

# Hole-Cleaning Performance Comparison of Oil-based and Water-based Drilling Fluids

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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 factors 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 rheological properties 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.

## Keywords

Cuttings transport, Drilling fluid, Horizontal drilling, Hole cleaning, Pipe rotation, Rheology

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## 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 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 than oil-based mud. Saasen and Løkklingholm (2002) found that the efficiency of oil-based muds is better compared to water-based muds with similar rheological profiles. The above conclusions

are drawn from laboratory investigations performed at various conditions which may or may not represent the actual field conditions closely.

As noted by (Saasen and Løklingholm, 2002), 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., 2015; Erge et al., 2014; 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 Figure 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.

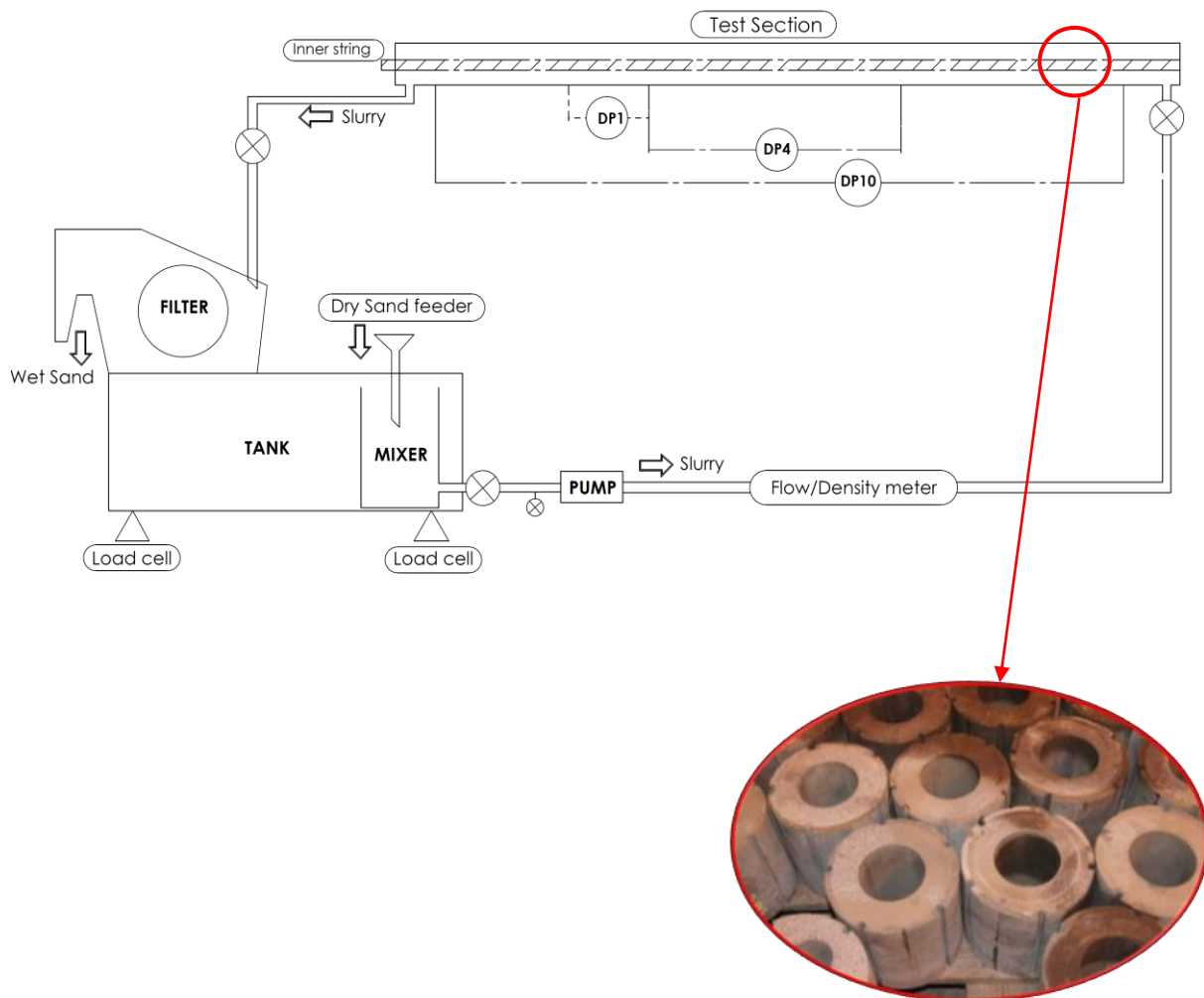


Figure 1 Schematic of the flow loop system (top) and concrete elements (bottom)

The test section consists of replaceable hollow cylindrical elements of concrete with an inner diameter of 100 mm representing the wellbore (see Figure 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  $30^\circ$  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.



*Figure 2 Advanced purpose-built flow rig*

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 5m<sup>3</sup> 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<sup>-1</sup>, which is the most relevant range for the flow loop experiments. Table 2 presents the composition of OBM and WBM fluids.

Table 1 Herschel-Bulkley parameter values of drilling fluids

Property	K [PaS]	n [-]	$\tau_y$ [pa]	Density [kgm <sup>3</sup> ]
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 <sub>2</sub> )	Xanthum gum
Lime (Ca(OH) <sub>2</sub> )	Polyanionic cellulose
Emulsifier	Starch
Fluid loss agent	Soda ash
	Barite
Oil-water ratio 80/20	Not applicable

