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EXPERIMENTAL STUDY OF HYDRAULIC SWEEPS IN HORIZONTAL WELLS

1. INTRODUCTION

Drilling deviated and horizontal wells has become increasingly common in the oil and gas industry. During the drilling of such wells, gravitational forces cause deposits of drill cuttings along the lower or bottom side of the wellbore, especially cuttings that are smaller sized or generally fine. Drilling fluid sweeps are usually applied in wells to augment hole cleaning, especially in high angle or extended reach wells where efficient hole cleaning is more difficult to maintain than in vertical or near vertical wells. In deviated and horizontal wells, drilled cuttings can accumulate on the lower side of the hole. If left unattended, this accumulation can become severe enough to lead to hole pack offs, stuck pipe, high torque and drag on the drill-string, wear and tear on the equipment and other unwanted incidents of non-productive time.

There is a deficit of information pertaining to use of drilling fluid sweeps available in the literature, an indication that this particular area of investigation has not received much attention among drilling fluid researchers. Also lacking is research into the use of flotation methods for improving the cuttings transport capacity of drilling fluid in horizontal and inclined wells. This study focuses on improving the cutting transport capacity of drilling fluid in horizontal wells by using conventional and enhanced sweeps. The enhanced sweeps employ a type of flotation method, attaching oil droplets to the surface of drilled cuttings with chemical surfactants (Fig. 1, 29, 30).

Much has been written about the role of drilling fluids in the cuttings transport literature [5, 6, 7]. These studies and others debated high viscosity versus low viscosity and which rheological parameters are most useful for characterizing hole cleaning efficiency.

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It has been suggested that flow index "*n*" plays a dominant role in the study of efficient hole cleaning [5] but also that all available rheological parameters (such as n, K and τ_y in the YPL model) should be considered. The use of density sweeps, which involve fluids having a higher density than the "base" drilling fluid in use, has also been proposed [10, 11]. Density sweeps are difficult to study with the available low pressure flow loop, as the addition of weighted material may cause clogging and/or degradation of valves and other problems due to the small size and abrasive nature of the weighting material. However, at this time weighted sweeps are still considered in the Test Matrix.

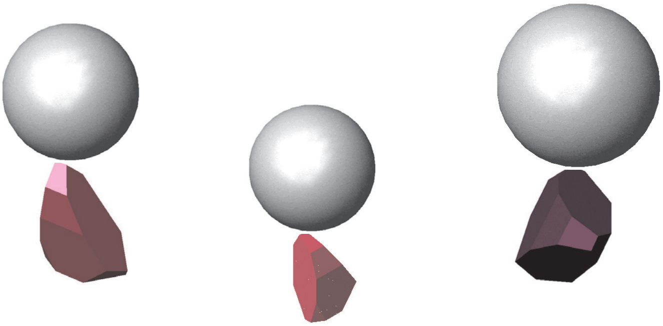

Fig. 1. Oil Droplets Attached to Drilled Cuttings

Studies [8, 9] have used the effective viscosity ratio (i.e, the ratio between the displacing phase to the displaced phase) to describe the effect of rheology of fluids on the efficiency of displacement. They suggest that high values of this ratio are desirable for good displacement efficiencies, all other variables remaining the same. Large values mean that the displacing phase is more viscous than the displaced phase. They also suggest that at low ratios the penetrating front of the displacing phase tends to channel through the center of the flow field, leaving a great deal of the external phase behind.

Fluid velocity is an important factor in the hole cleaning process. This has been cited by many researchers [12–14] in terms of a critical velocity. Fluid velocities can disturb the cuttings lying in the cuttings bed and push them up to the main flow stream. However, if the fluid has inadequate carrying capacity, many of the cuttings will fall back into the cuttings bed.

Pipe rotation significantly [9] influences cuttings bed erosion. Results indicate that rotation results in a velocity profile difference that makes bed erosion easier. Optimizing the use of rotation can also contribute to improvement of drilling efficiency. Sanchez *et al.* [3] focused on investigating the effects of drill pipe rotation on hole cleaning. This study shows that the effect of drill pipe rotation is promising enough that it should not be neglected. Valuri [4] reported that drill pipe rotation has a significant effect on cutting bed height reduction during sweep experiments.

