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Optimization of Mud Properties and Flow Rates for Cutting Transportation in Directional Wells

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Abstract

Bottom hole cleaning in wellbores is an important issue that has to be recognized when drilling an oil or gas well. This is due to special problems that have been occurring due to the removal of cuttings from high angle wells. The cuttings can settle and accumulate along the bottom of the hole, due to the gravitational pull, causing a number of problems, such as: mechanical sticking, slow drilling, excessive torque and drag on the drill string. Recently, there have been several developments regarding the slip velocity correlations and proper annular velocities in order to prevent the cuttings from slipping. The objective of this paper is to provide an overview of the impact that the various field-controllable parameters have on hole cleaning of directional wells. In this paper, a prototype is used to test the cutting transportation efficiency at different angles, using different drilling fluids and flow rates. A detailed comparison between the results was made in order to determine which properties are the most efficient in cleaning the directional well. After conducting the experiments, the results indicated that the 4% bentonite mud with 0.1% CMC has the highest hole cleaning efficiency when flow rate 2 (0.0211±0.0035 ft^3/s) was being used, regardless of the wellbore inclination.

Keywords: *Wellbore; Inclination; Removal of cuttings; High angle wells; Slipping.*

1. Introduction

Since decades, directional drilling has been an important part of the oil and gas industry, which drill wells at different angles to produce oil and gas from reservoirs that might be difficult to reach. It also reduces the environmental impact to drill several wells at different locations because directional drilling allows for multiple wells from the same vertical well [1].

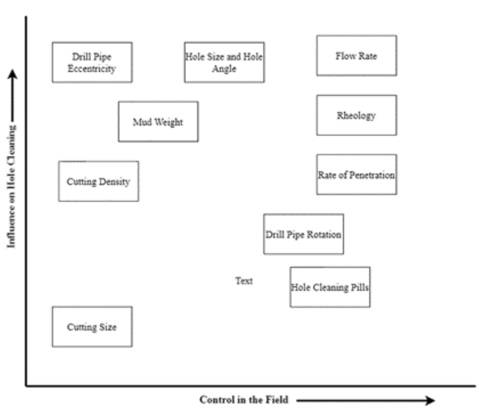

Figure 1. Controllability of the drilling parameters in the field

Numerous initiatives were put into consideration for vertical wells and their hole cleaning. If the hole is not cleaned efficiently, it can lead to problems such as lost circulation, slow penetration rates, and pipe sticking. The main parameters influencing on the efficiency of cutting transportation are the drill pipe eccentricity, density and flow rate of the drilling fluid, and the size of the cuttings [2]. These parameters can be used to control the efficiency of the cutting transportation; however, it depends on how controllable they are in the field. An example would be the drill pipe eccentricity. It has a strong effect on the cutting transportation; however, it is extremely difficult to control during the drilling operations. Figure 1 shows the different drilling parameters and how easily they are controlled in the field [3].There are numerous issues that influence on hole cleaning during directional drilling. The most important issues are:

1.1. Annular velocity of the drilling fluid

The flow rate of the drilling fluid controls the process of cutting transportation. It is anticipated that by increasing the flow rate of the drilling fluid, the cutting transportation efficiency will also increase [4]. However, the maximum allowable flow rate of the fluid is determined by several factors, such as:

- Power availability of the rig.
- Allowable equivalent circulating density (ECD).
- The vulnerability of the open wellbore sections to hydraulic erosion.

During directional drilling, due to the inclination of the well, the cuttings tend to settle on the lower side of the wellbore due to the effects of gravity. Therefore, the velocity should be high enough to keep the cuttings moving towards the surface. If the cuttings are not removed efficiently, they will begin to accumulate. If the annular cuttings concentration in a directional well exceeds a certain level, a cuttings bed will occur.

A bed of cuttings is defined as a large accumulation of cuttings that occurs in the wellbore due to insufficient fluid velocity. If weighted muds are used, the cuttings bed can also contain barite that has sagged to the lower side. Barite sag is described as the changes in the mud weight observed at the flow line. This usually occurs after circulation has stopped for a long time. Most times barite sag leads to problems similar to those caused by inadequate hole cleaning [5].

