liquid velocity at various string rotational speeds for OBMC

3.2 Cuttings Transport

3.2.1 Fluid Velocity Effects on Hole Cleaning

Figure 14 - Figure 17 shows a comparison of sand holdup of three oil-based drilling fluids OBMA, OBMB and OBMC at various velocities, and at various rotational speeds. The results here clearly demonstrate the positive effect of flow velocity on the removal of particles from the sand bed, as it can be seen in all the four figures. As the fluid velocity increases, sand holdup for all the three fluids decreases. Fluid velocity has greater effect on OBMA. At higher fluid velocities, sand holdup with OBMA without drill pipe rotation is less than 5% and it is the least one among the three fluids. Undoubtedly, annular velocity is reported in the literature to have a greater impact on cuttings transport and the same has been observed from over experimental investigations.

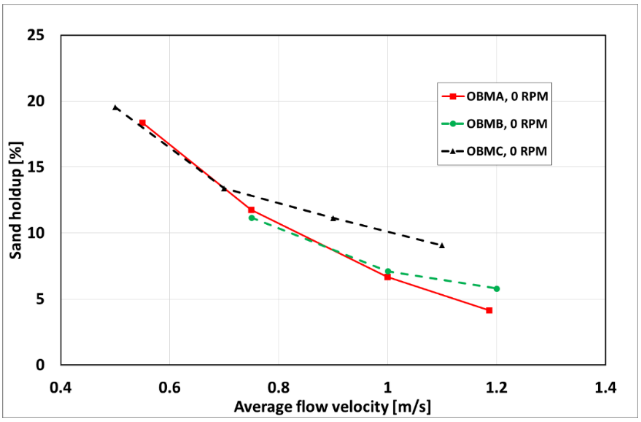

Figure 14. Measured sand bed holdup versus flow rate for OBMA, OBMB and OBMC without string rotation

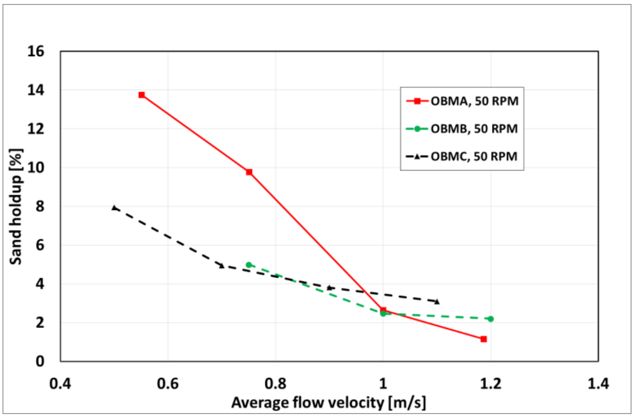

Figure 15. Measured sand bed holdup versus flow rate for OBMA, OBMB and OBMC with 50 RPM string rotation

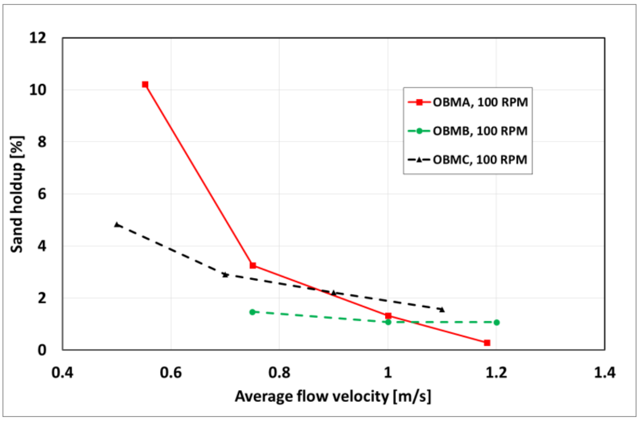

Figure 16. Measured sand bed holdup versus flow rate for OBMA, OBMB and OBMC with 100 RPM string rotation

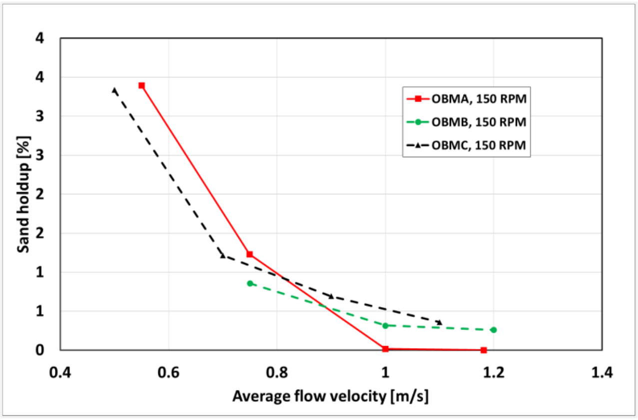

Figure 17. Measured sand bed holdup versus flow rate for OBMA, OBMB and OBMC with 150 RPM string rotation

In the following we shall compare our experimental data for non-rotating string to the predictions of a bedload transport model, making assumptions as required.

According to bedload transport theories for unconsolidated particles, the transport rate is only dependent on the shear stress at the bed surface, described in non-dimensional units in terms of the Shields number θ (Shields, 1936), which is the ratio of τ_b over the buoyed weight of a single particle. This can be expressed in dimensionless form through the Shield's number

$$\theta = \frac{\tau_b}{\left(\rho_s - \rho_f\right) g d_s} \tag{7}$$

For a fully eccentric annulus with a sand bed at the bottom we make a rough estimate of the shear stress at the bed as being equal to the average wall shear stress around the perimeter.

$$\tau_b \approx \tau_{avg} = \left|\frac{dp}{dx}\right| \frac{A}{P} \tag{8}$$

The flowing area A and the wetted perimeter P can be calculated from the sand bed holdup H_b and the eccentricity e.

Hydraulics theories of bedload transport provide a relationship between the volumetric sand rate per unit width q_b and the Shield's number.

Using the model (Beek and Van, 1976; Meyer-Peter and Müller, 1948)

$$\frac{q_b}{q_{ref}} \equiv \Phi = a\left(\theta - \theta_c\right)^b \tag{9}$$

With a = 5.7 and b = 1.5 and

$$q_{ref} = d_s\sqrt{\left(\rho_s/\rho_f - 1\right)gd_s} \tag{10}$$

The rate q_b is related to the bedload sand mass rate by

$$G_b = S_b q_b \rho_s \tag{11}$$

We assume that all sand is transported in the bed, i.e.

$$G_b \approx G_m \tag{12}$$

Here G_b is the sand mass transport rate (in our experiments 43 g/s), G_m is the measured sand mass rate and the other symbols are given in the nomenclature.

We can back-calculate the shear stress τ_b on the cuttings bed using the known holdup and the known cuttings transport rate. This shear stress will then be compared with the average wall shear stress $\tau_{w,avg}$ which is calculated from the pressure drop and the sand bed holdup. The bed shear stress τ_b will of course in general be different from $\tau_{w,avg}$. However, we may assume that the difference will not be significantly different for the different fluids at a given flow rate. The results are shown in Figure 18. The model predicts a bed shear stress which is about the same for all three fluids, but increasing with flow rate. Except for the lowest flow rate, the experimental data also show an increase in wall shear stress with increasing flow rate. The minimum can be attributed to the competing effects of flow area and flow rate on the pressure loss. Furthermore, we notice that the experimental results for OBM A and B are fairly similar, and consistently lower than the model prediction, whereas OBM C stands out; average experimental wall shear stresses are almost twice those of the other two fluids.

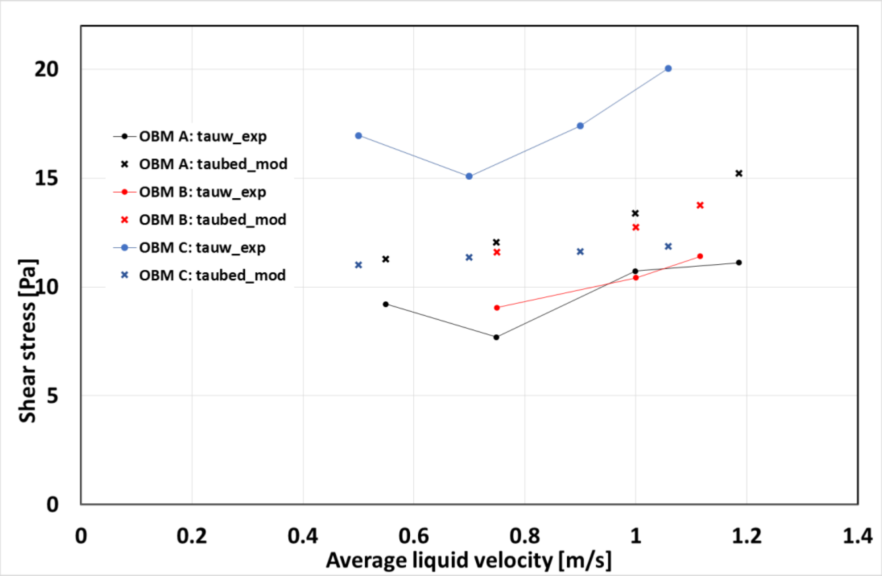

Figure 18. Predicted bed shear stress (taubed_mod) and measured average wall shear stress (tauw_exp) versus flow rate for OBMA, OBMB and OBMC with non-rotating string

3.2.2 Pipe Rotation Effects on Hole Cleaning

Another important parameter, which has a significant impact on hole cleaning is drill pipe rotation. Figure 20 demonstrates the positive effect of drill pipe rotation on cuttings transport. As seen from Figure 14 - Figure 17 , drill pipe rotation has significant effect on cuttings sand bed holdup at all the flow rates for all three drilling fluids. With the drill pipe rotation, sand bed holdup at a particular flow rate decreased compared to the sand bed holdup at the same flow rate without drill pipe rotation. At low flow rates the effect of string rotation is significantly better for OBM C than for OBM A (Figure 19). At high flow rates (Figure 20), the hole cleaning performance of OBM A and OBM B are quite similar and better than that of OBM C. It can also be observed that, the effect of drill pipe rotation is more at lower flow rates than at higher flow rates. For all three fluids the effect of rotation seems to diminish for increasing rotation rates. A similar trend was found in experiments by Ozbayoglu et al. (2008) (Figure 3). Saasen (1998) noted that "If the bed has been formed in an oil-based drilling fluid which has no gel structure that connects the cuttings particles, pipe rotation has little effect on hole cleaning". Here we do see a significant effect of rotation on hole cleaning. We postulate that this is due to the fact that the fluids we have used do have finite yield stress levels and that the fluids build a gel structure in the cuttings bed; a gel structure which is broken by the string rotation. Since the string is free whirling, the rotation also will be accompanied with some lateral movement which aids breaking the gel structure. The results presented here indicate that OBM C builds a stronger gel structure than the other two fluids. Gel strength measurements are done as part of rheological study (Werner et al., 2016). This is based both on the results for non-rotating string (Figure 18) which indicate that OBM C needs a larger shear stress to transport the cuttings, and is exposed to a greater effect of rotation on hole cleaning for OBM C (see e.g. Figure 19).

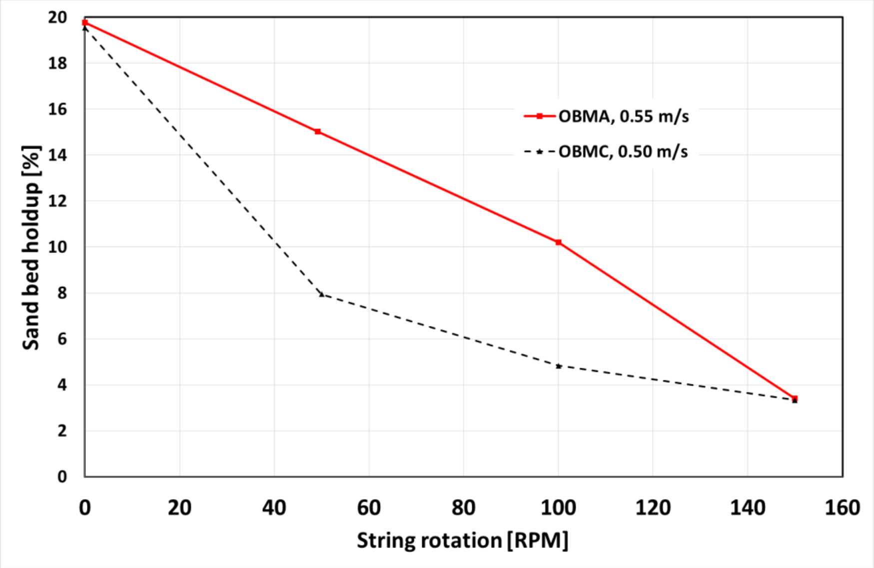

Figure 19. Measured sand bed holdup versus string rotation for OBMA and OBMC at low flow rates

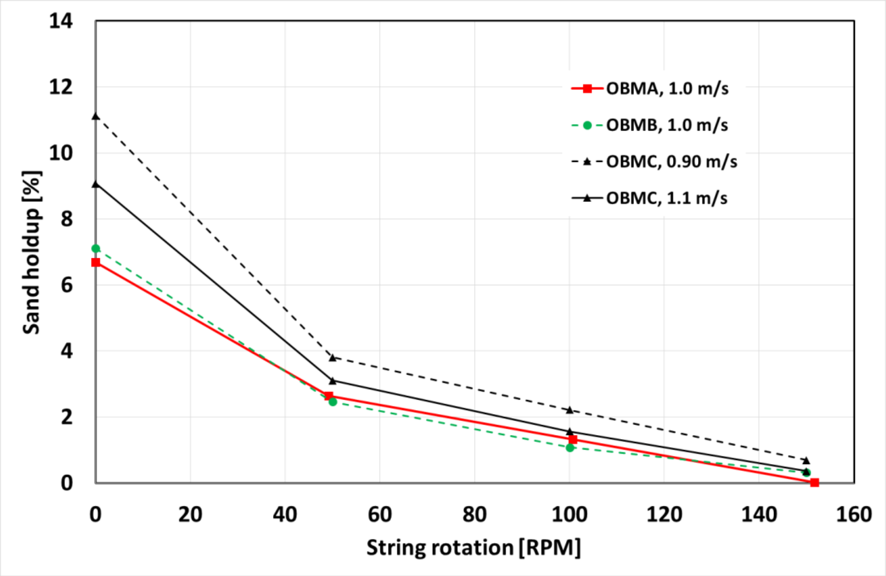

Figure 20. Measured sand bed holdup versus string rotation for OBMA, OBM B and OBMC at high flow rate

3.2.3 Rate of Penetration Effects on Hole Cleaning

Figure 21 shows the effect of ROP on cuttings transport for OBMA at various flow rates. Experiments were conducted at 43 g/s and 86 g/s sand rate corresponding to 8 m/hr and 16 m/hr ROP for all the three OBM's. From the Figure 21 there is no major increase in the sand holdup with the increase of sand rate at both the conditions, with and without the drill pipe rotation. We can also notice that, the effect of drill pipe rotation on cuttings transport is higher at lower penetration rates compared to higher penetration rates. Increase in the sand rate also has effect on the frictional pressure drop. Frictional pressure drop is higher at higher rate of penetration for OBMA and at all the flow rates (see e.g. Figure 22). All the above effects of ROP on cuttings transport and frictional pressure drop were observed in OBMB and OBMC as well.