Valuri [4] concluded in his paper that increasing yield stress from 20 lb/100 ft^2 to 30 lb/100 ft^2 and 40 lb/100 ft^2, i.e using fluids with increasingly high viscosity, does not have a significant effect on the bed erosion process within the test conditions. However, drill pipe rotation has a significant effect on bed erosion. In the absence of drill pipe rotation, water and less viscous fluid proved to be more effective than highly viscous fluids. The high viscous, high density sweep proved to be ineffective. The higher viscosity of the fluid may be the cause for this. Although water is very effective in the "bed erosion" process, it has the drawback of being unable to carry cuttings for a long distance. The effectiveness of the less viscous sweep and water are attributed to the flow regime; these two fluids are in turbulent flow at the effective flow rates as opposed to the high viscosity fluids being in laminar flow. This indicates that cuttings are being carried along the test section.

Yu *et al*. [1] proposed technology to counteract gravitation force while simultaneously increasing the drag force by attaching gas bubbles with chemical surfactants to drilled cutting particles. The gas bubbles will pull the cuttings upward because of their buoyancy in the drilling mud thereby counteracting the gravity force. Furthermore, the gas bubble/cutting aggregation will have a larger surface area than the cutting alone, resulting in an increase in the drag force.

2. EXPERIMENTAL SETUP AND FACILITY TESTING

Experiments were carried out on The University of Tulsa Drilling Research Projects (TUDRP) Small Scale Loop (SSL). This flow loop consists of the following sections: annular pipe test section, small cuttings and injection tanks, cuttings separation, sweep tank, pump and flow meter. Figure 2 shows the SSL in the horizontal position.

Fig. 2. Small Scale Loop in the Horizontal Position

Annular test section: The pipe test section is 10 feet long, consisting of an 8 ft. transparent acrylic outer casing (2.4 inches OD and 1.9 inches ID) and a steel inner drill pipe (1 inche OD). One end of the flow loop can be hooked to a pulley, which enables the user to incline the loop to a maximum 45^o from vertical.

Cuttings Injection and Separation System: The injection and separation system is a simple plastic tank connected to a hydrocyclone at the top for separation. Cuttings injection is estimated to take about 1 minute by manual adjustment.

Drilling Sweep Fluids Circulation System: The circulation system consists of a primary tank which is a one barrel sweep tank, a 3-HP centrifugal sweep pump, a sweep flow plastic pipeline, a bypass flexible plastic line and one cuttings transfer 2-inch flexible line. The range tested flow rate of water is 1–40 gallons per minute (gpm) when the test section is in the horizontal position. Once the initial bed has been generated, we perform a sweep liquid holdup in the test section. The "sweep" fluid is pumped through the bypass flexible plastic line in order to clean the cuttings that remain in the hose while transferring cuttings to the test section. Then the hold up valve is opened and fluid is pumped to the test section to perform sweep test. The largest advantage of the SSL is the short time required for running a test and possible reuse of the polymeric fluid.

A 3-Horsepower (HP) centrifugal mud pump (maximum capacity 45 gpm) is used to provide controlled circulation through the loop. A magnetic flow meter is used to measure the flow rate of the mud during the circulation time. A schematic of the SSL is shown in Figure 3.