1.2. Effect of mud rheology on hole cleaning

Rheology is defined as the science of deformation and flow, which refers to different properties and characteristics of the drilling fluid. These properties of the circulation fluid have an effect on solids transport. The rheology included yield values, yield point/plastic viscosity (YP/PV), and viscosity. The rheology is related to shear force, which mainly suspends and carries cuttings. However, the effect of rheology on cuttings transport depends on flow rate, flow regime and inclination [6-7]. As a rule of thumb, low viscosity drilling fluid is effective to erode cuttings bed, but high viscosity contributes to conduct cuttings [8-9].

1.3. Angle of inclination

The difficulty of hole cleaning increases as the angle of inclination increases to about 65° from the vertical. The flow rate requirements are at the highest at angles between 65° and 75°. While difficulties arise with increasing hole inclinations, the selection of the angle of inclination depends on the expected geological conditions. Some of the geological conditions that determine the angle of inclination are reservoir inaccessibility and avoiding troublesome formations [7].

1.4. Annulus eccentricity

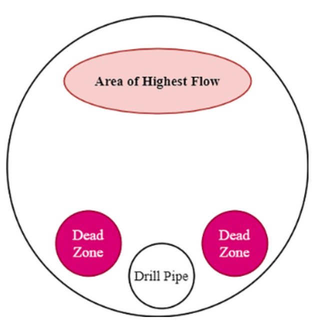

Figure 2. Effect of annular eccentricity on hole cleaning

In the inclined part of the wellbore, the position of the drill string has a significant effect on how efficiently the drilling fluid transports the cuttings in the annulus. The drill string tends to lie on the lower side of the hole due to the effects of gravity [10]. This is the worst position for the drill string because it causes low fluid velocities in the narrow part of the annulus (below the drill string) where most of the cuttings are found, and higher velocities in the broader part of the annulus (above the drill string) as seen in Figure 2. This issue becomes worse as the viscosity of the drilling fluid increases because it causes an increase in the deviation of the fluid from the narrow side to the broader side of the annulus. This is the key reason as to why a drilling fluid with a low viscosity would perform better in directional wells in terms of hole cleaning.

1.5. Rate of penetration

When the rate of penetration (ROP) is increased, the number of cuttings in the annulus also increases [11]. Therefore, it is important to adjust various controllable parameters, such as the rotary speed to maintain effective hole cleaning [12]. However, if the limits of these controllable parameters have been reached and the concentration of the cuttings in the annulus is still too high, the only other alternative is to decrease the rate of penetration. While decreasing the rate of penetration can have an undesirable effect on the cost, the benefits of evading several drilling complications, such as pipe sticking, can exceed the losses [13].

1.6. Characteristics of the cuttings

The size and the shape of the cuttings depend on two factors: the types of bits being used during the drilling operation, and the regrinding of the cuttings that might occur underneath the bit after they are produced. Therefore, it is difficult to control the shapes and sizes of the cuttings [14-15]. Increasing the size of the cuttings results in an increase in the slip velocity of the cuttings causing the difficulty in the transportation to increase [15]. However, by increasing the yield point and gel strength of the drilling fluid, the effects of the higher slip velocity can be overcome [16].

2. Methodology

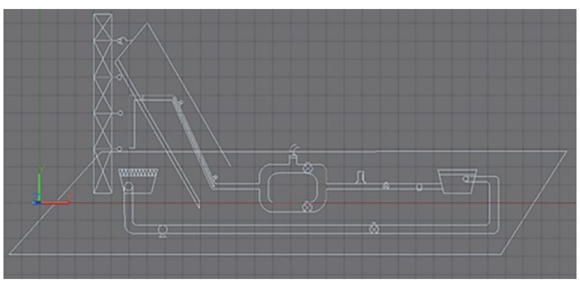

Figure 3. Prototype of a directional well using AutoCAD

Well flow loop set-up was made up in this paper to simulate the effect of different flow rates, cuttings size, and fluid viscosity to be efficiently evaluated. The lab-scale flow loop was tested to ensure function smoothly to obtain reliable data [14]. The prototype of the flow loop for a directional well was designed using AutoCAD as shown in Figure 3. After the design was completed, it was constructed in a workshop in Dasman and the components are as below:

- 1.2 meters wooden board; 1-meter wooden board; 1.5-inch diameter pipe;
- 0.5-inch diameter rod; 1 horsepower water pump; gate valve; support column
- hooks; mud tanks/buckets; sieve; pressure gauges; flow meters.

