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CUTTINGS TRANSPORT WITH OIL- AND WATER-BASED DRILLING FLUIDS

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ABSTRACT

Deviated well sections are common in modern well construction. In mature areas like the North Sea region, practically all producers or injector wells will have highly deviated sections. These wells must be drilled and completed in an optimal manner with respect to drill time, cost, risk and functionality. Most cuttings transport and hydraulic models are developed based on tests with model fluids and often in small diameter test sections. Hole cleaning properties and hydraulic behaviour of field fluids differ from those of most model fluids. Furthermore, results from small diameter tests may not always be relevant for, nor scalable to, field applications due to time, length and other scale differences. Hence, there is a need for studies in controlled laboratory environments with various field application designed drilling fluids to improve engineering models and practices.

This paper presents results from laboratory tests using field applied fluids. The drilling fluids have similar density and viscosity within the relevant shear rate range applied during drilling operations and in the tests. One of the fluids is oil-based and the other one is an inhibitive water-based drilling fluid.

Keywords: Cuttings transport, Drilling fluids, Hydraulics

1. INTRODUCTION

Deviated well sections are common in modern well construction. In mature areas like the North Sea region, practically all producers or injector wells will have highly deviated sections. These wells must be drilled and completed in an optimal manner with respect to drill time, cost, risk and functionality. To drill these wells properly, it is therefore necessary to optimise the hydraulic performance. This performance includes optimising hole cleaning with as low contribution to the frictional pressure loss as possible.

Most cuttings transport and hydraulic models are developed based on tests with model fluids and often in small diameter test sections. Hole cleaning properties and hydraulics behaviour of field fluids differ from those of most model fluids. Furthermore, results from small diameter tests may not always be relevant for, nor scalable to, field applications due to time, length and other scales. Li and Luft [1] conclude that "The empirical models for the sand concentration/sand bed height prediction during RIH or during the hole-cleaning period are limited to the conditions of the flow loop tests. Application of this type of correlation to different operational conditions should be done with caution.". Therefore, tests have been conducted in a sufficiently large laboratory setup using various field applied drilling fluids to improve engineering models and practices both for hole cleaning and frictional pressure losses [2-6]. Some attempts have been performed to describe fluid properties using a semi-physical description like the Quemada model [7, 8, 9]. It is still not yet clear if the use of this understanding will provide additional information for the cuttings transport properties. However, it is likely that the understanding of frictional pressure losses will be improved.

Several research groups focus on hole cleaning experiments. A thorough summary of their work including their experimental equipment has been developed by Li and Luft [10]. In the following, results from large scale laboratory tests using field applied fluids are used to compare the hole cleaning performance of oil and water-based drilling fluids. The drilling fluids have similar density and viscosity within the relevant shear rate range applied during drilling operations and in the tests.

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The experiments have been performed in a flow loop that consists of a 10 meters long test section with 50.4 mm (2") OD freely rotating steel drill string inside a 100 mm (about 4") ID wellbore made of cement. Sand particles were injected while circulating the drilling fluids through the test section. Experiments were performed at three wellbore inclinations: 48, 60 and 90 degrees from vertical. The applied flow loop dimensions are designed so that the results are scalable to field applications [4]; especially for the 12,25" and 8,5" sections. The selected setup is designed to provide correct shear rate ranges and comparable Reynolds numbers to the field application when the same fluids are applied.

Both field experience and laboratory investigations indicate that cuttings transport efficiency can be different when using oil-based drilling fluids compared to using water-based drilling fluids [11] even if the fluids have similar flow curves and fluid characteristics according to API at the exposed shear rates. Current explanations base their arguments on different colloidal effects [12] and presence of normal stress differences in the water-based drilling fluids [6] that is absent when using oil based drilling fluids. Furthermore, recent results have shown that hole cleaning can be different in open gauge hole and inside casing [2].

2. EXPERIMENTAL EQUIPMENT AND FLUID DESIGN

2.1 Experimental design

The experiments are conducted in the flow loop shown in FIGURE 1. In FIGURE 2 it is shown schematically. This experimental facility is constructed as an annulus with a free whirling motion of the fully eccentric drill string during the drill string rotation, illustrated in FIGURE 3. The test section is constructed such that it can tilt between angles from 90° (horizontal) to 48°. The annular dimensions of the flow loop are selected near the minimum of what may be considered relevant to compare the results with field experience. The fluid circulation system is constructed so that field fluids, both oil-based and water-based, can be used. The closed circulation system includes a particle handling system allowing dry cuttings to be injected from a feeder tank at a constant, controlled rate into the fluid. The speed of the particle feeder corresponding to the target particle mass flow rate was determined by a calibration prior to the experiments. The injected particles are in the experiments carried once through the flow loop with the circulating drilling fluid and removed in the separation unit. Particles are not re-injected after being removed from the system, ensuring that initial size distribution is maintained through all experiments. The presented experiments are conducted both without particles and with quartz sand particles in the size range from 0.9 mm to 1.6 mm.