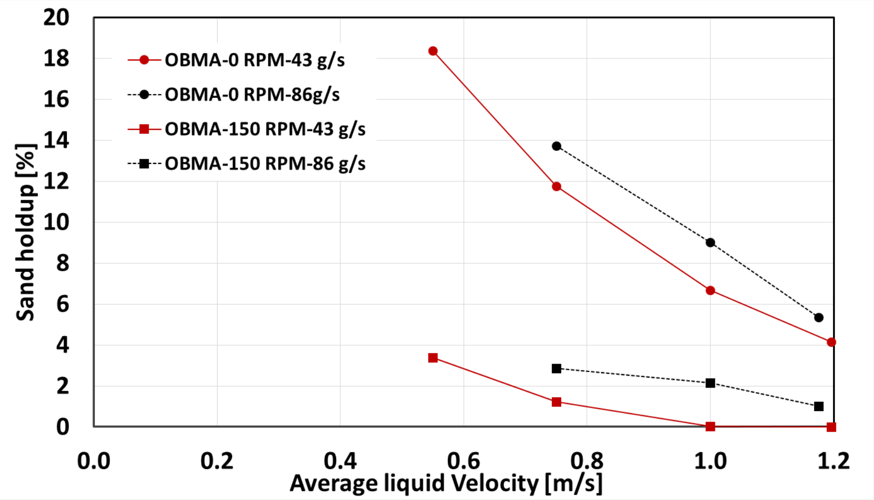

Figure 21. Measured sand bed holdup versus average liquid velocity for OBMA at 43 g/s and 86 g/s ROP and at 0 RPM and 150 RPM

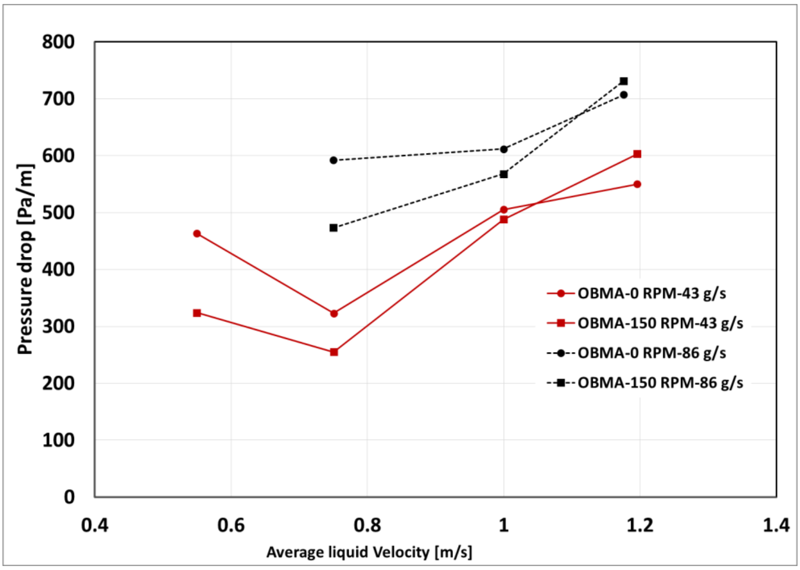

Figure 22. Pressure drop versus average liquid velocity for OBMA at 43 g/s and 86 g/s ROP and at 0 RPM and 150 RPM

3.2.4 Hole Inclination Effects on Hole Cleaning

Figure 23 presents a comparison of cuttings bed holdup of horizontal annulus and 60^o inclined annulus at various flow velocities and at 0 and 150 RPM drill string rotation. Experiments for testing the effect of inclination were conducted for OBMC fluid at 43 g/s ROP. Hole inclination has a slight effect on sand holdup at 90^o and 60^o inclined annulus both with and without drill string rotation. The effect further reduces at higher flow rates. Drill string rotation plays an important role even in an inclined annulus. Drill string rotation has significant effect on hole cleaning than inclination. Hole inclination has a greater effect on pressure drop as seen from Figure 24. Increase in the pressure drop for inclined annulus can be explained by the hydrostatic head effect. Pressure drop increases with inclination in the presence of particles.

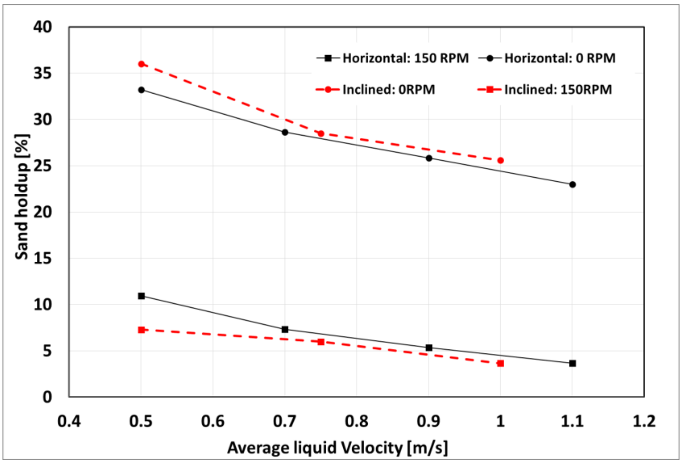

Figure 23. Measured sand bed holdup versus average liquid velocity for OBMC at 0 RPM and 150 RPM for horizontal and inclined annulus

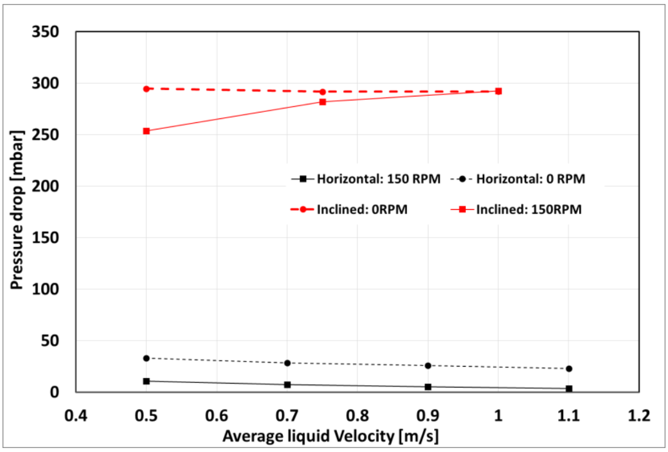

Figure 24. Pressure drop versus average liquid velocity for OBMC at 0 RPM and 150 RPM for horizontal and inclined annulus

4 Hole-Cleaning Performance Comparison of Oil-Based and Water-Based Drilling Fluids

This chapter presents the comparison of hydraulic behavior and hole cleaning performance of the oil-based drilling fluid OBMB and the water-based drilling fluid KCl with similar viscosity profiles. The Oil-based fluid OBMB will be referred to as OBM and the water-based fluid KCl will be referred to as WBM in the rest of this work. Composition, flow curves of fluids tested were presented and Herschel-Bulkley parameters of fluids tested are presented in chapter 2. Herschel-Bulkley parameters of fluids tested are presented again in Table 4 for reference.

Table 4. Herschel-Bulkley parameters of OBMB and KCl

Property	**K [Pa*s]**	**n [-]**	**τ_y [pa]**	**Density [kgm^{-3}]**
OBM B (OBM)	0.062122	0.8759	1.73073	1270
KCl (WBM)	1.0362	0.42975	0	1188

Results from flow loop experiments are presented in two sections. The first section includes results from experiments without the injection of sand and next section includes results from the experiments with injection of sand.

4.1 Hydraulics

Results to understand the hydraulic behavior of fluids in the absence of particles are presented in this section. Figure 25 shows a comparison of experimental pressure gradient with calculations using narrow slot approximation for laminar flow and the Herschel-Bulkley model with the parameters of Table 4. Here eccentricity was accounted for using the semi-empirical model by Haciislamoglu and Langlinais (1990). We notice that the model curves are sub-linear, due to the shear-thinning effect, while the experimental curves are close to linear.

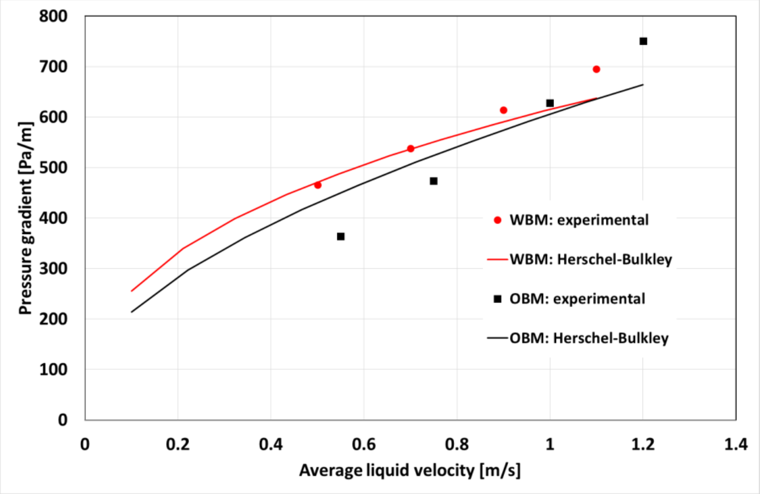

Figure 25. Comparison of experimental and calculated pressure gradient for WBM and OBM fluids at 0 RPM

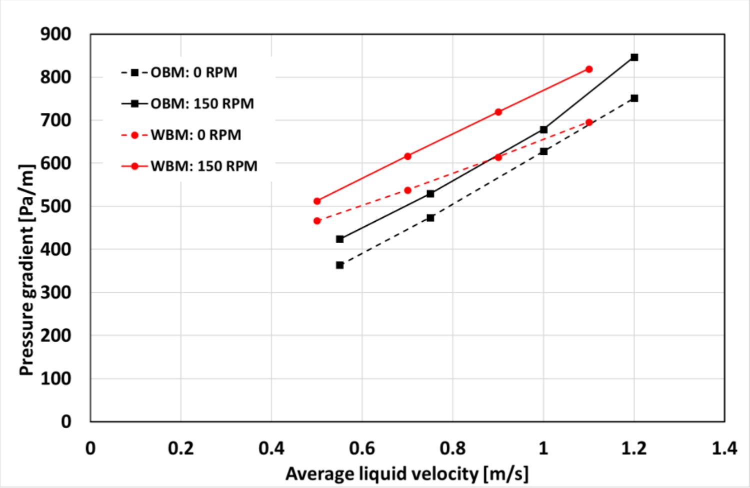

Figure 26. Observed pressure drop results (without sand) comparison for WBM and OBM

In Figure 26 a comparison of pressure drop (DP1815) measurements for OBM and WBM without and with the rotation of drill string is presented. The pressure gradient values for WBM are higher than OBM, though they have nearly similar density and viscosity profile. We notice that for both fluids there is a significant increase in pressure drop with 150 RPM string rotation compared with non-rotating string. For the OBM we observe that the pressure gradient increases more than linearly with string rotation, indicating an onset of turbulent activity. Since these fluids are shear-thinning we would expect the increase to be sub-linear in the laminar regime. In addition, rotation at 150 RPM increases the pressure gradient for a given flow rate, and this effect increases also with flow rate. This effect has been observed for WBM from Figure 26.

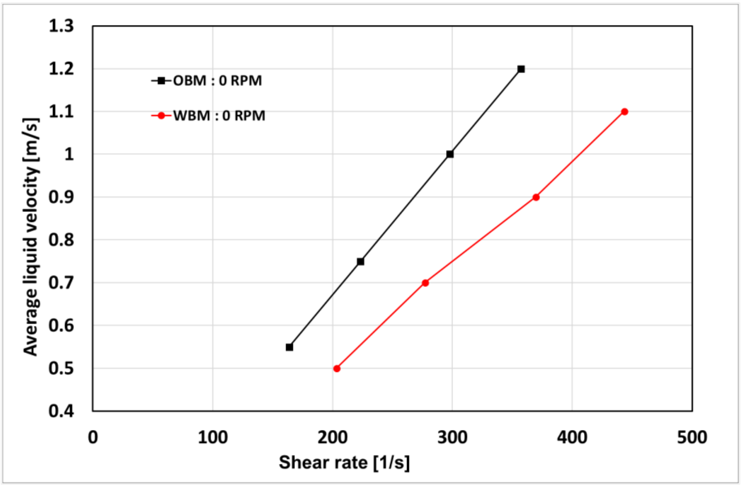

Figure 27. Average wall shear rates in the flow loop corresponding to flow velocities using equation 16

Figure 27 shows wall shear rates corresponding to various flow rates used in the experiments. The shear rates used in the plot are calculated using equation 17. This plot gives information about the shear rates occurring in the annulus corresponding to flow velocities.