The entire length of the pipe has a uniform friction factor. After the prototype was ready, it was used to conduct the experiments to test out the efficiency of cutting transportation in directional wells.

3. Experimental procedure

Figure 4 shows the experimental procedure. The first step to start conducting the experiments was to prepare the cuttings. The cuttings were prepared by thoroughly washing them and allowing them to dry. The number of cuttings used for each experiment was 216 grams. Each run involved 3 experiments per angle and 216 grams of cuttings were injected after every experiment. Each run involves 3 different flow rates, without rotating the rod. The flow rates used for each angle were 0.136±0.1 L/s, 0.6±0.1 L/s and 1±0.1 L/s. For the next run, the procedure was repeated with the same drilling fluid and flow rates but with a new angle. After three experiments were conducted for the four angles, a new drilling fluid was used and the process was repeated again. The flow rate is determined by adjusting the valve opening, turning the pump on and then measuring how long it takes to collect 3 liters of the mud. The flow rate is calculated using the following formula:

$$Q\left(\frac{L}{s}\right)=\frac{V}{t} \quad (1)$$

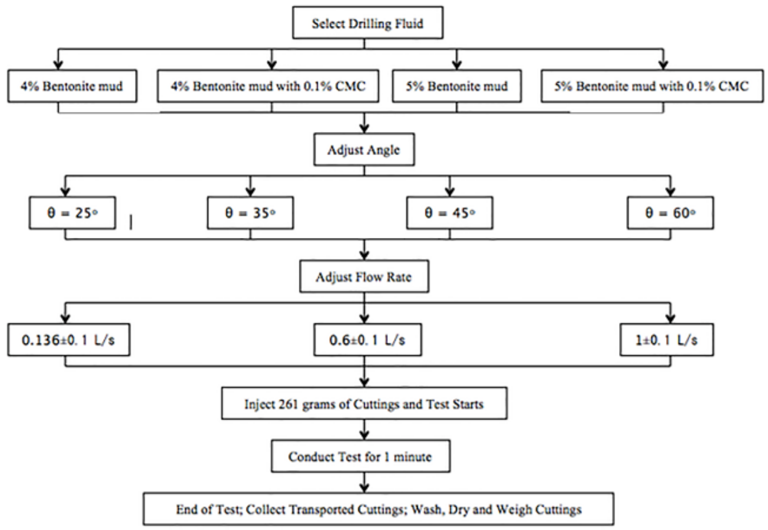

Figure 4. Experimental procedure

After preparing the mud samples, their rheological properties were tested. Different drilling fluids were used in this project as shown in (Table 1) along with their composition and rheological properties. The hole cleaning for horizontal and deviated wells drilling was analyzed experimentally in this paper. Parametric testing was conducted to understand the effect of each parameter on the cutting concentration with time of the directional drilling. The following parameters were considered in this study: flowrate, angle of inclination, yield point, plastic viscosity and depth of the well.

Table 1. Rheological Properties of Drilling Fluids.

Mud number	Composition	θ600	θ300	Plastic viscosity (cP)	Yield point (lb/100ft^2)	YP/PV	Gel strength (lb/100ft^2)	
							10 sec	10 min
Mud #1	Tap water (48L) + 4% Bentonite (2kg)	25	19	6	13	2.167	7	22
Mud #2	Tap water (48L) + 4% Bentonite (2kg) + 0.1% CMC (50g)	29	20	9	11	1.222	4	6
Mud #3	Tap water (47.5L) + 5% Bentonite (2.5kg)	25	17	8	9	1.125	15	21
Mud #4	Tap water (47.5L) + 5% Bentonite (2.5kg) + 0.1% CMC (50g)	35	23	12	11	0.917	12	19

4. Testing procedures

The rheological properties of the drilling fluid were measured using a viscometer. The procedure for testing the rheological properties was as follows:

1. Prepare the mud sample to be tested.
2. Place the recently agitated mud sample in the cup, tilt the upper housing of the viscometer backwards, place the cup by aligning the pins at the bottom of the cup with the holes on the base, then lower the chamber back to its normal position.
3. Turn the knob to raise/lower the base plate until it is submerged in the mud sample to the marked line.
4. Stir the mud sample for around 5 seconds at 600 rpm.