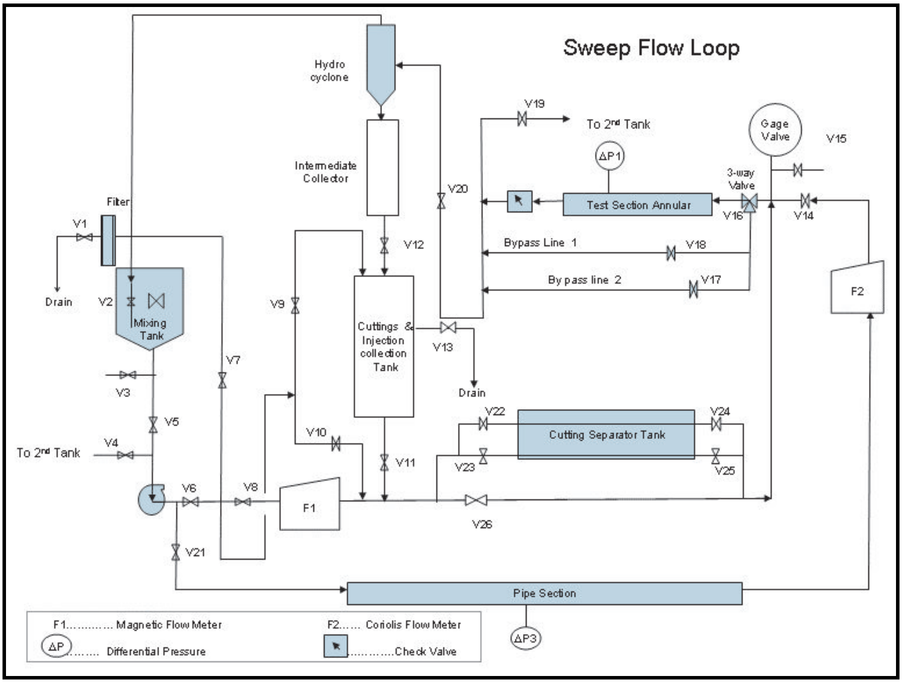

Fig. 3. Schematic Drawing of the Small Scale Loop

3. TEST MATRIX AND FLUID COMPOSITIONS

The project consists of two main stages: experimental and theoretical. Fluids are divided into three groups (Tab. 1) to quantify the properties of the drilling fluid that enhance the efficiency of the “sweep”. A total number of 150 sweep experiments were completed (including repeated tests).

Table 1

Two Main Stages of Study and Three Groups of Fluids

Stage I		Stage II
Group I Low Viscosity	Fluid 1: Water	
	Fluid 2: 0.5PAC / 0.5Xanthan Gum	Fluid 9: 0.5PAC
Group II High Viscosity High Density	Fluid 3: 1.5PAC / 1.5Xanthan Gum	Fluid 6: 2PAC / 2Xanthan Gum Fluid 7: 3PAC / 3Xanthan Gum
	Fluid 4: Density (10 lb/gal)	Fluid 8: Density (13 lb/gal)
Group III Enhanced fluid	Fluid 5: Water + (30%) Sodium Chloride (5%) Oil + Chemical	Fluid 5a: Water + (30%) Sodium Chloride

Group I: The base fluid is water and these fluids are classified as “Low viscosity” fluids; Fluids 1, 2, 9. The composition of these fluids is a mixture of PAC (Poly-Anionic cellulose) and Xanthan Gum in water.

Group II: The base fluid is water and these fluids are classified as “High viscosity, High Density” fluids; Fluids 3, 4, 6, 7, 8. The composition of these fluids is a mixture of PAC (Poly-Anionic cellulose) or Xanthan Gum and Barite in water.

Group III: Base fluid is water and these fluids are classified as “Enhanced” fluids, Fluids 5 and 5a. The composition of these fluids is a mixture of sodium chloride, mineral oil (with and without chemical surfactant) and water. This group investigates enhanced sweep fluids, in which surfactants are used to attach cuttings to oil droplets. The experiments in this part of the study consist of both static and dynamic tests: Initial experiments were conducted in a laboratory to investigate chemical surfactant type and concentration, strength of chemical collector, pH value, and concentration of sodium chloride.

The “Conventional sweep” fluids are mixtures of PAC (Poly-anionic cellulose), Xanthan Gum and barite in water. The “Enhanced sweep” fluids are mixtures of oil, sodium chloride and chemical surfactant in water. Table 2 shows the fluid compositions. Table 3 shows the fluid properties, flow rates, pipe rotation ranges and other test parameters.