The experimental setup, shown schematically in FIGURE 2, consists of the following main components:

1. Drilling fluid storage tank
2. Sand injector unit
3. Liquid slurry pump
4. Density and flow meter
5. Test section with pressure and differential pressure transducers
6. Sand separator
7. Sand reception system and fluid return to storage tank

The 10 m long test section is built with an outer support pipe, into which a continuous series of hollow cement inserts are placed to represent an open wellbore wall.

FIGURE 1. PHOTO OF THE FLOW LOOP TEST SECTION IN HORIZONTAL POSITION.

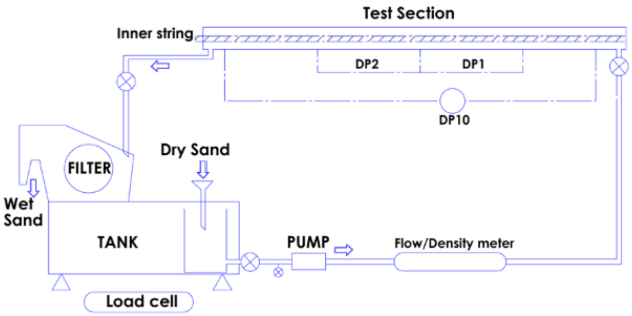

FIGURE 2. SKETCH OF THE FLOW LOOP [3].

Hollow cylindrical sections of cement, all with similar outer annular diameter, D_o = 100 mm, were applied.

The drill string is represented by a steel rod of D_i = 50.4 mm diameter inside the wellbore and defining the inner diameter of the annular test section. For additional information about the experimental equipment please consult Ytrehus et al.[3]. In agreement with Li and Luft [1], Saasen [4] concluded that “even though laboratory experiments are necessary to improve the understanding of well flow phenomena, is not straightforward to use experimental results directly to create correlations. The complexity of the geometry and fluid properties includes far too many dimensionless quantities that need to be within the same range to be valid”. With the used dimensions it is thus possible to stay within well dimensions of the same order of magnitude for drilling operations in 8 ½” section and 12 ¼” section.

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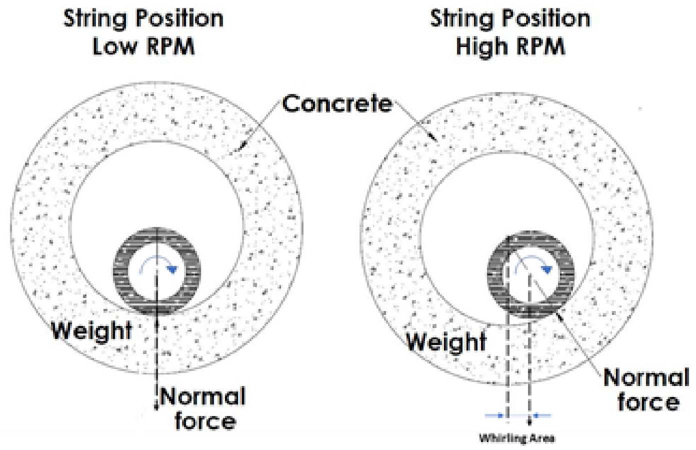

FIGURE 3: SKETCH OF DRILL STRING ROTATION AND WHIRL DURING THE EXPERIMENTS.

2.2 Fluid properties

The drilling fluid volumes are field fluids collected from onshore mud plants supplying offshore installations on the Norwegian continental shelf (NCS). Detailed information about fluid compositions is not available. However, the oil-based drilling fluid is built using a non-aromatic base oil. No low-end modifiers have been used. The water-based drilling fluid was a KCl/Polymer based fluid. The polymers consisted of a blend of PAC and Xanthan gum. No PHPA was used as offshore application of these polymers is limited on the NCS.

The properties are measured using an Anton Paar rheometer using a concentric cylinder option (rotating bob inside a stationary cup). Although the situation is better than when measuring in accordance with API procedures [13], some inaccuracy is expected during the very low shear rate measurements as the rheometer annulus gap is sufficiently large to handle the barite particles and the rheometer cup is relatively small. Within this accuracy, it is reasonable to approximate the drilling fluids' yield stresses by a linear extrapolation using the two lowest shear rate measurements as described by Power and Zamora [14,15] if using measurements in accordance with API. The fluids are modelled as Herschel-Bulkley fluids using dimensionless shear rates to ensure parameter independent Herschel-Bulkley parameters [16-18] as shown in Equation 1. The flow curves are shown in Figure 4 and the Herschel-Bulkley parameters are tabulated in Table 1.