The average wall shear rates at various flow rates in the annulus can be calculated using equation 2.

Equations 13-17 provides alternative ways of calculating average wall shear rates from the experimental pressure drops. However, there will be difference in the shear rates calculated using equation 2 and equation 17, as equation 2 does not account for eccentricity and yield stress.

The momentum balance gives

$$\frac{dp}{dx}A = \frac{dp}{dx}\delta P = 2\tau_w P \tag{13}$$

Where P is the circumference of the annulus, A is the area of the annulus and $\frac{dp}{dx}$ is the pressure gradient

$$P = \pi\left(R_o + R_i\right) \tag{14}$$

$$A = \pi\left(R^2{}_o - R^2{}_i\right) \tag{15}$$

The shear strain rate at the wall is found from the constitutive equation for Herschel-Bulkley fluids

$$\tau = \tau_y + K\dot{\gamma}^n \tag{16}$$

Thus

$$\dot{\gamma} = \left[\left(\tau_w - \tau_y\right)/K\right]^{1/n} \tag{17}$$

Several researchers observed different trends of pressure loss changes with the inclusion of drill string rotation (Ahmed and Miska, 2008; Saasen, 2014). Hansen et al. (1999) and (Sterri et al., 2000) observed that pressure drop increases with the increase in drill string rotation while the reverse behavior was reported by Hansen and Sterri (1995). In our case, we observed an increase in the pressure drop with the increase of drill string rotational speed, which is in accordance with most field observations. These seemingly contradictory results can be explained by the competing effects of fluid inertia and shear thinning. In a concentric annulus string rotation will reduce the pressure drop in a shear-thinning fluid. As eccentricity increases inertia becomes more important due to three-dimensional flow effects. Also, in field operations the string will move laterally, adding to the inertia effects. Thus, for a sufficiently eccentric annulus the pressure gradient increases with rotation as the inertial effects dominate over the shear thinning effects (Wan et al., 2000). In both fluids investigated here, the shear-thinning effect is relatively small. In addition, the string is fully eccentric with free lateral movement during rotation (whirling), which explains the observed pressure increase.

Reynolds numbers has been calculated at 0 RPM and 150 RPM cases, using the expression provided by Escudier et al. (2002), in order to understand the hydraulic behaviour of the fluids. As shown in Figure 28, the Reynolds numbers indicate that both fluids are in the laminar region.

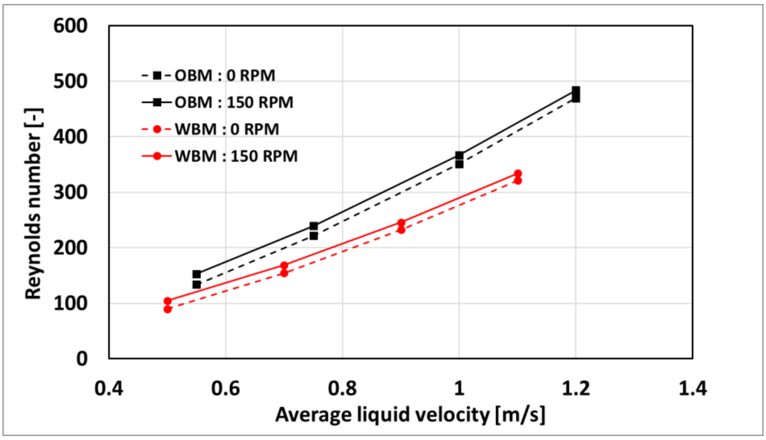

Figure 28. Reynolds number at various flow velocities for WBM and OBM at 0 RPM and 150 RPM

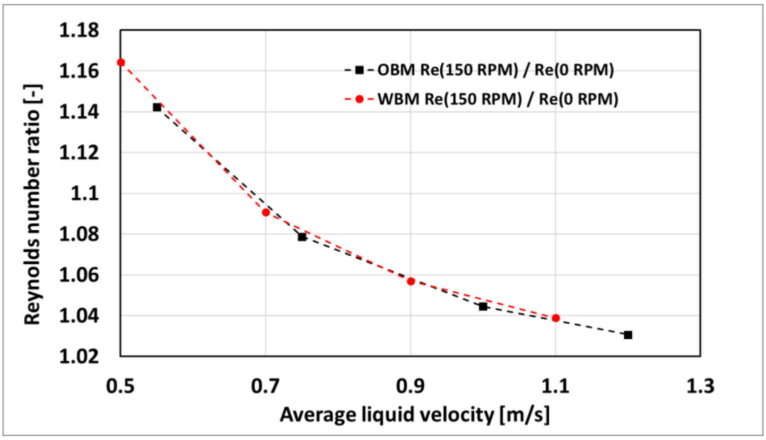

Figure 29. Variation of Reynolds number ratio with flow velocity for OBM and WBM

It was observed, however, that there was no major change in the Reynolds number with the inclusion of rotational shear rate component using the definition in Escudier et al. (2002). Effect of rotation has less effect on Reynolds number at a particular velocity, but it has varying effect at various velocities as seen from Figure 29. Figure 29 shows a variation of Reynolds number ratio with flow velocity. Reynolds number ratio is defined as the ratio of Reynolds number at 150 RPM to the Reynolds number at 0 RPM. Also, rotation of drill string has a diminishing effect on Reynolds number at higher flow rates. Since we observe a significant effect of rotation on pressure gradient the Reynolds number definition used for our calculations is not sufficient to characterize the pressure gradient with rotation (Sayindla et al., 2016).

4.2 Cuttings Transport

Figure 30 presents the results from the experiments with continuous injection of sand particles. Experiments with the injection of sand are performed to evaluate the hole cleaning performance of an oil-based and a water-based drilling fluid in a horizontal flow loop. Figure 30 shows a comparison of sand holdup of OBM and WBM at four flow rates 0.50, 0.75, 1.0 and 1.2 m/s and at 0 RPM and 150 RPM drill string rotational speed. From the flow loop experiments, it has been observed that the hole cleaning performance of an oil-based fluid is significantly better than the hole cleaning performance of a water-based fluid without drill string rotation. With the presence of drill string rotation, hole cleaning performances of both the fluids are nearly the same. Compared to the sand holdup of OBM without drill string rotation, the sand holdup of WBM is significantly higher as seen from Figure 30. At 150 RPM drill string rotational speed, sand holdup of WBM and OBM fluid are likely the same. The same data are shown in Figure 31 along with data for 50 RPM and 100 RPM, illustrating the positive influence of drill string rotation on the hole cleaning performance. With the introduction of drill string rotation, the sand holdup with both the fluids is significantly reduced. Drill string rotation provides an additional component of velocity, i.e., it introduces tangential flow along with the axial flow. This flow improves cuttings transport from the cuttings bed in the annulus.

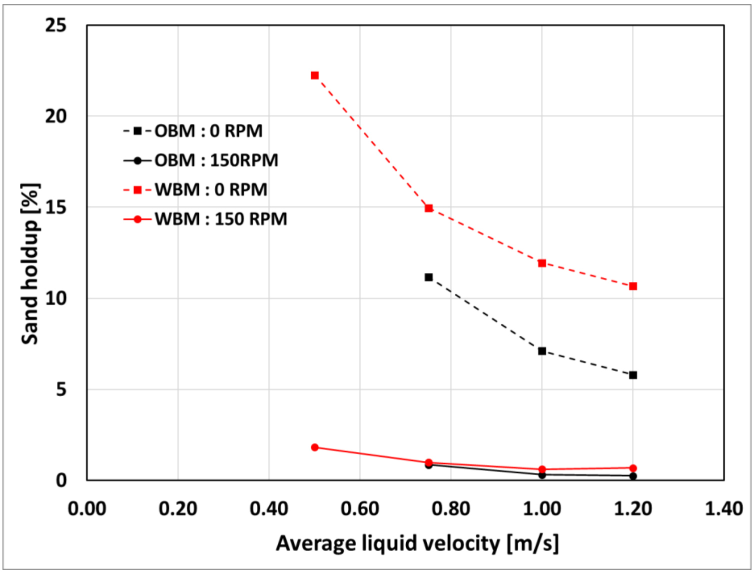

Figure 30. Sand holdup comparison of WBM and OBM

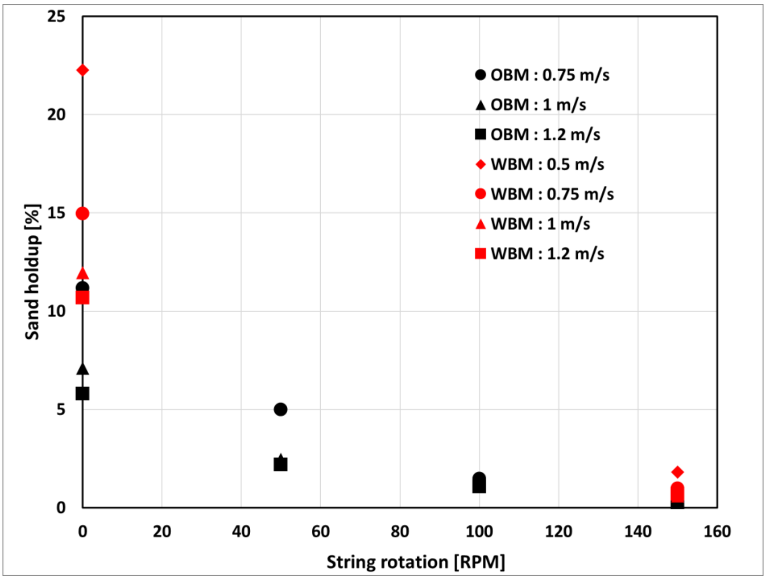

Figure 31. Effect of rotation on sand holdup with OBM and WBM

One possible reason for the difference in the hole cleaning behavior of water-based and oil-based fluids without the drill string rotation is bed consolidation. The method of preparation of fluids also has an impact on hole cleaning which in turn effects the consolidation of the bed. Water-based fluids form a more consolidated bed than oil-based fluids (Saasen and

Løklingholm, 2002). Polymers present in the water-based fluids can form a strong gel structure in the cuttings bed which resists a large strain. In the absence of drill string rotation this gel structure in the cuttings bed is not broken and is capable of resisting a large strain and therefore OBM has better hole cleaning properties than WBM. Whereas at 150 RPM drill string rotation the gel structure of water based fluid gets broken. This provides similar hole cleaning as in the case with oil-based mud. If the bed has been formed in an oil-based drilling fluid which has no gel structure that connects the cuttings particles, pipe rotation will have less effect on hole cleaning (Saasen, 1998), but the effect can still be noticeable (Ytrehus et al., 2015). From Figure 31 we can see that rotation of drill string has a significant effect even on OBM which indicates that OBM also could form a gel structure in the cuttings bed. The above argument is apparently in contradiction to the fact that the flow curves indicated a zero yield stress for the WBM and a finite yield stress for the OBM. However, such a dynamic yield stress is not the same as a gel strength which could build up in a cuttings bed with stagnant fluid. Additional rheological measurements conducted on these fluids revealed differences in the viscoelastic responses which resolves this apparent contradiction (Werner et al., 2017). Amplitude-sweep tests are oscillatory tests with a constant frequency and increasing amplitude. The outcome of the measurements are curves of the storage modulus ($G^{'}$) and the loss modulus ($G^{''}$), characterizing the materials elastic, viscous, or viscoelastic behavior. If $G^{'} > G^{''}$, the elastic behavior dominates over the viscous behavior and the sample shows a solid like character. In the opposite case where $G^{'} < G^{''}$, the viscous behavior is dominating and the sample acts liquid like (Werner, 2018). Amplitude sweep tests showed (see Figure 32) that WBM exhibits dominant viscous behavior and OBM exhibits dominant elastic behavior, which indicates the presence of microstructure in the OBM. This microstructure helps to suspend the cuttings in the fluid and hence provides better cuttings transport with OBM. However, at large shear strain values the storage (elastic) modulus G' of the OBM becomes lower than that of the WBM. Thus, the WBM is able to resist larger strain amplitudes and this can explain why WBM appears to form a more consolidated bed, exhibiting a larger resistance to erosion. Thus, the rheological investigations supported the findings from flow loop study.

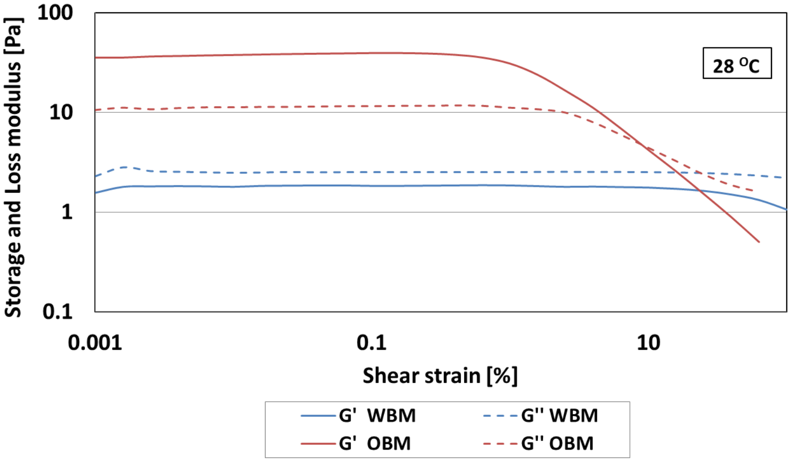

Figure 32. Amplitude sweep showing storage (G') and loss (G") moduli of OBM and WBM fluids at 28°C. Amplitude test data taken from Werner et al. (2017)

As mentioned above, the sand holdup was calculated from the change in the measured weight of the processing unit. Thus, the calculated sand holdup does not distinguish between a compact bed and suspended sand. However, the no-slip holdup of the sand at the injection rate used (43 g/s) accounts for only 0.28% (at 1 m/s flow rate). This value should be compared to the measured holdup values with 150 RPM rotation and 1 m/s flow rate, which are 0.3% for OBM and 0.6% for WBM, indicating that virtually all particles are transported in suspended mode for this condition.