Table 2

Compositions of Sweep Fluids

Fluid No	Sweep Type	Composition					Density lb/gal
		PAC lbs/bbl	Xanthan Gum lbs/bbl	Barite lbs/bbl	Sodium Chloride (% of Weight)	Oil (% of Volume)	
Fluid 1	Water	–	–	–	–	–	8.3
Fluid 2	Low Viscosity	0.5	0.5	–	–	–	8.3
Fluid 3	High Viscosity	1.5	1.5	–	–	–	8.3
Fluid 4	High Density	1.5	1	100	–	–	10
Fluid 5	Enhanced Fluid with and without chemical	–	–	–	30	5	9.65
Fluid 5a	Sodium Chloride	–	–	–	30	–	9.65
Fluid 6	High Viscosity	2	2	–	–	–	8.3
Fluid 7	High Viscosity	3	3	–	–	–	8.3
Fluid 8	High Density	1.5	1	300	–	–	13
Fluid 9	Low Viscosity	0.5	–	–	–	–	8.3

Table 3

Test Matrix on SSL

Fluid No	Sweep Type	Flow rate (gpm)	Pipe Rotation (rpm)	Test Time (min)	Bed Height
Fluid 1	Water	5/10/15	0-60-120	3-6-9	50–55% of Pipe
Fluid 2	Low Viscosity	5/10/15/20	0-60-120	3-6-9	50–55% of Pipe
Fluid 3	High Viscosity	5/10/15/20	0-60-120	3-6-9	50–55% of Pipe
Fluid 4	High Density	5/10/15/20	0-60-120	3-6-9	50–55% of Pipe
Fluid 5	Enhanced Fluid with and without chemical	5/10/15	0-60-120	3-6-9	50–55% of Pipe
Fluid 5a	Sodium Chloride	5/10/15	0-60-120	3-6-9	50–55% of Pipe
Fluid 6	High Viscosity	5/10/15/20	0-60-120	3-6-9	50–55% of Pipe
Fluid 7	High Viscosity	5/10/15/20	0-60-120	3-6-9	50–55% of Pipe
Fluid 8	High Density	5/10/15/20	0-60-120	3-6-9	50–55% of Pipe
Fluid 9	Low Viscosity	5/10/15	0-60-120	3-6-9	50–55% of Pipe

Group I “sweep” tests were conducted by using water as the base fluid and the fluids termed as the low viscosity fluids, Fluids 1, 2, 9. An initial test matrix required flow rates of 5, 10, 15 and 20 gpm. Results from these tests indicate that Fluids 1 and 9, reached the maximum (100%) sweep efficiency at 15 gpm, therefore we did not test these fluids at 20 gpm. The test matrix was modified to incorporate sweep tests with maximum flow rates. All the sweep tests were designed for nine-minute sweeps. Group II "sweep" tests were conducted by using high viscosity or high density fluids, Fluids 3, 4, 6, 7, 8. The main idea behind these tests was to study the influence of the change in viscosity or density of the fluid on the sweep efficiency as well as on the cuttings bed height in the test section. Group III "Enhanced fluid" tests were conducted with water as the base fluid, Sodium Chloride and mineral oil (with or without chemical surfactant), Fluids 5 and 5a. The purpose of Group III tests was to study the influence of oil droplets attached to the surface of drilled cuttings with chemical surfactant.

4. FLUID CHARACTERIZATION

Experiments were conducted to estimate the concentration (in lb/bbl) of PAC and Xanthan Gum in water needed to obtain the desired rheological parameters at ambient temperature and pressure. These mixtures were then tested using Chan 35 and Chan 3500 LS$^+$ viscometers. The Chandler 3500LS$^+$ has a spring factor of five so that more precise dial readings at low revolutions per minute (RPM) can be obtained. Shear stress and shear rate were calculated from viscometer dial readings and RPM. The average viscometer readings of sweep fluids from Chan 35 and Chan 3500 LS+ (factor 5) are presented in Table 4.