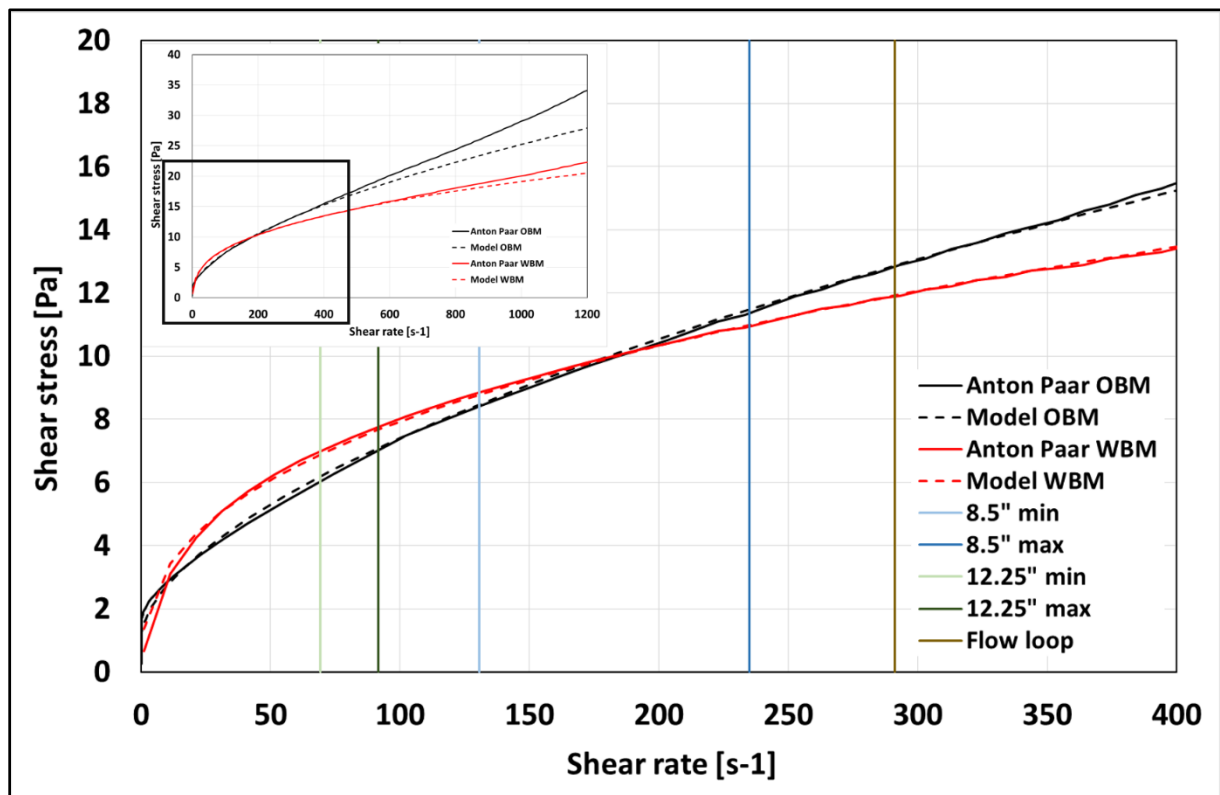


Figure 3 Flow curves of drilling fluids at 28°C with Maximum shear rates in the annulus for various hole sizes

Flow curves of the two fluids OBM and WBM are shown in Figure 3. The shear rates encountered in the flow loop are below about 400 s<sup>-1</sup>. Within that shear rate range, viscosity

profiles of the drilling fluids OBM and WBM are similar as seen from the Figure 3. A rheological analysis of the drilling fluids WBM and OBM were presented in (Werner et al., 2016).

The shear rates in Figure 3 were calculated using equation 1 for OBM fluid, with  $\omega = 0$  (Saasen, 2014). 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.

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