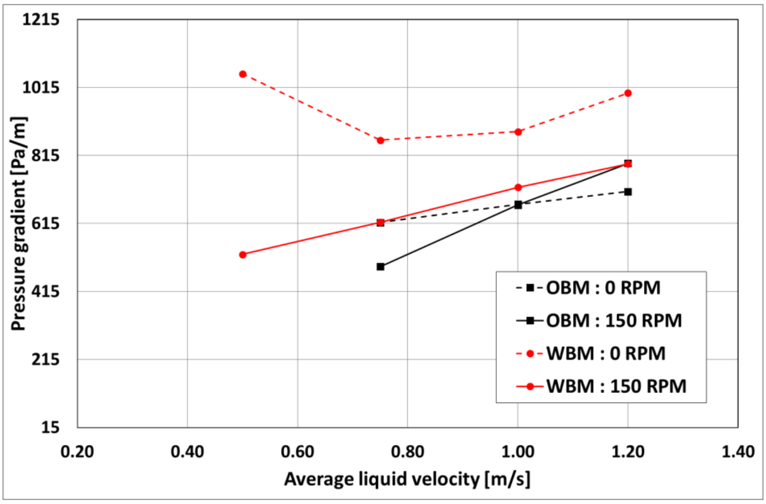

Figure 33. Pressure drop (with sand) variation with flow velocity for drilling fluids

Figure 33 shows a comparison of pressure gradient values with sand for OBM and WBM at various flow rates and at 0 and 150 RPM drill string rotational speeds. The pressure gradient with KCl at 0 RPM stands out from the other curves, due to the higher bed. Also, the trend is different for OBM and WBM.

5 Computational Fluid Dynamics Model Development

This chapter describes the development of a computational fluid dynamics (CFD) model. In addition, CFD simulation results are compared with the experimental observations from Chapter 3 and Chapter 4.

5.1 Geometry and Drilling Fluids Specifications

The annulus between the drill pipe and the borehole or casing has been represented as a concentric and an eccentric annulus. The eccentricity of the pipe is defined as

$$e = \frac{2E}{d_0 - d_i} \tag{18}$$

Here E is offset distance between the centres of the inner pipe and the outer pipe of the annulus. Eccentricity of the annulus considered in the present work is e = 0.8. The inner diameter of the annulus d_i is 50 mm and the outer diameter d_o is 100 mm. The length of the annulus is 10 m, which is $200(R_\mathrm{o} - R_\mathrm{i})$ sufficient to remove entrance length effects. The geometry and computational grid for an eccentric annulus are shown in Figure 34. Structured hexahedral computational mesh is generated using the commercially available program ANSYS ICEMCFD. Optimum mesh size of 360×48×12 in axial, azimuthal and radial directions was adopted after performing grid independence study on the results reported. The simulation is assumed to be converged when the root mean square residual error for continuity and momentum equations reaches 10^{-5}.

The rheology of the non-Newtonian drilling fluids is described by the Herschel–Bulkley model defined by equation 1. The properties of the different drilling fluids investigated in the present work are shown in Table 2 in chapter 2.

5.2 Computational Methodology

Simulations were performed for laminar non-Newtonian fluid in the steady-state regime. Phase coupled SIMPLE algorithm was used for coupling pressure and velocity. Second order QUICK scheme was used for the discretization of the momentum and volume fraction equations. The velocity inlet and outlet-vent boundary conditions were adopted at the entrance and outlet of the annulus section. No-slip velocity boundary condition was assumed at the pipe wall, where velocity of the fluid is zero. Simulations were performed for flow velocity varying from 0.4 to

1.2 m/s. Simulations were performed on a Windows 7 64-bit computer with 32 GB RAM and the Intel dual core i7 3.4GHz processor.

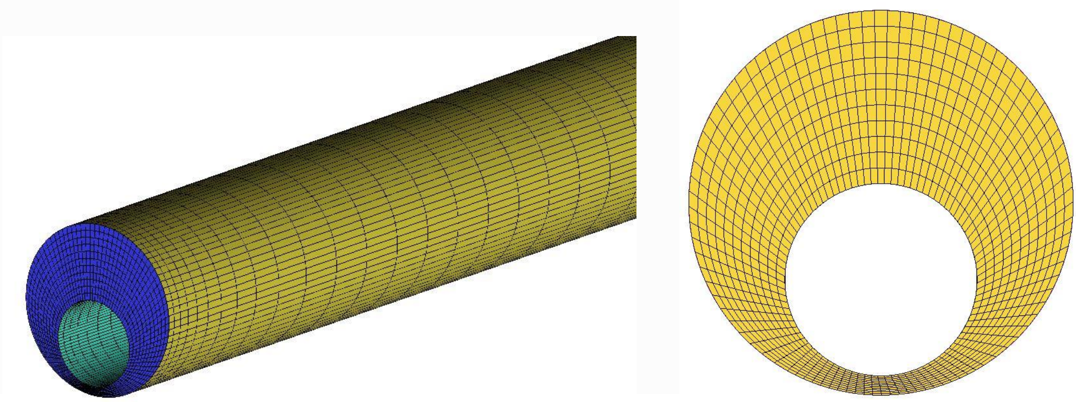

Figure 34. Annulus geometry and computational mesh

5.3 Model Validation

The CFD simulation model is validated against experimental data and narrow-slot analytical method reported in the literature. Figure 35 presents the comparison of pressure gradient values with the experimental data reported by Kelessidis et al. (2011) for 1.85 % bentonite suspension in water in a 70-by-40 mm concentric annulus. In Figure 36 annular pressure drop from CFD simulations for OBMA fluid for concentric annulus is compared with the analytical pressure drop calculated using the narrow slot approximation method (Founargiotakis et al., 2008; Ytrehus et al., 2015). Simulation results are in close agreement with the experimental data as seen from Figure 35 and analytical calculation as seen from Figure 36 and confirming the validity of CFD model adopted in the current study.

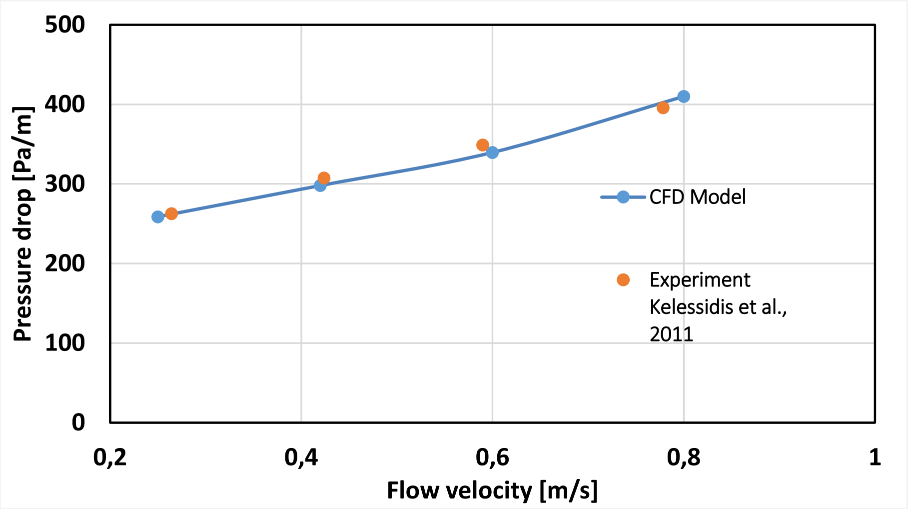

Figure 35. Pressure drop for 1.85 % bentonite suspension in water by CFD and experimental results (Kelessidis et al., 2011)

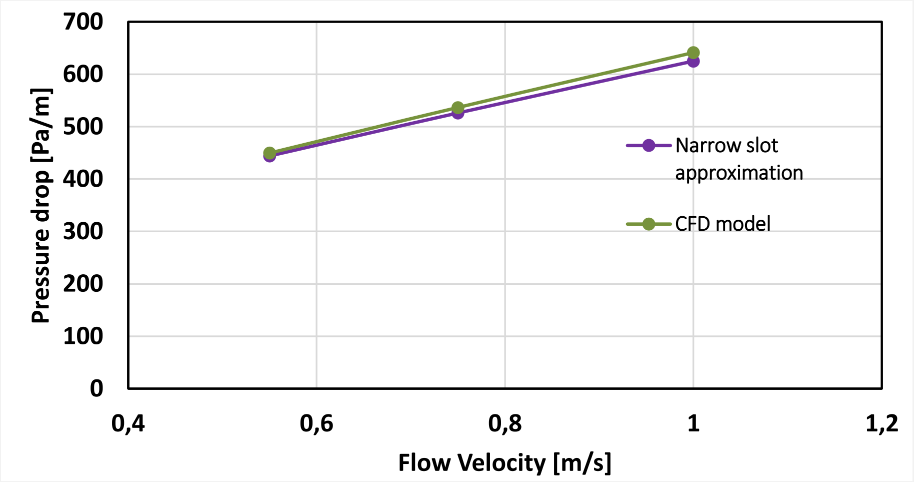

Figure 36. CFD model comparison with narrow slot approximation for concentric annulus for OBMA. Narrow slot approximation results taken from Ytrehus et al. (2015)

5.4 Drilling Fluid Hydraulics

Simulations without the injection of sand particles in an eccentric annulus are presented here. These results are important in analysing the hydraulic behavior of drilling fluids in the absence of particles. Velocity contour plots for OBMA fluid in a concentric and eccentric annulus in a plane normal to the flow direction are shown inFigure 37 for the case of average inlet fluid velocity 1 m/s. The velocity profile is axisymmetric in case of a concentric annulus, whereas the velocity of the drilling fluid in the narrow part of the eccentric annulus is significantly reduced and fluid velocity in the wider part is increased. The velocity in the narrow part of the annulus is reduced due to the increased resistance to the flow as the gap between inner and outer pipe is decreased. Therefore, as expected, these observations are in agreement with the earlier results reported by Haciislamoglu and Langlinais (1990).

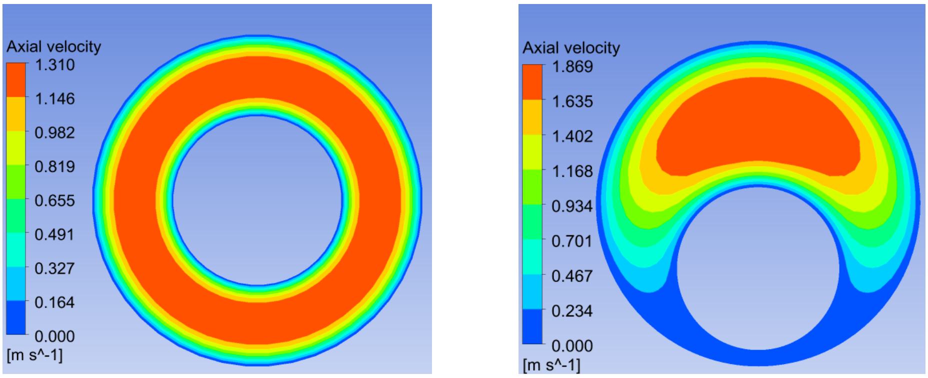

Figure 37. Velocity contour plots for OBMA fluid for average inlet velocity 1 m/s for (a) concentric annulus and (b) eccentric annulus