Table 4

Rheologies Properties of Sweep Fluids

Fluid No	Rheological Properties						
	Yield Power Law Model			Power Law Model Ty = 0		Bingham Plastic Model n = 1	
	Flow Behavior Index, n	Consistency Index, K (lbf*sec^n/100ft^2)	Yield Point, Ty (lbf/100ft^2)	Flow Behavior Index, n	Consistency Index, K (lbf*sec^n/100ft^2)	Plastic Viscosity (lbf*sec^n/100ft^2)	Yield Point, Ty (lbf/100ft^2)
1	1.0000	–	–	1.0000	–	–	–
2	0.4762	0.8530	–	0.4872	0.7870	0.0220	3.2260
3	0.4398	4.1490	–	0.4697	3.3210	0.0830	12.8320
4	0.3843	5.9380	–	0.3867	5.8300	0.0790	17.8340
5	0.3225	0.6870	–	0.4865	0.2050	0.0070	0.8800
5a	0.9949	0.0040	–	1.0106	0.0030	0.0040	–
6	0.2660	19.3110	–	0.2885	16.0060	0.0990	36.3850
7	0.2242	49.7050	–	0.3004	25.9360	0.1760	60.9270
8	0.3334	14.6840	–	0.3809	10.1350	0.1300	30.3460
9	0.7111	0.0990	–	0.7251	0.0900	0.0140	0.6350

5. THE STATIC TEST OF OIL DROPLETS

These tests seek to attack the cuttings transport problem by counteracting gravitational forces and increasing drag forces simultaneously. The primary objective of these tests is to develop a new technology for improvement of cuttings transport using surface chemistry fundamentals. Chemical surfactants were used to attach oil droplets to the surface of cutting particles, resulting in an oil droplet/solid aggregation.

Eighty nine oil droplet static tests in all were performed in test tubes. Table 5 presents the oil droplet static test results. The effect of different parameters such as presence of surfactant, polymer concentration, pH and sodium chloride concentration were investigated in these tests. The oil droplet static tests proved the concept that when an oil droplet adheres to the cutting the increased buoyancy lifts the particle in the fluid to the surface (see Figs. 29–30). This also demonstrates that the oil preferentially adheres to particles depending on the composition of the fluid. There was some attachment of oil droplets to dilled cuttings in tests 53–56 (Tab. 5). However, the fluids in tests 35 and 36 are the best fluid for floating the particles. In the latter fluids the percentage of sodium chloride was 25 and 30% by weight when mixed with 10 ml oil in 400 ml of water.

Table 5

Enhanced Fluid Static Tests in Lab

"Enhanced Fluid" Static Test in Lab							
No	Water	Sodium Chloride	Xanhthan Gum	PAC	Chemical (*)	Oil	Note
	ml	g	g	g	g	ml	
1	200	0	0	0	0	10	pH – 8.11
2	200	2	0	0	0	10	pH – 7.49
3	200	4	0	0	0	10	pH – 7.60
4	200	6	0	0	0	10	pH – 7.70
5	200	8	0	0	0	10	pH – 7.50
6	200	10	0	0	0	10	pH – 7.04
7	200	12	0	0	0	10	pH – 7.40
8	200	14	0	0	0	10	pH – 7.10
9	200	16	0	0	0	10	pH – 7.20
10	200	6	0	0.5	0	10	pH – 7.16
11	200	6	0	0.6	0	10	pH – 7.13
12	200	6	0	0.7	0	10	pH – 7.10
13	200	6	0	0.8	0	10	pH – 7.07
14	200	6	0	0.9	0	10	pH – 7.00
15	200	6	0	1	0	10	pH – 7.04
16	200	0	0	0	0.005	10	0% of Salt
17	200	2	0	0	0.005	10	1% of Salt

Table 5 cont.

18	200	4	0	0	0.005	10	2% of Salt
19	200	6	0	0	0.005	10	3% of Salt
20	200	8	0	0	0.005	10	4% of Salt
21	200	10	0	0	0.005	10	5% of Salt
22	200	12	0	0	0.005	10	6% of Salt
23	200	14	0	0	0.005	10	7% of Salt
24	200	16	0	0	0.005	10	8% of Salt
25	200	6	0	0.5	0.005	10	3% of Salt
26	200	6	0	0.6	0.005	10	3% of Salt
27	200	6	0	0.7	0.005	10	3% of Salt
28	200	6	0	0.8	0.005	10	3% of Salt
29	200	6	0	0.9	0.005	10	3% of Salt
30	200	6	0	1	0.005	10	3% of Salt

(*) Surfactant

First, the concentrations of polymer, sodium chloride, chemical surfactant and oil were prepared according to the test matrix and shown in Table 5. Then the cuttings were poured into the tube from the top. Once the solution and cuttings were in place, a plastic stick was used to agitate the solution to see whether or not the oil droplets attached to the surface of the particles.