5. Wait for the dial reading to stabilize and then record the value.
6. Repeat steps 4 and 5 for 300 rpm.
7. The plastic viscosity and yield point of the drilling fluid are calculated using the formulas:

$$Plastic\ viscocity\ (cenitpose) = \theta 600 - \theta 300 \qquad (2)$$

$$Yield\ point\ \left(\frac{lb}{100ft^2}\right) = \theta 300 - plastic\ viscocity \qquad (3)$$

8. The apparent viscosity in the Bingham Plastic fluid model is calculated using the following formula:

$$Apparent\ viscocity = 0.5\ \times \theta 600 \qquad (4)$$

9. To measure the gel strength, the sample was stirred at a high speed for 10 seconds or until a constant reading was obtained. Afterward, the sample was uninterrupted for 10 seconds. Turn the viscometer to 3 RPM; the value from the dial reading was recorded in units of lbs/100ft^2. The mud was then stirred again for 10 seconds and was allowed to sit uninterrupted for 10 minutes. The measurement was repeated in the same manner as before, and was recorded as the 10-minute gel strength in units of lbs/100ft^2.
10. The flow behavior index and the consistency factor were calculated using the following formula: $n = 3.32log\left(\frac{\theta 600}{\theta 300}\right)$ (5); $k = \frac{\theta 300}{511^n}$
11. The specific gravity of the cuttings was calculated using the formula: $SG = \frac{1}{2^{-(0.12\times Rw)}}$

where: SG is the specific gravity of the cuttings – bulk density, and Rw is the resulting weight of the cuttings + water in ppg.

The Rw is obtained by following the procedure listed below:

- Wash and dry all the cuttings.
- Set up the mud balance and move the counterweight to 8.33 ppg.
- Fill the mud balance with cuttings, place the lid and move the counterweight until the level bubble is centered.
- Remove the lid and fill the cup with water while the cuttings are still inside.
- Dry the cup from the outside.
- Move the counterweight until the level bubble is centered to obtain the new value. This value is the resulting weight of the cuttings plus water, Rw.

5. Results and discussions

Along with horizontal wellbores with greater inclination angle or/ and longer lateral section, the percentage of cuttings concentration at the wellbore increases. In horizontal portion of the wellbore, cuttings accumulate horizontally; therefore, the fluid velocity has a reduced horizontal constituent [5]. The amount of the cuttings increases with time at a specific horizontal section. So, less distance will be available for the particles/cuttings to be conveyed before they travel through the buildup angle and eventually hit the borehole wall. Improper hole cleaning and formation of beds cause problems such as, premature bit wear, high torque and drag, stuck pipe and slow drilling rates which increase drill time and costs [18]. Optimizing the effect of such parameters will result in maintaining the carrying capacity of the drilling fluids and ultimately enhance the design of horizontal well-bores.

By using trial and error on the flow model, calibration was conducted on diffusivity for indicating a good input velocity regarding diffusivity values. Flow velocity from field method and the approximate solution were compared to verify the groundwater flow model. The velocity computed with the groundwater flow velocity was compared to validate the groundwater flow velocity. The results were simulated and compared for the validation and verification for 1D analytical and numerical codes. Due to the complexities in the 2D numerical coding and time insufficiency, the 2D analytical code was simulated but was not validated and verified.

5.1. Calculating cutting transportation efficiency

$$Recovery\ (\%) = \frac{Final\ Dried\ Weight}{Initial\ Dried\ Weight} \times 100 \qquad (6)$$

The amount of cuttings recovered was calculated using Equation 6. Altogether, 48 experiments were performed. The percentage of recovered cuttings for each run is as follows:

5.2. Effect of fluid viscosity

Increasing the plastic viscosity of the drilling fluid results in a decrease in the number of cuttings recovered. This means that the hole cleaning was improved when the viscosity was not very high. As the viscosity increases, the hole cleaning efficiency starts to decrease. From (Figure 5-8), it has been observed that a plastic viscosity of 9 centipoise results in an increase in cutting recovery for flow rate 2. This would be the second drilling fluid, which is the 4% bentonite mud mixed with 0.1% CMC.