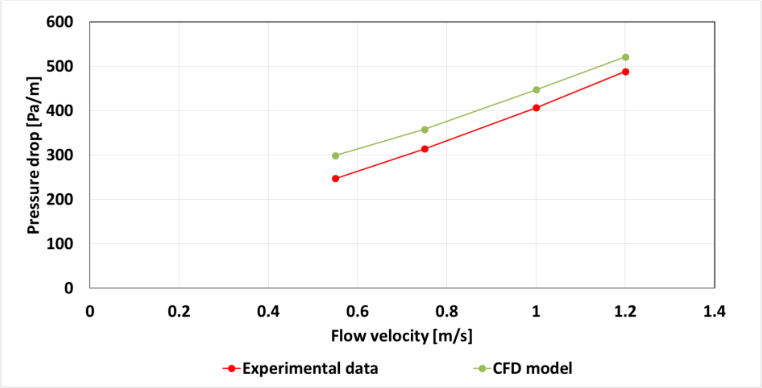

Figure 38. Flow loop results comparison with CFD model results for fluid OBMA

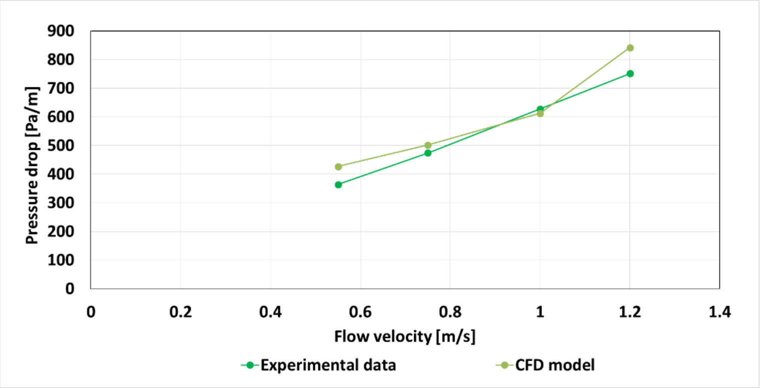

Figure 39. Flow loop results comparison with CFD model results for fluid OBMB

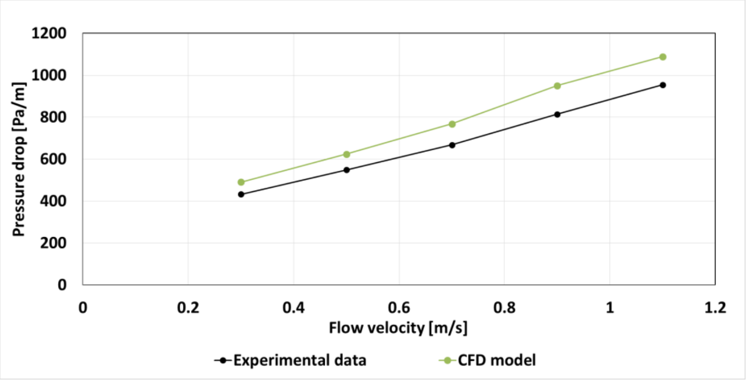

Figure 40. Flow loop results comparison with CFD model results for fluid OBMC

Figure 38 - Figure 40 shows a comparison of pressure drop from the flow loop investigations with the pressure drop values from CFD simulations as a function of the increased fluid velocity for the three OBM's in an eccentric annulus. For all the drilling fluids considered, the pressure drop from the CFD simulations increases with the fluid velocity. The three OBM's tested are fluids with various viscosity and density values. The fluid with the highest viscosity and density, OBMC, has the highest pressure drop among all the three fluids, and the OBMA fluid, which has lowest density and viscosity, has the least pressure drop among the three fluids. Similar behavior has been reported from the flow loop investigations by (Sayindla et al., 2016) (see Figure 41). Both the simulation and experimental results show that the pressure drop increases with increase in fluid velocity. Also, it can be observed that the reported simulation results are in close agreement with the flow loop experimental results, with a deviation less than 15%. Numerical simulations were performed for eccentricity 0.8 but the experiments were conducted

on a fully eccentric annulus. This might result in the small differences observed between the flow loop and CFD model pressure drop as seen from above Figure 38 - Figure 40.

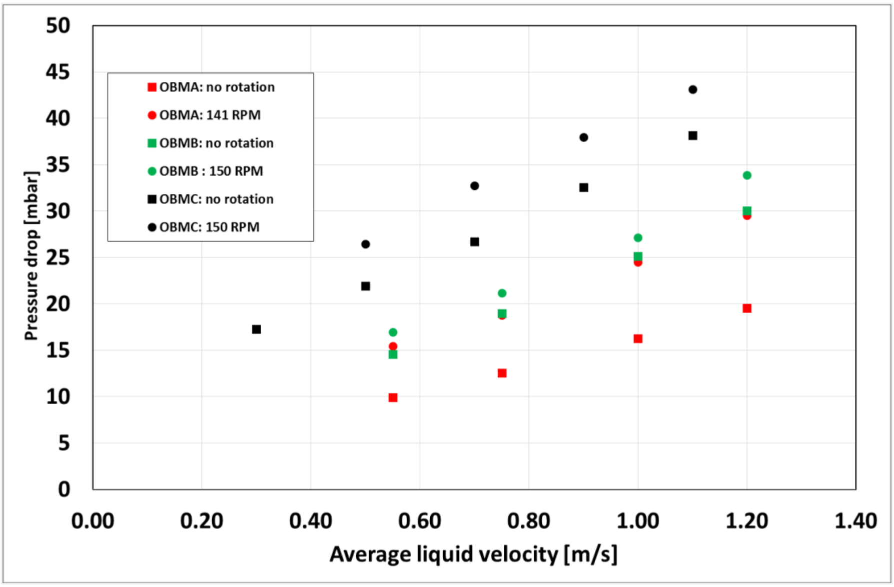

Figure 41. Flow loop results comparison of fluids OBMA, OBMB and OBMC (Sayindla et al., 2016)

The CFD model was also extended to introduce drill pipe rotation. In Figure 42 pressure drop from CFD simulations of OBMB fluid at 150 RPM drill pipe rotation is compared with the pressure drop from flow loop investigations at 150 RPM. In a concentric annulus, string rotation will reduce the pressure drop in a shear-thinning fluid. As eccentricity increases inertia becomes more important due to three-dimensional flow effects. Also, in field operations and in our flow loop the string moves laterally, adding to the inertia effects. Thus, for a sufficiently eccentric annulus the pressure gradient increases with rotation as the inertial effects dominate over the shear thinning effects (Wan et al., 2000). In both fluids investigated here, the shear-thinning effect is relatively small. In addition, the string is fully eccentric in our experimental setup with free lateral movement during rotation, which explains the observed pressure increase (Sayindla et al., 2017). Simulation results with the inclusion of drill pipe rotation in the CFD model are in close agreement with the flow loop results.

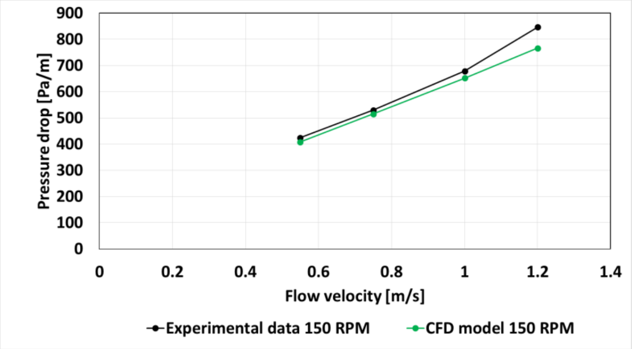

Figure 42. Flow loop results comparison with CFD model for fluid OBMB at 150 RPM

In addition, Pressure drop results from CFD simulations for a water-based drilling fluid (KCl) and an oil-based drilling fluid (OBMB) having similar viscosity profiles are compared. The pressure gradient values for water-based mud are higher than oil-based mud, though they have nearly similar density and viscosity profile as seen from the Figure 44 by Sayindla et al. (2017). KCl is referred to as WBM and OBMB is referred to as OBM in Figure 44. CFD simulation pressure drop results of KCl as compared with the flow loop results can be seen in Figure 43. CFD simulations for both the fluids (OBMB and KCl) are in line with the flow loop results. Pressure drop of the two fluids with nearly similar viscosity profile is different. Figure 45 shows a comparison of pressure drop from CFD simulations and flow loop for KCl at 150 RPM drill pipe rotation. As discussed above pressure drop increases with rotation in an eccentric annulus and simulation results agree well with the flow loop results. These results are in line with the previous theoretical and experimental research. KCl has zero yield stress, and it has been modelled using power law in CFD simulations. OBMB fluid has a definite yield stress and has been modelled using Herschel-Bulkley model. The main aim of investigating drilling fluids with similar viscosity profile is to study if there will be any difference in their hole cleaning behavior in spite of having similar viscosity profiles. Based on the field experience, industrialists believe that oil-based muds provide better hole cleaning performance than water-based muds. Whereas, laboratory investigations provide contradictory results. A recent study by Sayindla et al. (2017) provides flow loop investigations performed with an oil-based mud (OBM) and a water-based mud (WBM) with nearly similar viscosity profiles under identical conditions. As per the study, OBM provides better hole cleaning performance than WBM in the absence of drill string rotation. In addition, hole cleaning performance of both OBM and WBM is nearly the same in the presence of drill string rotation. These experimental studies coupled with CFD simulations can be used to construct better and more accurate cuttings transport models.

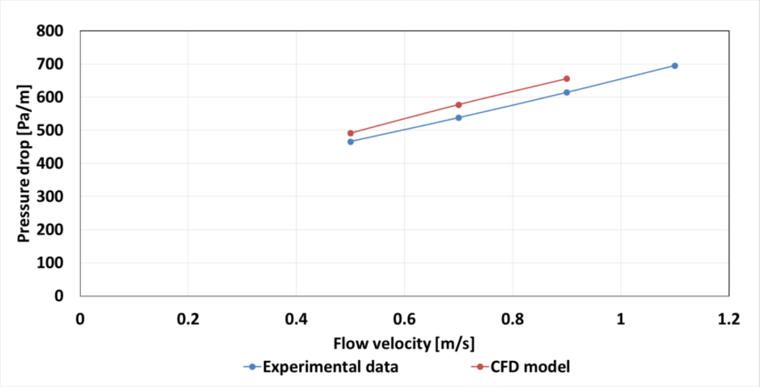

Figure 43. Flow loop results comparison with CFD model results for fluid KCl

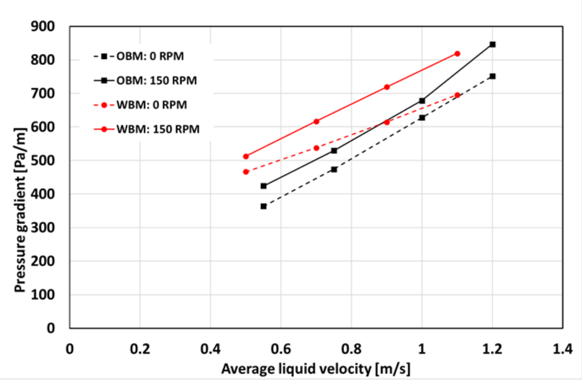

Figure 44. Flow loop results comparison of fluids KCl and OBM (Sayindla et al., 2017)

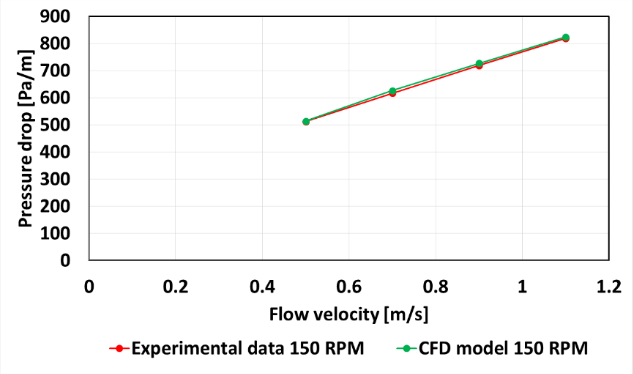

Figure 45. Flow loop results comparison with CFD model for fluid KCl at 150 RPM

CFD model developed has been validated with the published literature and also with the performed flow loop investigations as discussed above. Undoubtedly, the developed CFD model agrees well with the results from flow loop investigations. The developed model can be used for further investigations with various fluids, which can save a lot of time and money. The developed model can be further extended to study cuttings transport with different drilling fluids.

6 Conclusions

In this study, hydraulic and cuttings transport behaviour of various oil-based and water-based muds are studied in an eccentric annulus. Various parameters influencing cuttings transport behavior of fluids e.g., ROP, drill string rotational speeds, and fluid velocity are studied. The results from these experimental campaigns demonstrate a difference in the hydraulic and hole cleaning performance of tested drilling fluids.

Oil-based and water-based mud with nearly similar viscosity profiles was studied to identify the reasons for their difference in behaviour. Results in this study illustrate a significant difference in hole cleaning performance of the drilling fluids with similar viscosity profiles. The hypothesis that oil-based fluids clean better than water-based fluids is derived from observations of field operations. A question has been if these observations are due to differences in the behaviour of the fluids cuttings transport capability or to other factors, like the interaction with formation can cause the effects. This study should have eliminated other factors that could cause the observed difference in field operations. Other factors may still contribute to hole cleaning effects in field operations, but it can be concluded that the difference in observed hole cleaning efficiency in these experiments is due to differences in the fluids cuttings transport efficiency and/or the fluid-cuttings bed interaction. Knowledge gained from these studies will be helpful in selection of fluids and also to construct better models for the estimation of cuttings transport.

A CFD model for estimating frictional pressure loss inside horizontal eccentric annuli was developed by using the commercial software program ANSYS. The conclusions drawn from the study are listed below

- Fluid velocity has the most significant positive effect on cuttings transport
- The cuttings removal capability is significantly positively affected by the string rotational speeds. The effect of drill string rotation on cuttings transport is more significant at lower flow rates.
- Frictional pressure losses increase with increasing rotational speed for all fluids tested, as expected for a fully eccentric configuration. However, frictional pressure losses decreases as the pipe rotation is increased, compared to no-rotation case in the presence of cuttings. This is due to the improved cuttings transport with the drill string rotation.
- Low density or/and low viscosity fluid is preferably used in drilling well operations because of its good hole cleaning capability. But in a case where tripping is involved, a

fluid with significantly higher yield stress is preferred in order to suspend the cuttings. Though there is a compromise on hole cleaning, gel strength is considered to be important in such situations.

- From the experimental studies, no major increase in sand holdup was found vs increase of ROP, with and without drill pipe rotation. Also, the effect of drill pipe rotation on cuttings transport is higher at lower penetration rates compared to higher penetration rates.
- From the experimental studies, hole inclination has a slight effect on cuttings transport compared to horizontal annulus
- In the absence of drill string rotation, hole cleaning was significantly better using the OBM than the WBM.
- At high drill string rotation rate, the hole cleaning performance of the WBM approaches that of the OBM.
- The differences in the hole cleaning abilities of OBM and WBM are attributed to construction of fluids and consolidation of bed. Polymers in the WBM form a more consolidated bed and resists a larger strain. Therefore, particle removal from bed becomes more difficult with the WBM. Absence of polymers in the OBM makes the bed less consolidated. An initial amount of force to overcome its yield stress is required to remove the particles from the bed. Thus, better hole cleaning is experienced with the OBM. However, drill string rotation helps in breaking the particle-particle bond in the bed and thus, hole cleaning is similar with the OBM and WBM at higher drill string rotation speeds.
- The main hypothesis, that oil-based fluids clean the hole better than water based while the fluids are being similar according to API measurements is significantly supported.
- CFD model developed predicts with acceptable accuracy the frictional pressure loss in laminar and turbulent flow of non-Newtonian fluid for liquid flow through in horizontal annulus with and without drill string rotation

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Is not included due to copyright

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Hole-cleaning performance comparison of oil-based and water-based drilling fluids

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A R T I C L E I N F O

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Rheology

A B S T R A C T

Cuttings transport is a topic of great interest in the oil and gas drilling industry. Insufficient cuttings transport leads to several expensive problems. Knowledge and selection of the drilling fluids is one of the important factor for efficient hole cleaning. It has been observed, however, that the hole cleaning performance of drilling fluids can be different even if the fluid rheological properties are similar as measured in accordance with API specifications. The reasons for stated difference in the behavior of drilling fluids are not well understood. The main objective of present work is to evaluate hole cleaning efficiency of an oil-based drilling fluid (OBM) and a water-based drilling fluid (WBM) whose viscosity profiles are similar as per API specifications.