The Herschel-Bulkley model is here expressed as

$$\tau = \tau_y + \tau_s \left(\frac{\dot{\gamma}}{\dot{\gamma}_s}\right)^n \qquad (1)$$

where the surplus stress, $\tau_s = \tau - \tau_y$ is calculated from the yield stress τ_y and the shear stress τ measured at a representative shear rate of $\dot{\gamma}_s$. In this work we used $\dot{\gamma}_s$.= 302 s^{-1}. The flow behavior index, n, must be determined at a different relevant shear rate. This shear rate to match the shear stress was selected to be 152 s^{-1}.

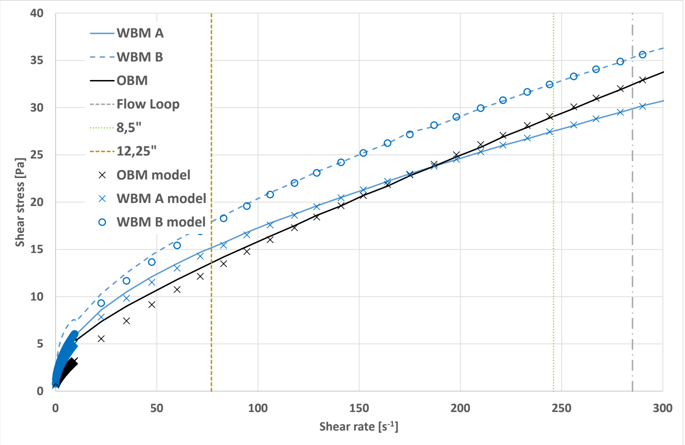

FIGURE 4: VISCOSITY CURVES FOR THE DIFFERENT FLUIDS ARE PLOTTED. VERTICAL LINES INDICATE MAXIMUM SHEAR RATE FOR ANNULAR FLOW IN THE FLOW LOOP CONFIGURATION AND IN RELEVANT WELLBORE SIZES WITH A 5,5" DRILL STRING.

TABLE 1. HERSCHEL-BULKLEY PARAMETERS FOR THE FLUIDS. WBM A INDICATES THE WBM PROPERTIES WHEN STARTING THE CAMPAIGNS AND WBM B IS THE PROPERTIES TOWARDS THE END OF THE EXPERIMENTAL CAMPAIGNS.

	OBM	WBM A	WBM B
τy [Pa]	0.63838	0.61442	0.77715
τs (302 1/s) [Pa]	33.2616	30.1856	35.6229
n (152 1/s) [-]	0.73643	0.55048	0.54981
k [Pa· s^n]	0.49612	1.302	1.5424

The water-based fluid did not maintain a fully constant viscosity profile through the period of experiments. It is very difficult to keep the properties of a large volume field applied water-based drilling fluid completely constant through many circulations in a flow loop. This is well known in field operations and continuous adjustments are made to the fluid batch to maintain the properties. Facilities for such adjustments was not available at our test site. This fluid is therefore represented by a WBM A and a WBM B where the first is reported measurements at the beginning of the experimental campaign and the second from the latest parts. The observed increase in viscosity must be kept in mind when evaluating the results. Possible causes of the viscosity increase are evaporation of water and inclusion of fines from the sand used as cuttings. In the plots the water-based fluid is normally denoted WBM and this fluid will have properties between WBM A and WBM B. For the oil-based fluid these effects were not significant and this fluid is represented by the same fluid parameters through the entire test series.

3. RESULTS AND DISCUSSION

The applied fluids are circulated through the experimental system without any cuttings prior to any tests with injected sand particles. This is to investigate pressure drop profiles for the

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fluids without any disturbances. Such tests will indicate if there are problems with the instrumentation system or if the fluid behavior diverts from the expected. The results can be observed in FIGURE 5.