### 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

- Drilling fluid is circulated through the flow loop at a preset velocity
- 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
- 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
- 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
- Cuttings injection is stopped and the flow rate along with the rotation is continued till the hole is clean
- Experiment is 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 the sand in the test section
- 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 Figure 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 Hacıislamoglu 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.

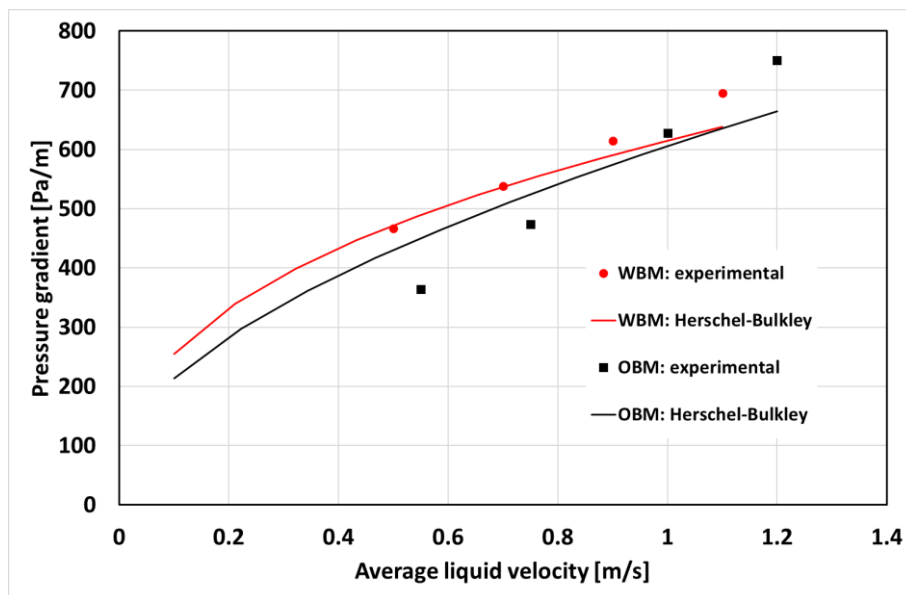


Figure 4 Comparison of experimental and calculated pressure gradient for WBM and OBM fluids at 0 RPM