Hole cleaning efficiency of an oil-based drilling fluid and a water-based drilling fluid whose viscosity profiles are similar was investigated. The fluids tested were industrial fluids used in the field and were sent to us after reconditioning. Experimental studies were performed on an advanced purpose-built flow-loop by varying flow velocities and drill string rotation rates. The flow loop had a 10 m long annulus section with 4″ inner diameter wellbore and 2″ outer diameter fully eccentric drill string. Pressure drop and sand holdup measurements were reported. Rheological investigations of the same fluids were used to understand the difference in the behavior of the drilling fluids tested. Higher pressure drop was observed for WBM compared to OBM, and for both fluids, the pressure drop increased with drill string rotation speed. In case of no drill string rotation, better hole cleaning performance was observed with the oil-based fluid compared to the water-based fluid. With the presence of drill string rotation, hole cleaning performance of both the fluids was nearly the same.

1. Introduction

Significant resources are spent by oil and gas companies annually on drilling, out of which a large fraction is lost due to various drilling problems. One such drilling problem which has been in focus for many researchers for several decades is inadequate cuttings transport. It is considered to be a major issue in high angle oil well design. Cuttings generated during drilling have to be transported to the surface, in order for the drilling operation to proceed. Insufficient hole cleaning may result in reduced rate of penetration (ROP), formation fracturing with resulting fluid loss, premature bit wear, increased drill string torque and drag, and stuck pipe. Previous studies indicate that cuttings transport is influenced by many factors, such as cuttings characteristics, drilling fluid type and rheology, operational parameters including drill pipe rotation, pump rate, weight on bit, ROP, eccentricity and diameter of hole and drill pipe, and wellbore inclination (Okrajni and Azar, 1986; Sifferman and Becker, 1992; Zeidler, 1972). A comprehensive review of cuttings transport studies was reported by Kelin et al. (2013) and Nazari et al. (2010).

Cuttings are transported to the surface by circulating a drilling fluid and it is vital for the drilling operator to be able to select an appropriate fluid for each individual well, including the decision of using oil-based or water-based fluids or “muds” (OBM or WBM). Each of these two fluid types has its own advantages and disadvantages, as shown in the review by Apaleke et al. (2012). Over the years drilling fluids have become more complex and expensive in order to satisfy diverse requirements and there is a need to increase the knowledge of drilling fluid behavior in order for the operator to select and apply the appropriate fluid.

Oil based drilling fluids have been claimed to be superior to water based drilling fluids when it comes to hole cleaning, even if the fluid rheological properties are similar as measured in accordance with API

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specifications. The reasons for this difference are not completely understood, but a theory was put forward by Saasen (1998). There are no standards available which suggest the type of drilling fluid to be used for a particular well. According to industry wisdom and field practice, water-based fluids are used when possible, and oil-based fluids are used when needed. Field studies show that drilling ROP improves by using OBM, whereas laboratory evaluations have indicated that it is not obvious that drilling ROP improves with OBM. Many researchers have been working with oil-based and water-based drilling fluids to understand and identify differences in their behavior, but conclusions differ. Results from some studies contradict results from other studies. Some researchers have reported that oil-based drilling fluids with similar rheological properties as water-based drilling fluids behave similarly in terms of hole cleaning, while other researchers have reported that hole cleaning performance of oil-based fluids and water-based fluids differ in spite of similar rheological properties. Hareland et al. (1993) reported that except at hole inclinations of 40° to 50°, oil-based muds and water-based muds with similar rheological properties behave similarly, whereas at 40° to 50° hole inclinations water-based muds outperform oil-based muds. Hemphill and Larsen (1996) found out that oil-based and water-based drilling fluids with similar rheological properties and at a particular velocity behave similarly at all the hole inclinations from 0° to 90°. Seeberger et al. (1989) reported that above a particular fluid velocity, drilling fluids with similar rheological properties behaves in an equivalent fashion, whereas, below that particular fluid velocity water-based mud has better performance that oil-based mud. The above conclusions are drawn from laboratory investigations performed at various conditions which may or may not represent the actual field conditions closely. However, Saasen and Løklingholm (2002) also found that the efficiency of oil-based drilling fluids is better compared to water-based drilling fluids with somewhat similar viscosity profiles when they were evaluating field data.

As noted by (Saasen et al., 1998), cuttings transport efficiency is closely related to annular pressure loss. The cuttings transport efficiency of drilling fluids increases with increasing shear stress acting on the bed which in turn contributes to frictional pressure loss. Therefore, frictional pressure loss estimation is important to study the hole cleaning behavior of drilling fluids.

Proper estimation of the frictional pressure loss is also important for pump capacity design and in order to keep ECD within the pressure margin. Several researchers investigated the drill string rotation effect on the annulus pressure drop by ascribing to the flow regime (laminar or turbulent), formation of Taylor vortices, drill pipe eccentricity and various other parameters (Ahmed and Miska, 2008; Cartalos and Dupuis, 1993; Erge et al., 2015a, 2015b, 2015c; McCann et al., 1995; Ozbayoglu and Sorgun, 2010; Saasen, 2013; Sorgun et al., 2011).

In the literature, there are very few comparative studies reported for OBM and WBM under equivalent conditions, to understand their difference in behavior in cuttings transport. Hemphill and Larsen (1996) provide an overview of laboratory experiments conducted at the University of Tulsa, more than two decades ago. Apparently, not much research has been conducted in this area since then. Clearly, the identification of the differences in performance of OBM and WBM determined at controlled flow loop conditions will increase the understanding of the fluid's behavior and enable the development of improved drilling fluids, both operationally and environmentally, for both oil-based and water-based fluids. In this study flow loop experiments will be performed on a custom built flow-loop apparatus. The main objective of this work is to evaluate hole cleaning performance of an oil-based drilling fluid and a water-based drilling fluid whose viscosity profiles are similar. Hole cleaning efficiency will be evaluated at various operational conditions. Operational parameters are selected to represent actual field conditions like an eccentric annulus, realistic flow velocities, ROP and drill string rotational speeds. This study is designed to understand the difference in the hole cleaning behavior of fluids with similar rheological profiles. In addition, this study helps to identify if the observation made in the field that OBM cleans better than WBM is due to differences in the behavior of the fluids cuttings transport capability or if other factors, like interaction with the formation can cause the effects.

2. Experimental

2.1. Flow loop

A schematic diagram of the experimental facility is shown in Fig. 1. All the experiments are conducted on an advanced purpose-built flow rig. The flow rig consists of a 10 m long test section, a processing unit (sand injection, sand separation, fluid storage tanks and pumps), connecting hoses, valves, and instrumentation (see Fig. 2).

The test section consists of replaceable hollow cylindrical elements of concrete with an inner diameter of 100 mm representing the wellbore (see Fig. 1) and a steel rod of 50 mm diameter, representing a drill string. One end of the rod is connected to a drive motor to simulate a variable speed system and the rod is supported laterally at both ends using universal flexible joints allowing free whirling (lateral) motion within the constraints of the wellbore. Movement of the drill string in the axial direction is constrained. Thus flow loop is fully eccentric due to the gravity of the drill string. The flow loop can also be tilted to an angle of 30° from horizontal. A transparent section is placed in the middle of the test section to visualize the formation of cuttings bed (Ytrehus et al., 2014). However, in this case, drilling fluids are opaque, which makes visual measurements difficult.

Instrumentation includes a Coriolis flow meter and differential pressure (DP) transducers connected to the logging system. Differential pressure cells measure differential pressure between pressure ports which are located at positions 3 m, 7 m and 8 m from the inlet. DP cell measurements (DP1815) which measured the pressure difference between ports at 3 m and 7 m location are reported. The DP transducers are flushed regularly before each experiment to ensure that there are no air bubbles in the test section. Sand injection system is calibrated to a preset sand rate. The outlet of the test section is connected to sand separator unit, where the fluid and sand gets separated. Fluid storage system is capable of holding 5 m^3 of drilling fluid. Load cells under the processing unit are used to measure the variation in weight due to the corresponding variation in the amount of sand in the test section. Thus, the cuttings holdup in the system could be calculated as a function of time.

The loop is designed for ambient pressure and temperature conditions, which was considered sufficient for the purpose of this investigation, and is much less expensive than performing experiments at reservoir conditions.

2.2. Fluids

Various oil-based and water-based fluids are tested. Results from the experimental investigation of oil-based fluids were reported (Sayindla et al., 2016). This paper presents comparative results of the oil-based and water-based fluids. An oil-based fluid OBMB and a water-based fluid KCl with similar rheological profiles were chosen for our study. These fluids were provided by the company MI Swaco. These fluids were industrial fluids used in the field, and were reconditioned and cleaned and were delivered to us for our research activities. Oil-based fluid OBMB will be referred to as OBM and water-based fluid KCl will be referred to as WBM in the rest of paper. The Herschel- Bulkley parameters of the drilling fluids were obtained by a least squares fit to Anton Paar rheometry data and are listed in Table 1 along with matched Herschel-Bulkley parameters. Matching was conducted for shear rates below 400 s^{-1}, which is the most relevant range for the flow loop experiments. Table 2 presents the composition of OBM and WBM fluids.

Flow curves of the two fluids OBM and WBM are shown in Fig. 3. The shear rates encountered in the flow loop and in field conditions are below about 400 s^{-1}, as shown in Fig. 6. Within that shear rate range, viscosity profiles of the drilling fluids OBM and WBM are similar as seen from

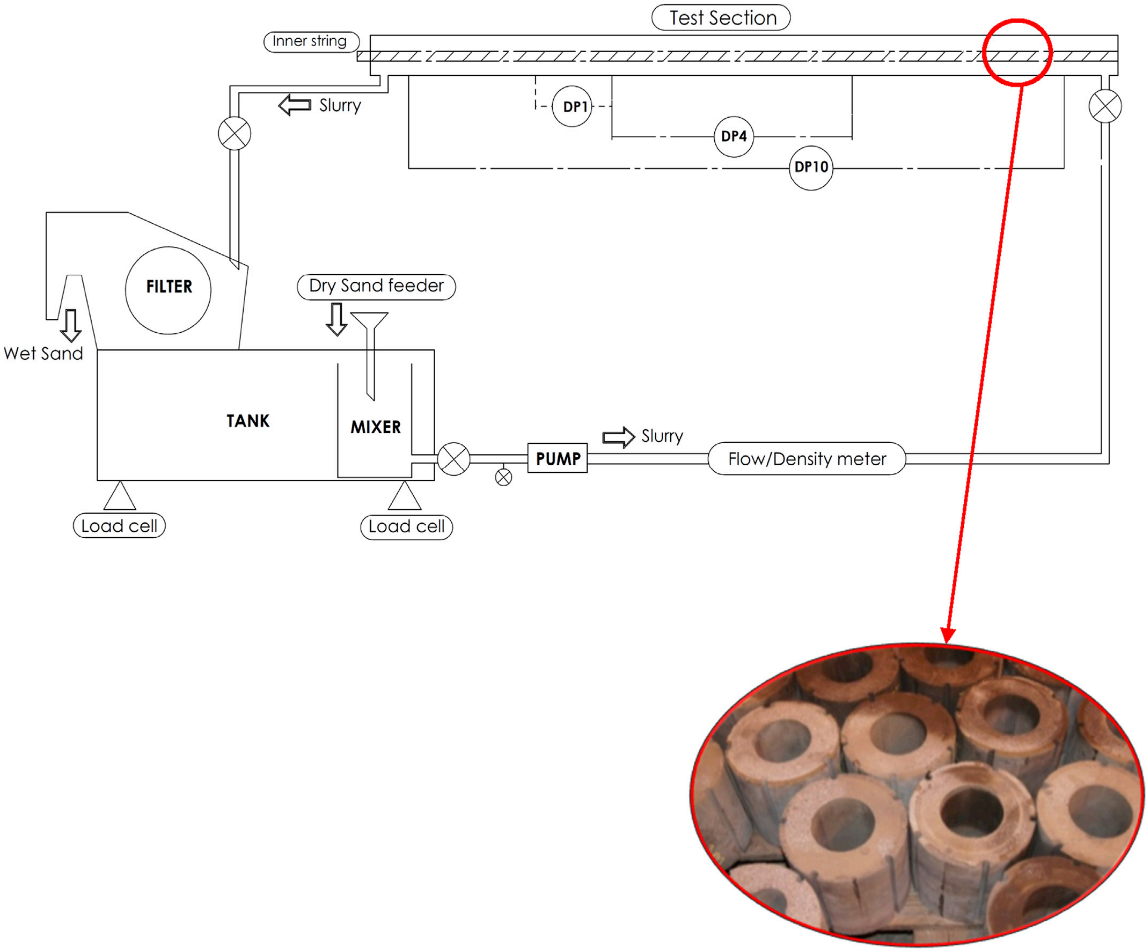

Fig. 1. Schematic of the flow loop system (top) and concrete elements (bottom).