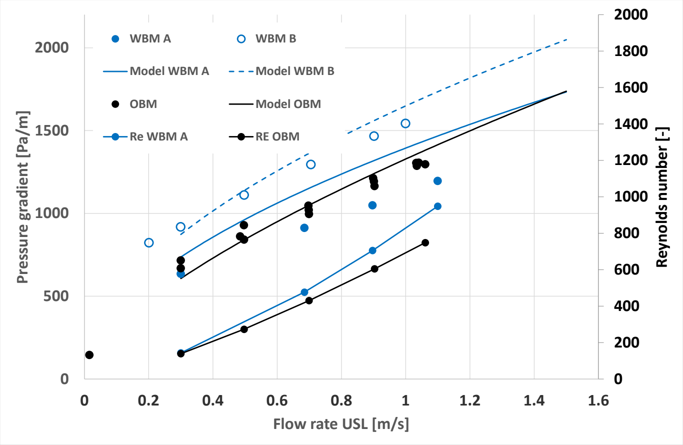

FIGURE 5: PRESSURE DROP PLOTTED AT FLOW RATES FOR OBM AND WBM IN HORIZONTAL POSITION. MODEL DATA AND EXPERIMENTAL DATA ARE INCLUDED. CORRESPONDING REYNOLDS NUMBERS ARE PLOTTED USING SECONDARY AXIS.

One of the most challenging parameters to scale properly between laboratory and field applications is the drill string rotation. In field applications this is often run at RPMs of 100-150. For the flow loop setup, the corresponding rotation rates are likely much lower, but it is difficult to estimate the exact values. The plotted results in FIGURE 6 indicate a significant effect from string rotation already at 10 RPM in the flow loop at a typical flow rate during drilling operations, here represented by 0.7 m/s superficial annular velocity. It can be observed that cuttings are almost fully removed from the test section at 50 RPM and higher rotations when the test section is in horizontal position.

To quantify the cuttings transport efficiency the term relative bed height is introduced. In the following analysis the term bed height refers to the height of a bed with given porosity in the annulus between the wellbore and a fully eccentric drill string. The relative bed height is normalized with respect to the wellbore diameter. The term implies that all cuttings particles are sedimented on the low side of the annulus with a bed porosity. Measurement of the test section weight, mass balance, and a representative bed porosity is used to derive this factor [2, 3]. The contribution of the suspended particles to the mass balance is relatively small and should not give significant inaccuracies.

It can also be observed in FIGURE 6 that the water-based fluid gives a slightly higher cuttings bed than the corresponding oil-based fluid at a flow rate of 0.7 m/s in horizontal section. This observation is in line with the reported results in Sayindla [11], except that the difference in cuttings transport efficiency between the fluids without drill string rotation is significantly less in this plot.

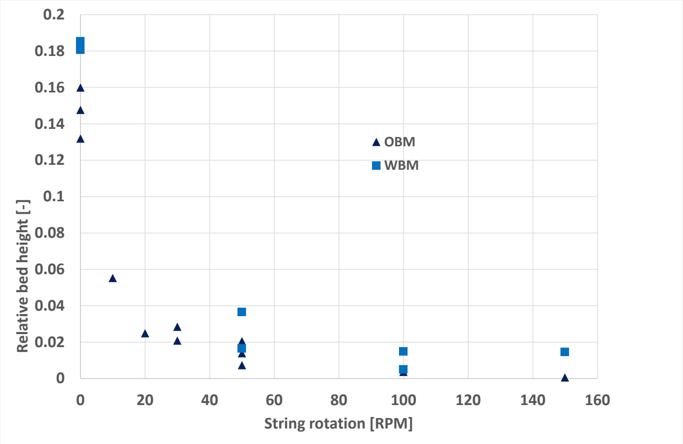

FIGURE 6: PLOT OF CUTTINGS BED FOR OBM AND WBM IN HORIZONTAL POSITION AT INCREASING STRING ROTATION AT CONSTANT FLOW RATE CORRESPONDING TO 0.7 M/S ANNULAR VELOCITY.

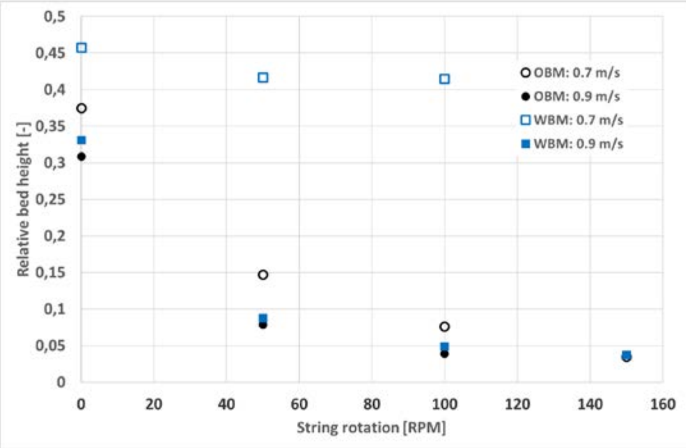

FIGURE 7: CUTTINGS BED IS PLOTTED FOR OBM AND WBM AT 60^o INCLINATION AT FLOW RATES CORRESPONDING TO 0.7 AND 0.9 M/S AT VARIOUS STRING ROTATION SPEEDS.