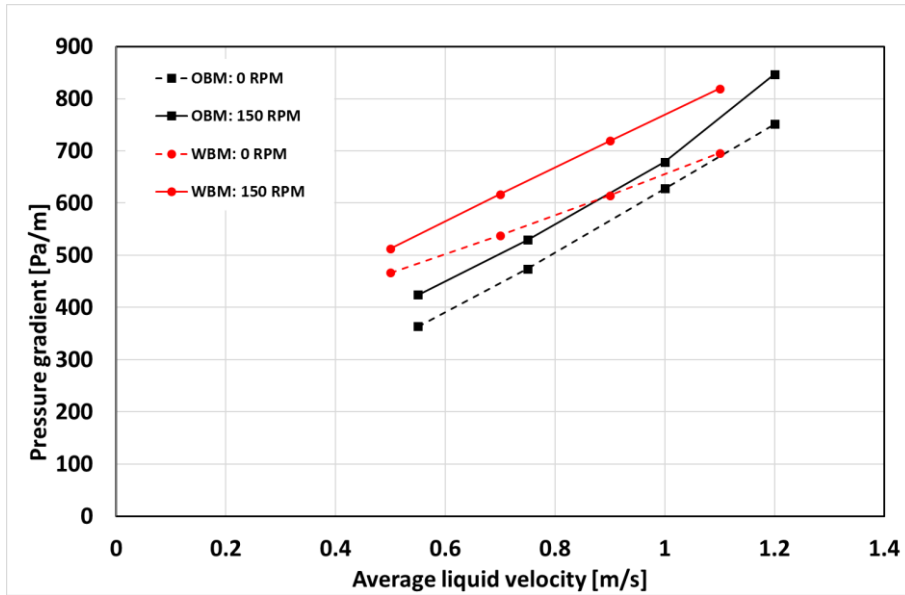


Figure 5 Pressure drop results (without sand) comparison for WBM and OBM

In Figure 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.

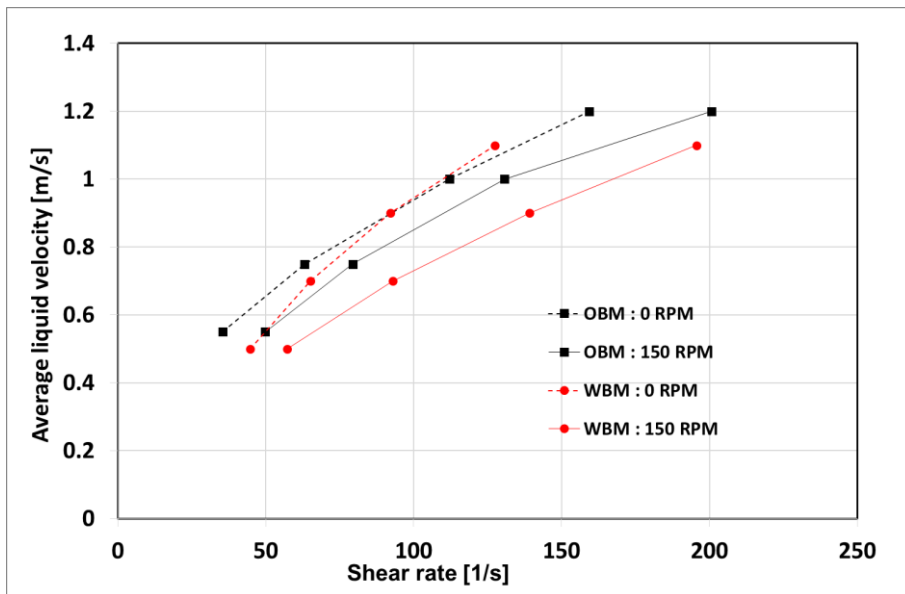


Figure 6 Average wall shear rates in the flow loop corresponding to flow velocities

Figure 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 rate at various flow rates in the annulus is calculated using the equations 2-6.

Momentum balance gives

$$\frac{dp}{dx} A = \frac{dp}{dx} \delta P = 2\tau_w P \quad (2)$$

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

$$P = \pi(R_o + R_i) \quad (3)$$

$$A = \pi(R_o^2 - R_i^2) \quad (4)$$

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

$$\tau = \tau_y + K\dot{\gamma}^n \quad (5)$$

Thus

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

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 Figure 7, the Reynolds numbers indicate that both the fluids are in the laminar region. However, the highest Reynolds numbers are close to the transition to turbulence.