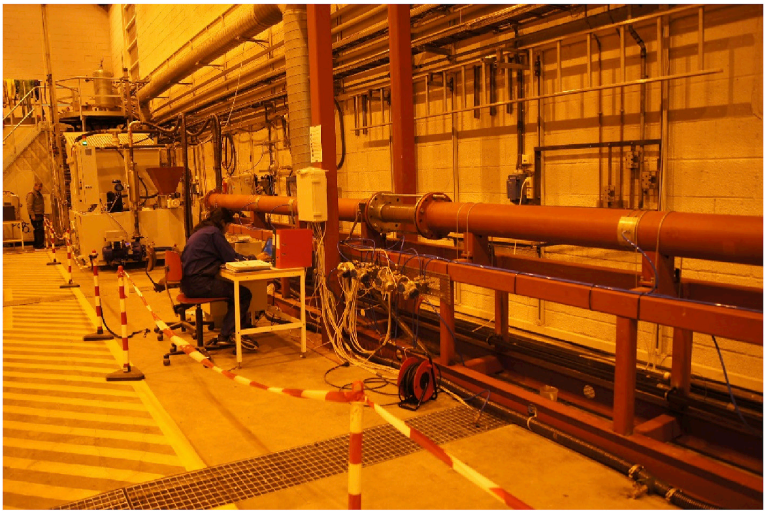

Fig. 2. Advanced purpose-built flow rig.

Table 1
Herschel-Bulkley parameter values of drilling fluids.

Property	K [PaS]	n [−]	τ_y [pa]	Density [kgm^3]
OBM	0.437	0.581	1.07	1260
WBM	1.36472	0.382	0	1188

Table 2
Composition of WBM and OBM.

Composition	
OBM	WBM
Base oil EDC 95-11	Fresh water
Barite	KCl
Organophilic clay (Bentonite)	Glycol
Salt ($CaCl_2$)	Xanthum gum
Lime ($Ca(OH)_2$)	Polyanionic cellulose
Emulsifier	Starch
Fluid loss agent	Soda ash
	Barite
Oil-water ratio 80/20	Not applicable

Fig. 3. A rheological analysis of the drilling fluids WBM and OBM were presented in (Werner et al., 2016).

The wall shear rates for laminar flow in a concentric annulus can be calculated using equation (1) (narrow slot approximation) (Saasen, 2014). This equation holds good for power law fluids and does not count for yield stress fluids and eccentricity. However, as the contribution of drill pipe rotation to the shear rate is much smaller than the contribution from the axial flow, the values shown in Fig. 3 were calculated using $\omega = 0$. These shear rates are included to show what flow velocities and shear rates are commonly found at relevant hole sizes, pump rates, and drill pipe size. It is included so that results from flow loop campaign and fluid lab, presented later for various annular velocities and shear rates, can be related to relevant drilling conditions.

$$\dot{\gamma} = \left[\left(\frac{12U}{(d_o-d_i)}\,\frac{2n+1}{3n}\right)^2+\left(\frac{\omega R_i}{(R_o-R_i)}\right)^2\right]^{\frac{1}{2}} \tag{1}$$

2.3. Fluids

Test parameters chosen for flow loop experiments includes.

- Flow velocities of 0.55/0.5, 0.75/0.7, 1.0 and 1.2/1.1 m/s for OBM/WBM
- Drill string rotational speeds of 0, 50, 100 and 150 RPM
- Sand rate of 43 g/s corresponding to a ROP of 8 m/hr
- Quartz sand particles from Dansand A/S were used in the experiments with their size ranging from 0.9 to 1.6 mm to represent cuttings

Sand rate chosen represents a typical averaged ROP value in the field. The flow rates and drill string rotation rates were chosen to cover typical operational ranges.

Various steps involved in the experiments are described as below.

1. Drilling fluid is circulated through the flow loop at a preset velocity
2. For the experiments with sand, cuttings are injected at a calibrated rate into the flow upstream of the test section using a dry sand feeder and are separated from the recirculating fluid in the processing unit
3. Experiment is run until steady state condition is reached. Weight of the sand in the test section is continuously measured. Initially, amount of the sand entering the test section will be greater than the amount of the sand leaving the system. After certain time, the amount of the sand entering and leaving the test section will be the same. It is considered as a steady state condition. The amount of the sand left in the test section indicates formation of the cuttings bed
4. To see the effect of rotation, drill string is rotated at a preset speed and experiment is run till a steady state condition is reached

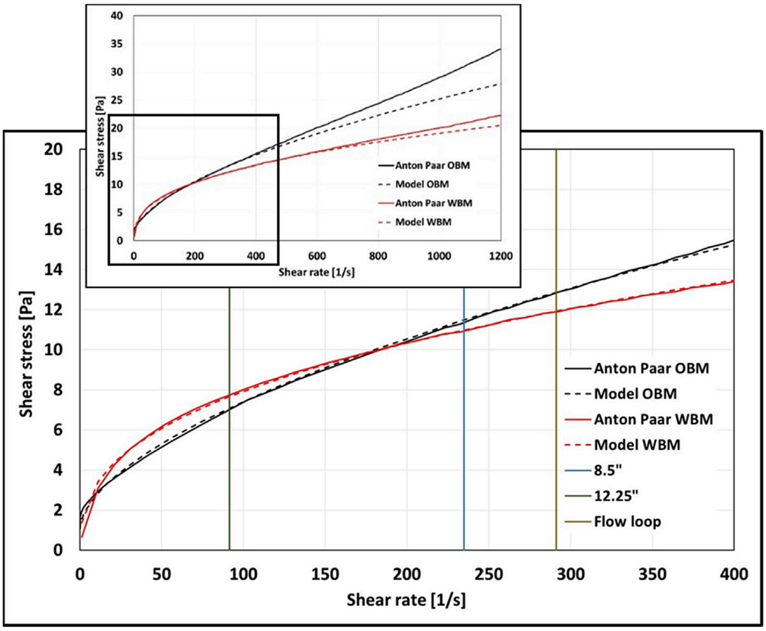

Fig. 3. Measured (at 28 °C) and calculated flow curves of WBM and OBM. Figure in the insert show same flow curves data over the entire tested shear rate range up to 1200 1/s. Vertical lines indicate corresponding wall shear rates for OBM flow in our flow loop (at 1 m/s), in an 5.5″ by 8.5″ annulus at 1.41 m/s (1800 lpm), and in an 5.5″ by 12.25″ annulus at 1.24 m/s (4500 lpm).

5. Cuttings injection is stopped and the flow rate along with the rotation is continued till the hole is clean
6. Experiment is repeated with another set of operational parameters
7. Throughout the experiment pressure drop measurements using available pressure transducers are made. Weight of the fluid storage system along with the sand injection unit is continuously monitored, to be able to calculate the amount of the sand in the test section
8. Sand bed formation could not be visualized due to the opacity of the fluids. In our experiments, sand hold up is used to compare the hole cleaning efficiencies of fluids. Sand bed holdup is defined as the average amount of the sand left in the test section over the length of the section, at the end of the experiment. Weight of the fluid and sand handling system is measured throughout the experiment and difference of the weight before and after experiment indicates the amount of the sand left in the flow loop. And the sand bed holdup was determined by averaging the mass of sand in the flow loop over the length of the section, assuming all sand to be in a bed with an assumed constant porosity. However, it is not possible to distinguish between a stationary cuttings bed and transported cuttings with this measurement

Some experiments were repeated, confirming the reliability of results. Also, to check the stability of the drilling fluids, Fann viscometer measurements and emulsion stability (ES) measurements (for the OBM) were done on a daily basis. The constant readings from the ES meter proved that the emulsions of the OBM were stable through the tests. The temperature was maintained at 28 °C throughout the experiment as the viscosity of the fluids depends on the temperature. Viscometric measurements were conducted both with Anton Paar and Fann 35 viscometers, at the same temperature as the flow loop experiments.

3. Results and discussion

Results from flow loop experiments are presented in two sections. The first section includes results from experiments without the injection of sand and next section includes results from the experiments with the injection of sand.

3.1. Hydraulics

Results to understand the hydraulic behavior of fluids in the absence of particles are presented in this section. In Fig. 4 compares the experimental pressure gradient with calculations using narrow slot approximation for laminar flow and the Herschel-Bulkley model with the parameters of Table 1. Here eccentricity was accounted for using the semi-empirical model by Haciislamoglu and Langlinais (1990). We notice that the model curves are sub-linear, due to the shear-thinning effect, while the experimental curves are close to linear.

In Fig. 5 a comparison of pressure drop (DP1815) measurements for OBM and WBM without and with the rotation of drill string is presented. The pressure gradient values for WBM are higher than OBM, though they have nearly similar density and viscosity profile. We notice that for both fluids there is a significant increase in pressure drop with 150 RPM string rotation compared with non-rotating string. For the OBM we observe that the pressure gradient increases more than linearly with string rotation, indicating an onset of turbulent activity. Since these fluids are shear-thinning we would expect the increase to be sub-linear in the laminar regime. In addition, rotation at 150 RPM increases the pressure gradient for a given flow rate, and this effect increases also with flow rate.

Fig. 6 shows wall shear rates corresponding to various flow rates used in the experiments. This plot gives information about the shear rates occurring in the annulus corresponding to flow velocities. The average wall shear rates at various flow rates in the annulus are calculated using equation (1). Equations (2)–(6) provides alternate way of calculating average wall shear rates from the experimental pressure drops. However, there will be difference in the shear rates calculated using equation (1) and equation (6), as equation (1) does not account for eccentricity and yield stress.Momentum balance gives

$$\frac{dp}{dx}A = \frac{dp}{dx}\delta P = 2\tau_w P \tag{2}$$

where P is the circumference of the annulus, A is the area of the annulus and $\frac{dp}{dx}$is the pressure gradient

$$P = \pi(Ro + Ri) \tag{3}$$

$$A = \pi\left(R^2 o - R^2 i\right) \tag{4}$$

The shear strain rate at the wall is found from the constitutive equation for Herschel-Bulkley fluids

$$\tau = \tau_y + K\dot{\gamma}^n \tag{5}$$

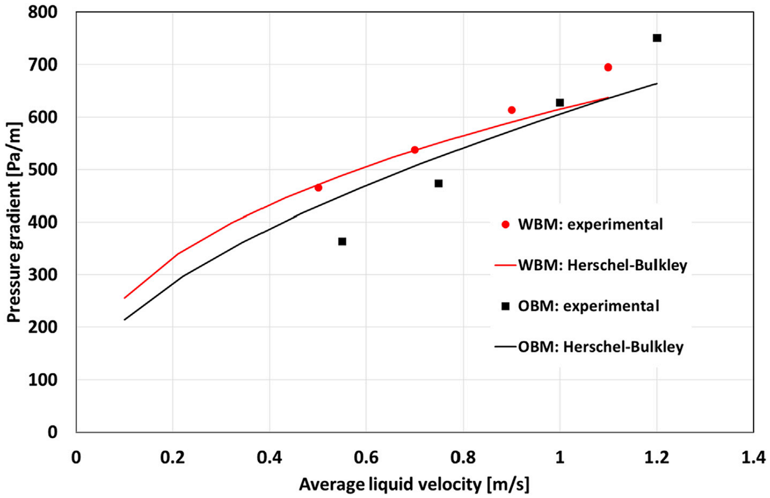

Fig. 4. Comparison of experimental and calculated pressure gradient for WBM and OBM fluids at 0 RPM.

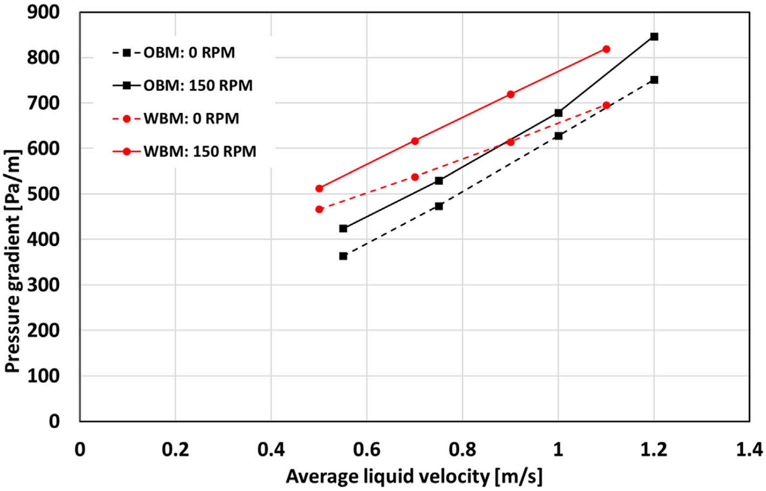

Fig. 5. Pressure drop results (without sand) comparison for WBM and OBM.

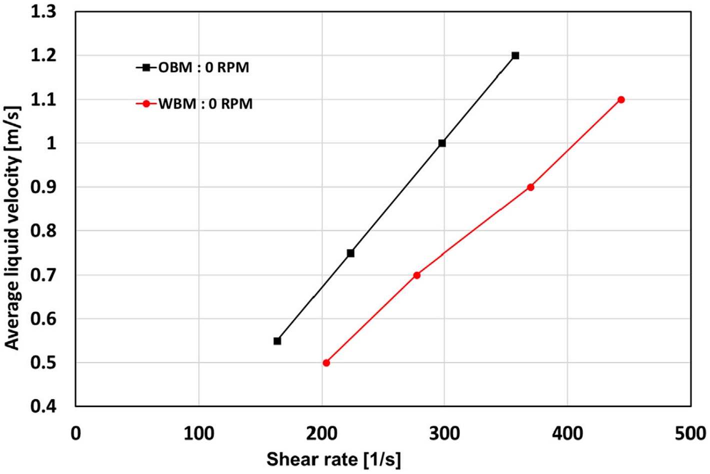

Fig. 6. Average wall shear rates in the flow loop corresponding to flow velocities.