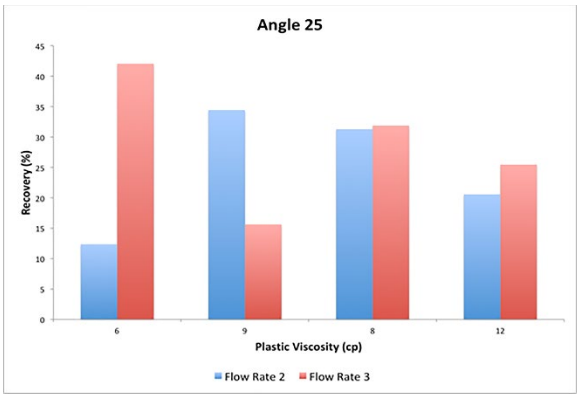

Figure 5. Recovery of cuttings versus plastic viscosity for 25° angle well

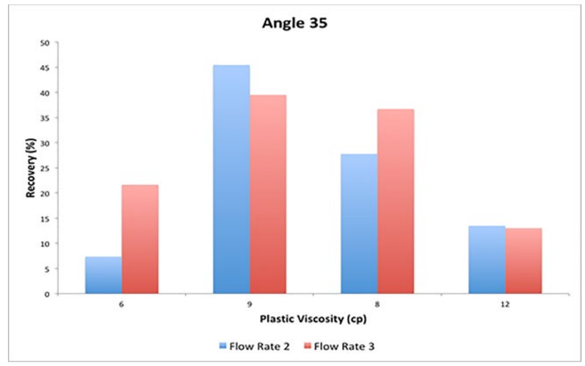

Figure 6. Recovery of cuttings versus plastic viscosity for 35° angle well

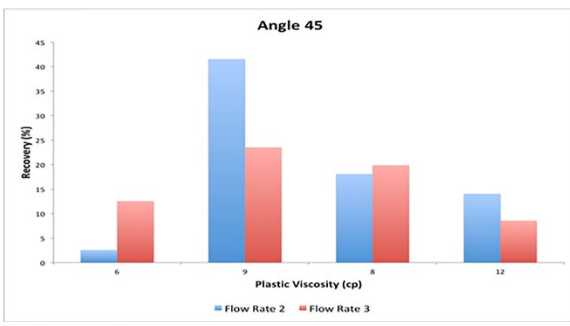

Figure 7. Recovery of cuttings versus plastic viscosity for 45° angle well

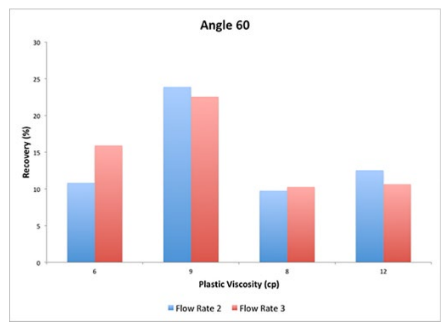

Figure 8. Recovery of cuttings versus plastic viscosity for 60° angle well

The fracture storage generates the flow at the start of the pumping time, which is then gradually supplied from the matrix block primarily from the fracture storage until the late time of pumping. The non-blocked fracture of the pumped well along with the aquifer system is explained as the pure fractured with variable degrees. The double porosity of the weathered quartzite aquifer is observed in the BH9 well graph. The aquifer demonstrates two systems such as high permeability fractures and low storage, and second low permeability matrix blocks and high storage capacity. Initially, at the time of pumping, the fracture storage serves as the source generating flow. A transitional area is observed amid the pumping time when water feeding of the matrix block takes place at an escalated fracture rate through a partly stabilized drawdown. At the time of pumping, both storage and matrix blocks produce water as a consequence of which fracture domain displays an aquifer system with dual porosity aquifer system.