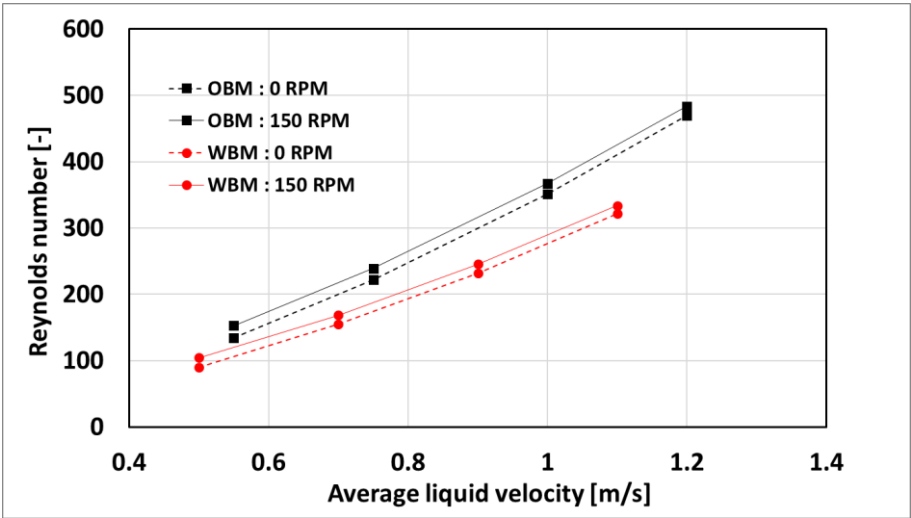


Figure 7 Reynolds number at various flow velocities for WBM and OBM at 0 RPM and 150 RPM

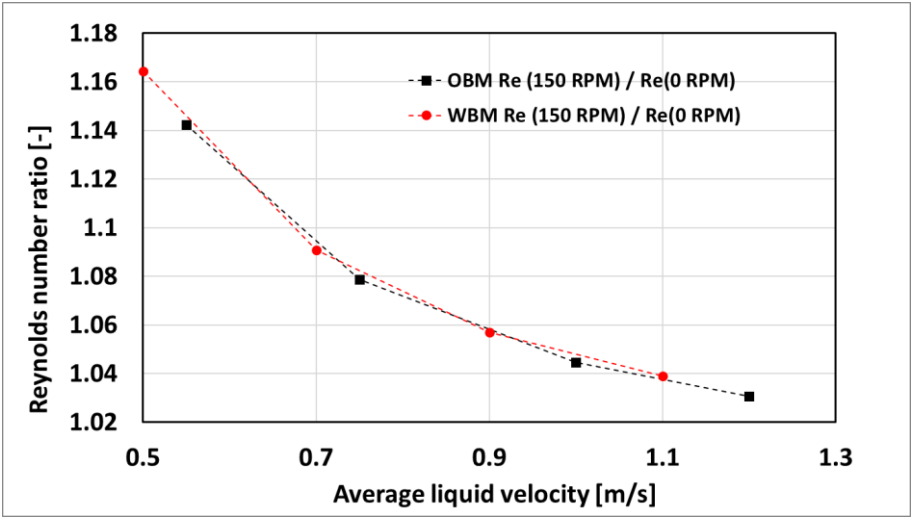


Figure 8 Variation of Reynolds number ratio with flow velocity for OBM and WBM

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 8. Figure 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).

### 3.2. Cuttings transport

Figure 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. Figure 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 Figure 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 Figure 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.