Thus

$$\dot{\gamma} = \left[\left(\tau_w - \tau_y\right)/K\right]^{1/n} \tag{6}$$

Several researchers observed different trends of pressure loss changes with the inclusion of drill string rotation (Ahmed and Miska, 2008; Saasen, 2013). Hansen et al. (1999) and Sterri et al. (2000) observed that pressure drop increases with the increase in drill string rotation while the reverse behavior was reported by Hansen and Sterri (1995). In our case, we observed an increase in the pressure drop with the increase of drill string rotational speed, which is in accordance with most field observations. These seemingly contradictory results can be explained by the competing effects of fluid inertia and shear thinning. In a concentric annulus string rotation will reduce the pressure drop in a shear-thinning fluid. As eccentricity increases inertia becomes more important due to three-dimensional flow effects. Also, in field operations the string will move laterally, adding to the inertia effects. Thus, for a sufficiently eccentric annulus pressure gradient increases with rotation as the inertial effects dominate the shear thinning effects (Wan et al., 2000). In both fluids investigated here, the shear-thinning effect is relatively small. In addition, the string is fully eccentric with free lateral movement during rotation, which explains the observed pressure increase.

Reynolds numbers has been calculated at 0 RPM and 150 RPM cases, using the expression provided by Escudier et al. (2002), in order to understand the hydraulic behavior of the fluids. As shown in Fig. 7, the Reynolds numbers indicate that both the fluids are in the laminar region.

It was observed, however, that there was no major change in the Reynolds number with the inclusion of rotational shear rate component using the definition in Escudier et al. (2002). Effect of rotation has less effect on Reynolds number at a particular velocity but it has varying effect at various velocities as seen from Fig. 8. Fig. 8 shows a variation of Reynolds number ratio with flow velocity. Reynolds number ratio is defined as the ratio of Reynolds number at 150 RPM to the Reynolds number at 0 RPM. Also, rotation of drill string has a diminishing effect on Reynolds number at higher flow rates. Since we observe a significant effect of rotation on pressure gradient the Reynolds number definition used for our calculations is not sufficient to characterize the pressure gradient with rotation (Sayindla et al., 2016).

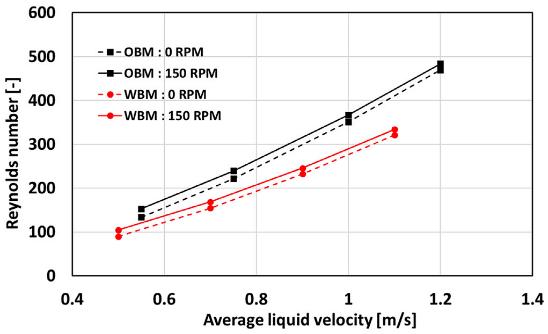

Fig. 7. Reynolds number at various flow velocities for WBM and OBM at 0 RPM and 150 RPM.

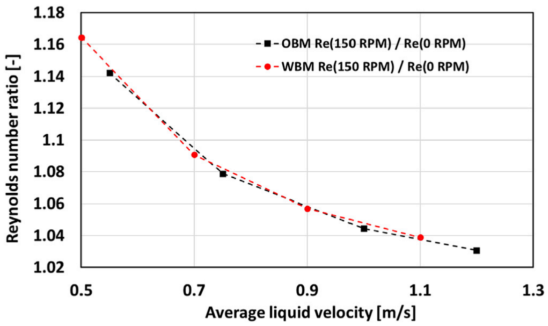

Fig. 8. Variation of Reynolds number ratio with flow velocity for OBM and WBM.

3.2. Cuttings transport

Fig. 9 presents the results from the experiments with continuous injection of sand particles. Experiments with the injection of sand are performed to evaluate the hole cleaning performance of an oil-based and a water-based drilling fluid in a horizontal flow loop. Fig. 9 compares sand holdup of OBM and WBM at four flow rates 0.50, 0.75, 1.0 and 1.2 m/s and at 0 RPM and 150 RPM drill string rotational speed. From the flow loop experiments, it has been observed that the hole cleaning performance of an oil-based fluid is significantly better than the hole cleaning performance of a water-based fluid without the drill string rotation. With the presence of drill string rotation, hole cleaning performances of both the fluids are nearly the same. Compared to the sand holdup of OBM without drill string rotation, the sand holdup of WBM is significantly higher as seen from Fig. 9. At 150 RPM drill string rotational speed, sand holdup of WBM and OBM fluid are likely the same. The same data are shown in Fig. 10 along with data for 50 RPM and 100 RPM, illustrating the positive influence of drill string rotation on the hole cleaning performance. With the introduction of drill string rotation, the sand holdup with both the fluids is significantly reduced. The drill string rotation provides an additional component of velocity i.e., it introduces tangential flow along with the axial flow. This flow helps in improved cuttings transport from the cuttings bed in the annulus.

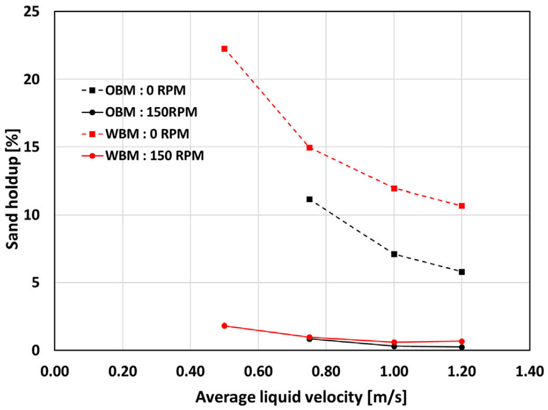

Fig. 9. Sand holdup comparison of WBM and OBM.

One possible reason for the difference in the hole cleaning behavior of water-based and oil-based fluids without the drill string rotation is consolidation of bed. The method of preparation of fluids also has an impact on hole cleaning which in turn effects the consolidation of the bed. Water-based fluids form a more consolidated bed than oil-based fluids (Saasen and Løklingholm, 2002). Polymers present in the water-based fluids can form a strong gel structure in the cuttings bed which resists a large strain. In the absence of drill string rotation this gel structure in the cuttings bed is not broken and is capable of resisting a large strain and therefore OBM has better hole cleaning properties than WBM. Whereas at 150 RPM drill string rotation the gel structure of water based fluid gets broken. This provides similar hole cleaning as in the case with oil-based mud. If the bed has been formed in an oil-based drilling fluid which has no gel structure that connects the cuttings particles, pipe rotation will have less effect on hole cleaning (Saasen, 1998), but the effect can still be noticeable (Ytrehus et al., 2015). From Fig. 10 we can see that rotation of drill string has a significant effect even on OBM which indicates that OBM also could form a gel structure in the cuttings bed. The above argument is in apparent contradiction to the fact that the flow curves indicated a zero yield stress for the WBM and a finite yield stress for the OBM. However, such a dynamic yield stress is not the same as a gel strength which could build up in a cuttings bed with stagnant fluid. Additional rheological measurements conducted on these fluids revealed differences in the viscoelastic responses which resolves this apparent contradiction (Werner et al., 2017). Amplitude sweep tests showed (see Fig. 11) that WBM exhibits dominant viscous behavior and OBM exhibits dominant elastic behavior, which indicates presence of microstructure in the OBM. This microstructure helps to suspend the cuttings in the fluid and hence provides better cuttings transport with OBM. However, at large shear strain values the storage (elastic) modulus G' of the OBM becomes lower than that of the WBM. Thus, the WBM is able to resist larger strain amplitudes and this can explain why WBM appears to form a more consolidated bed, exhibiting a larger resistance to erosion. Thus, rheological investigations made support the findings from flow loop study.

As mentioned above, the sand holdup was calculated from the change in the measured weight of the processing unit. Thus, the calculated sand holdup does not distinguish between a compact bed and suspended sand. However, the no-slip holdup of the sand at the injection rate used (43 g/s) is only 0.28% (at 1 m/s flow rate). This value should be compared to the measured holdup values with 150 RPM rotation and 1 m/s flow rate, which are 0.3% for OBM and 0.6% for WBM, indicating that virtually all particles are transported in suspended mode for this condition.

Fig. 12 compares the pressure gradient values with sand for OBM and WBM at various flow rates and at 0 and 150 RPM drill string rotational speeds. The pressure gradient with KCl at 0 RPM stands out from the other curves, due to the higher bed. Also, the trend is different for OBM and WBM.

4. Conclusions

The hole cleaning performance of a KCl/Polymer water based drilling fluid (WBM) was compared with that of an oil based drilling fluid. Both fluids had similar viscosity profiles. Results in this study illustrate a

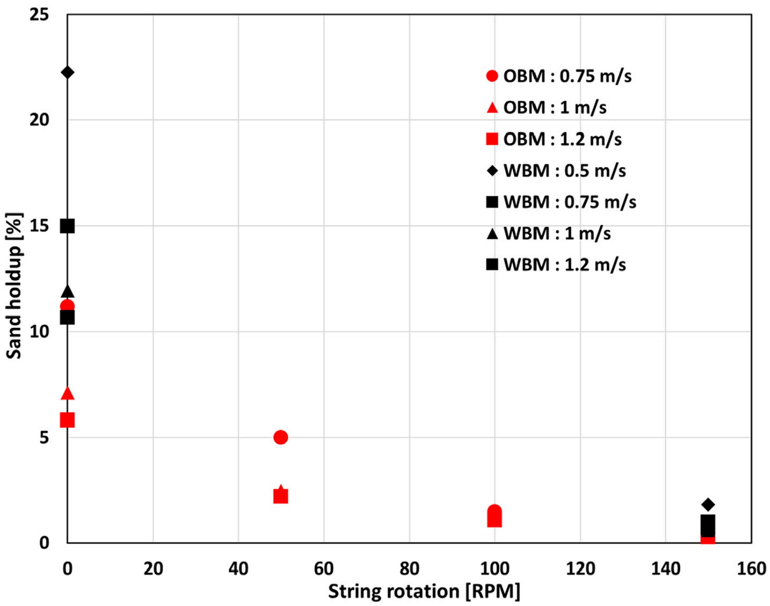

Fig. 10. Effect of rotation on sand holdup with drilling fluids.

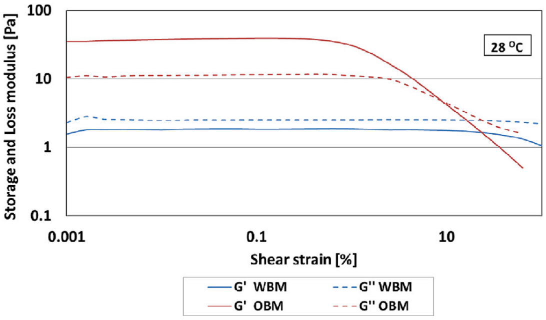

Fig. 11. Amplitude sweep showing storage (G′) and loss (G″) moduli of OBM and WBM fluids at 28 ^{O}C. Amplitude test data taken from Werner et al. (2017).

significant difference in the hole cleaning performance of the drilling fluids with similar rheological properties. In the absence of drill string rotation, hole cleaning was significantly better using the OBM than the WBM. For high drill string rotation rate, the hole cleaning performance of the WBM approaches that of the OBM. This knowledge will be helpful in selection of fluids and also to construct better models for the estimation of cuttings transport. The main hypothesis, that oil-based fluids clean the hole better than water based while the fluids being similar according to API measurements is significantly supported. This hypothesis is derived from observations in field operations. A question has been if these observations are due to differences in the behavior of the fluids cuttings transport capability or if other factors, like the interaction with formation can cause the effects. This study should have eliminated other factors that could cause this observation in a field operation. Such other factors may still contribute to hole cleaning effects in field operations, but it can be concluded that the difference in hole cleaning efficiency observed in these experiments is due to differences in the fluids cuttings transport

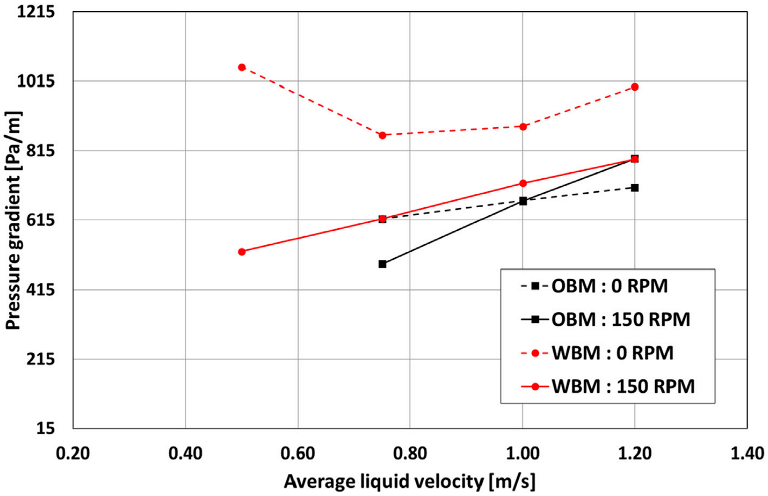

Fig. 12. Pressure drop (with sand) variation with flow velocity for drilling fluids.

efficiency and/or the fluid-cuttings bed interaction.

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Nomenclature

ω	Angular velocity of inner cylinder (rad/s)
U	Bulk axial velocity [m/s]
K	Consistency index (Pa s^{n})
do	Inner diameter of annulus (m)
di	Outer radius of drill pipe (m)
ρ	Liquid density [kgm^{-3}]
Ri	Outer radius of drill pipe (m)
Ro	Inner radius of annulus (m)
$\dot{\gamma}$	Shear rate
n	Flow behavior index
A	Area of annulus section
τ_w	Wall shear stress (Pa)
τ_y	Yield stress (Pa)

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Paper III

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