5.3. Effect of hole inclination

The inclination of the wellbore was the main reason why directional drilling is difficult. Throughout the experiments, it was observed that the angle of inclination had a major impact on the hole cleaning efficiency. Figure 9 and 10 shows the number of cuttings recovered for flow rate 2 and flow rate 3, respectively, when the angle of deviation is increased. One chart combines the four different drilling fluids used. The drilling fluid with a plastic viscosity of 9 centipoise always has the highest hole cleaning efficiency. This is the 4% bentonite mud with 0.1% CMC. As the deviation of the wellbore from the vertical increases, the hole cleaning efficiency of the drilling fluid decreases.

In general, the visualization of the hydrogeologic domains is complicated, though, the study attempted the Dahomeyan System visualization concerning the aquifer response to disturbance. Figure 3 first legends exhibit that topography elevation concerning the individual points highlight the location of the borehole at respective elevation comparative to sea level mean. The second level indicates the well depth at the location geological stratum. The subsurface static water level (SWL) is shown in the third legend, showing the comparison between the water level and the sea level mean prior to commencement of pumping. The fourth legend shows the aquifer top relative to the mean sea level. Due to the inadequate yield of the fractures, the BH1, BH6, and BH10 top section aquifer could not be determined as a result of which their position was not recorded in the pumping test. The fifth legend shows the dynamic water level (DWL) which indicates during pumping water level. It is recorded that the rate of pumping is not the same whereas, the pumping duration was similar for just seven bore holds which were recognized as being successful (such as six hours). Moreover, boreholes DWL shows loss of some well due to the persistent pumping which gives resolves some of the well ineffectiveness

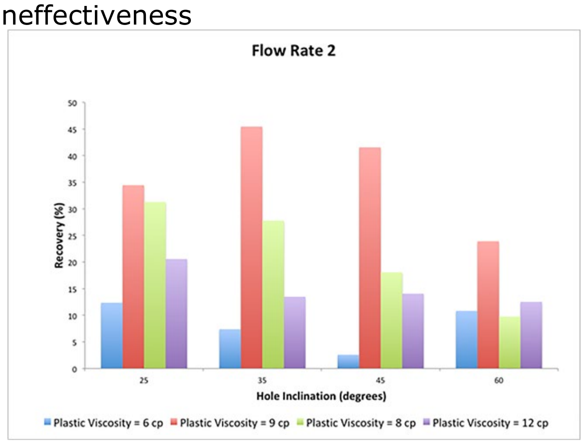

Figure 9. Recovery of cuttings versus hole inclination for flow rate 2

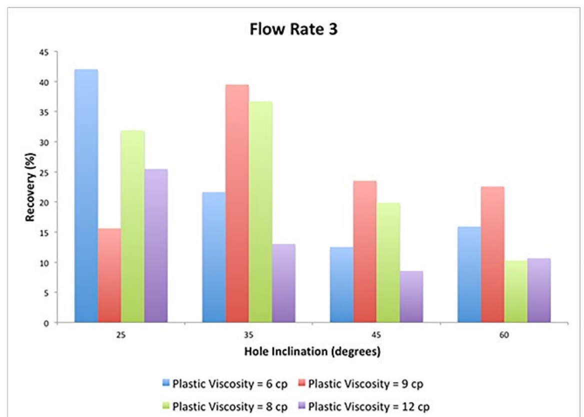

Figure 10. Recovery of cuttings versus hole inclination for flow rate 3

5.4 Effect of flow rate

The effect of the flow rate has an overall positive effect on hole cleaning. Figure 11-14 illustrate what happens when the flow was increased for each angle. When the flow rate was increased from flow rate 2 to flow rate 3 (0.0211±0.0035 to 0.0353±0.0035 ft3/sec), the general effect on hole cleaning was positive because the percentage of recovered cuttings increases.