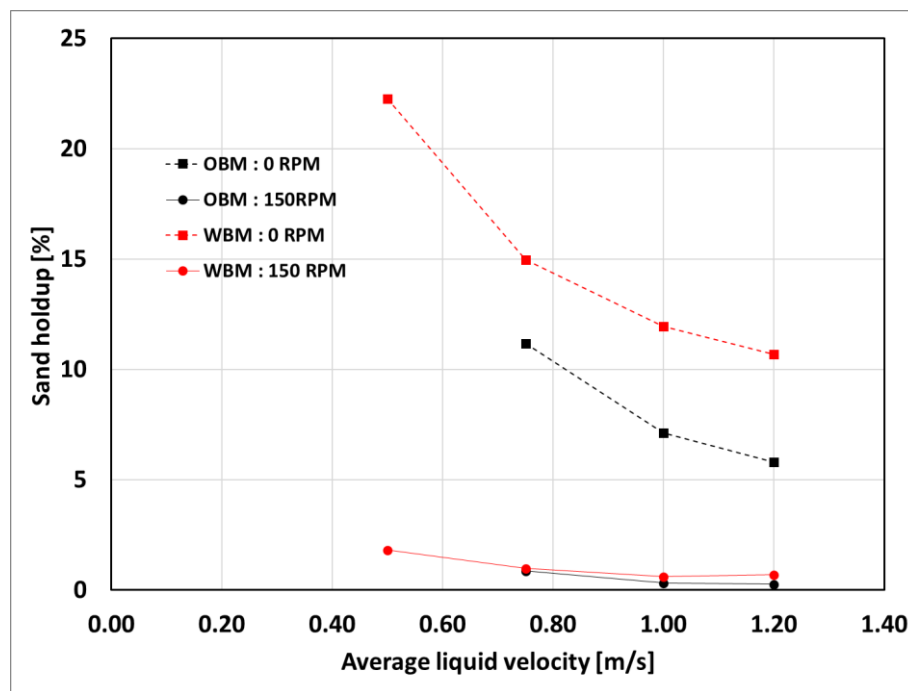


Figure 9 Sand holdup comparison of WBM and OBM

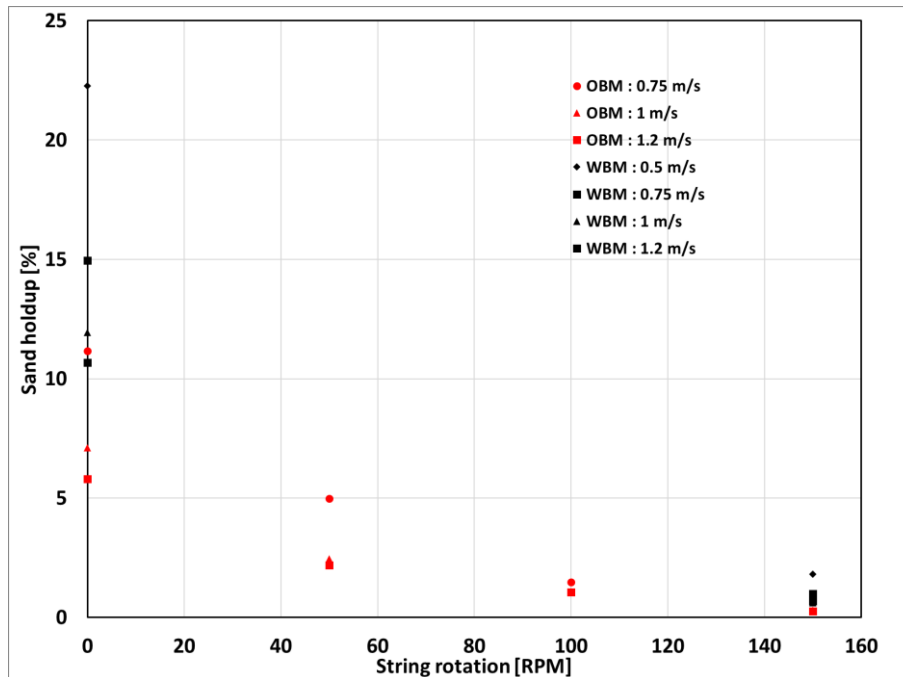


Figure 10 Effect of rotation on sand holdup with drilling fluids

One possible reason for the difference in the hole cleaning behaviour 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 Figure 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 Figure 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.