The cuttings bed height at 60^o inclination is shown in FIGURE 7. A significant difference in cuttings transport efficiency is observed for the flow rate 0.7 m/s superficial velocity. For this flow rate the oil-based fluid provides a distinctly lower cuttings bed height than the water-based fluid. When the flow rate is increased to 0.9 m/s superficial velocity the cuttings bed height for the water-based fluid is significantly reduced, and the differences between the fluids hole cleaning performance is almost not observable when string rotation is present. This observation indicates that the water-based fluid has a critical condition for cuttings transport efficiency with flow rates between 0.7 and 0.9 m/s. For no string rotation the oil-based fluid appears more efficient than the water-based fluid also at the highest flow rate.

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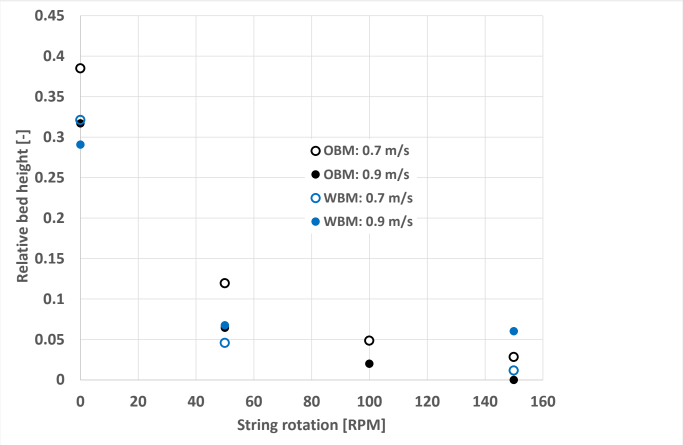

FIGURE 8: CUTTINGS BED HEIGHT, PLOTTED FOR OBM AND WBM, AT 48° INCLINATION AT FLOW RATES CORRESPONDING TO 0.7 AND 0.9 M/S AT VARIOUS STRING ROTATION SPEEDS.

The cuttings bed heights at 48° inclination, plotted in FIGURE 8, show that for flow rate of 0.7 m/s the water-based fluid gives a lower cuttings bed height than the oil-based fluid. This is in contradiction to the observations at the other well inclinations. At a flow rate of 0.9 m/s without string rotation a similar trend is observed. When string rotation is introduced the oil-based fluid is equally or more efficiently in removing cuttings. Since this is more vertical like well section, this effect is likely to be caused by a slightly higher viscosity in the water-based fluid. Initially the water-based fluid had a slightly higher viscosity at the lower shear rates (FIGURE 4). This effect was increased with time due to changes in the water-based fluid. The experiments at 48° were performed as one of the later series, so it is likely a higher viscosity difference between the fluids than in most other plots. In near vertical wells cuttings beds do not exist and increased viscosity is anticipated to improve cuttings removal. For inclinations where cuttings beds are likely to appear during the drilling process the cuttings bed properties may impact the cuttings transport efficiency since different drilling fluids may give different properties in the respective cuttings bed. A possible explanation why oil-based fluids are more efficient for cuttings transport than KCl/polymer water-based fluids at highly deviated sections could likely be effects within the cuttings bed due to polymer chains or other bindings consolidating the bed more efficiently. These aspects are addressed both generally [19] and specifically with the presently used fluids [20] together with a thorough viscoelastic analysis by Pedrosa et al.

4. CONCLUSION

Results show that hole cleaning abilities of the tested fluids vary significantly with well angle, drill string rotation and flow rate. Results support field experience showing that the typical oil-based fluid in most conditions is more efficient for hole cleaning than the similar viscosity water-based KCl/polymer fluids. The results show the effect of cuttings transport efficiency as function of flow rate, demonstrating methods to achieve more optimal hydraulic design in the tested conditions.

The findings support the main conclusions presented for horizontal conditions by Sayindla et al. [11] that oil-based and water-based drilling fluid show differences in cuttings transport capabilities even if their viscosities are similar.

For other inclination angles comparable results are not known. At such tested inclinations, the relative behavior differed a little. In well inclination angle of 60° the oil-based fluid was significantly more efficient at flow rate of 0.7 m/s, while at 48° the water-based fluid was more efficient at the same flow rate, especially in combination with low or no string rotation. For higher flow rates (0.9 m/s) the differences were small or moderate.

ACKNOWLEDGEMENTS

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