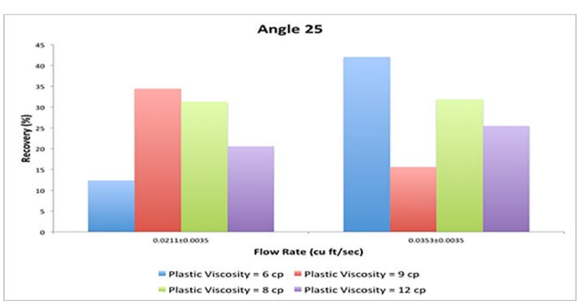

Figure 11. Recovery of cuttings versus flow rate for 25° angle well

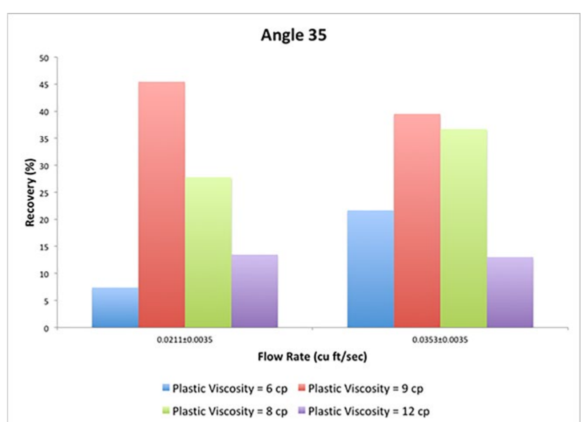

Figure 12. Recovery of cuttings versus flow rate for 35° angle well

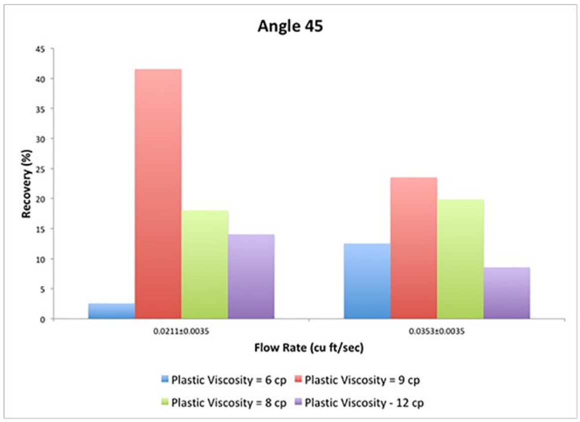

Figure 13. Recovery of cuttings versus flow rate for 45^{o} angle well

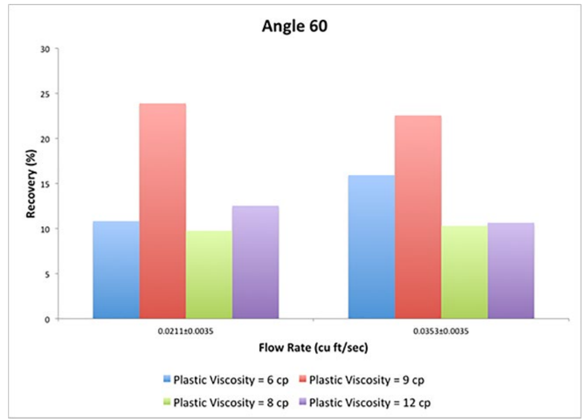

Figure 14. Recovery of cuttings versus flow rate for 60^{o} angle well

6. Conclusions

Based on the experimental results and discussions, the angle of inclination plays a very important role in the hole cleaning of directional wells.

For highly deviated and horizontal sections, cuttings bed removal tool and fiber sweep can be considered. When the plastic viscosity of the drilling fluid was increased, hole cleaning was improved to a certain level. A very high plastic viscosity reduces the hole cleaning efficiency. Generally, by increasing the flow rate, hole cleaning efficiency was increased because the amount of cuttings recovered increases. In general, the 4% bentonite mud with 0.1% CMC had the highest hole cleaning efficiency with a plastic viscosity of 9 centipoise.

This paper recommends that the drill pipe should not be fixed at 100% eccentricity to remove the obstruction and allow the cuttings to flow more freely. Due to the drill pipe being 100% eccentric, when the pump is switched on and the mud gets to the cutting injection site, it carries most of the cuttings all the way to the flexible connection. Due to the drill pipe (rod) being fixed in place to achieve 100% eccentricity, the pathway for the cuttings is somewhat obstructed causing the pipe to be congested. The problem only increases with higher flow rates because the mud will be able to move more cuttings, increasing the congestion.

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