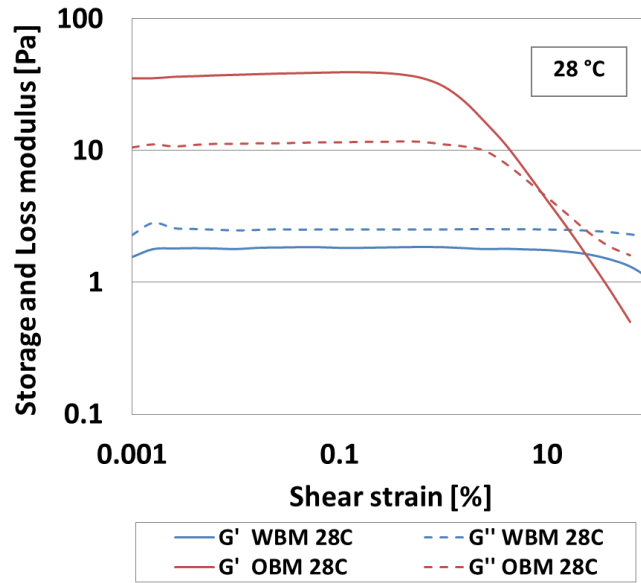


Figure 11 Amplitude sweep showing storage ( $G'$ ) and loss ( $G''$ ) moduli of OBM and WBM fluids at 28°C

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.

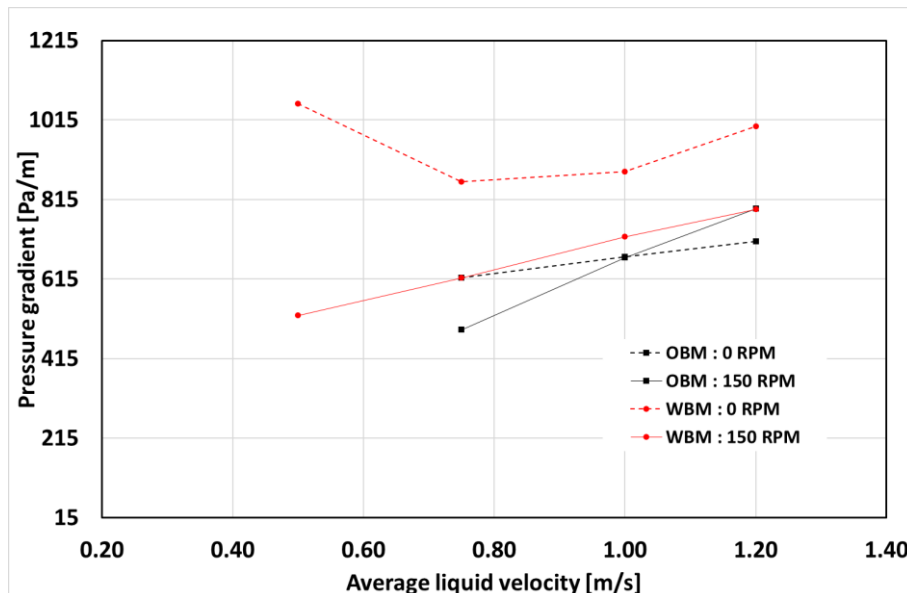


Figure 12 Pressure drop (with sand) variation with flow velocity for drilling fluids

Figure 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 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 behaviour 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 efficiency and/or the fluid-cuttings bed interaction.

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#### Nomenclature

$\omega$	Angular velocity of inner cylinder (rad/s)
$U$	Bulk axial velocity [m/s]
$K$	Consistency index (Pa s <sup>n</sup> )
$d_o$	Inner diameter of annulus (m)
$d_i$	Outer radius of drill pipe (m)
$\rho$	Liquid density [kgm <sup>-3</sup> ]
$R_i$	Outer radius of drill pipe (m)
$R_o$	Inner radius of annulus (m)
$\dot{\gamma}$	Shear rate
$n$	Flow behavior index
$A$	Area of annulus section
$\tau_w$	Wall shear stress (Pa)
$\tau_y$	Yield stress (Pa)

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