The experiments showed that oil droplets of 3 mm diameter can attach and lift the cuttings 2.83 to 3 mm in diameter to the surface. The primary objective of the static experiments is to evaluate the effects of various factors such as chemical surfactant, polymer type, Barite, pH value and sodium chloride concentration on the ability of oil droplets to attach to cuttings.

The effects of different particle sizes were also investigated. Particles with the maximum cuttings size of 2.83 mm millimeter were found to float at the top of the mixed fluid. The cuttings ranging in size from 2–2.83 mm were found to stay on the bottom with oil droplets attached to them. When the fluid was stirred, the cuttings became mobile and those with oil droplets attached to them quickly floated to the surface

6. THE SMALL SCALE LOOP TEST RESULTS

The data that is collected from the data acquisition system is obtained in the form a spreadsheet. From this spreadsheet pertinent information can be selected. This includes the differential pressure, flow rate and drill pipe rotational speeds. Bed heights were recorded at six different locations along an 8-ft long transparent test section in the horizontal position. The tape on the test section and the arrangement of the tapes is shown in Figure 4. It should be noted that the bed heights vary with the eccentricity of the drill pipe. Rotation of the pipe causes the bed height to drop on one side and increase on the other side. Therefore, average values of the bed heights on the two sides of the annulus were measured and plotted. The sweep efficiency term used in this study is defined according to Equation (1).

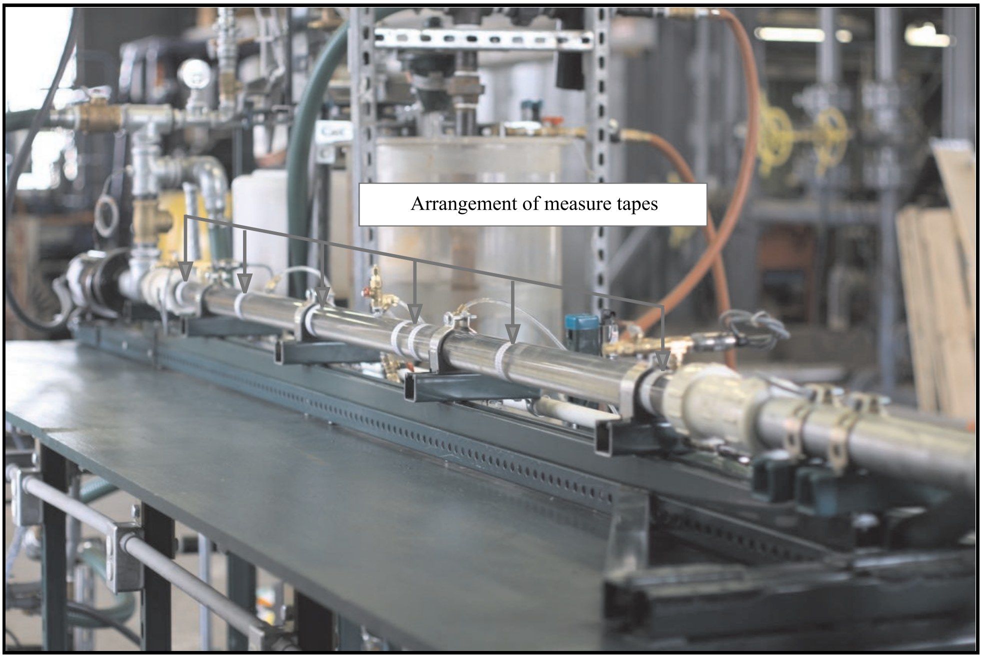

Fig. 4. The arrangement of the measure tapes

The sweep efficiency is also presented as a new term in this study, this term is defined by the following equation

$$E_{Sweep}(t) = \frac{\sum\limits_{Average} \left({}^{h_0}\!/_{D} \right)_{t=0} - \sum\limits_{Average} \left({}^{h_i}\!/_{D} \right)_{t=i}}{\sum\limits_{Average} \left({}^{h_0}\!/_{D} \right)_{t=0}} 100\% \tag{1}$$

where:

$E_{Sweep}(t)$ – the sweep efficiency at given time t (%),

h_0 – the initial bed height (in),

h_i – the bed height at a given time $t = i$ (in),

D – the inner diameter of the casing (in),

$\sum\limits_{Average} \left({}^{h_0}\!/_{D} \right)_{t=0}$ – the average of initial dimensionless bed height at time $t = 0$,

$\sum\limits_{Average} \left({}^{h_i}\!/_{D} \right)_{t=i}$ – is the average of dimensionless bed height at a given time $t = i$.

A total of 150 sweep experiments were completed on the SSL (including repeat tests). This paper presents the results obtained in the SSL with ten different fluids. The tested fluids included Group I (low viscosity), Group II (high viscosity, high density) and Group III (enhanced fluids) respectively. The test fluids differed from each other in the amount of PAC, Xanthan Gum, Barite, Sodium chloride or oil used. The effect of different drilling parameters, i.e. the fluid rheological parameters, drill pipe rotation and flow rate, on cuttings removal are presented in this paper.

Fluid Rheology: Much has been written about the role of drilling fluid rheology in the cuttings transport literature. These studies and many others have debated whether conditions of high viscosity, high density or low viscosity are most useful for characterizing hole cleaning efficiency. The question of which rheological parameters are most important has also been argued. This study includes three of the types of fluids mentioned above and can give an overall picture of the fluid rheology effect on hole cleaning.

Effect of Rheological Parameters

Three different fluids including water were prepared to study the effect of less viscous sweeps on the bed erosion and cutting removal process. The sweep efficiency of low viscosity group is presented in Figure 5. There is no effect of time on the bed erosion at flow rate (5 gpm). The bed height is very much constant along the annulus during the “sweep”. This flow rate is not sufficient to erode the cuttings bed. However, at pump rate 10 gpm, water and Fluid 9 (0.5 PAC) performed well in reducing the cuttings bed height and those two fluids have similar performance. An interesting result presented in this group is the difference between Fluid 9 (0.5 PAC) and Fluid 2 (0.5 PAC, 0.5 Xanthan Gum). The performance of Fluid 2 is poor while Fluid 9 performed well. This may be due to the flow regime when using water or low concentration of PAC.

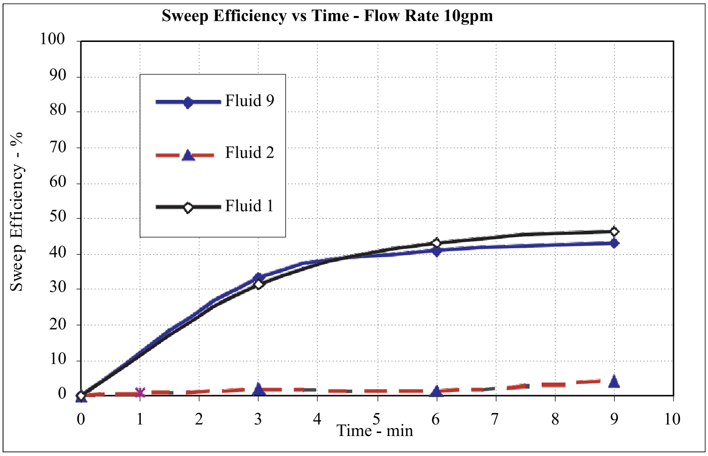

Fig. 5. Sweep Efficiency versus Time at 10 gpm and 0rpm, $V = 1.59$ ft/s

Four different fluids had Bingham Plastic yield points of 12.8, 36.4 and 60.9 lb/100ft^2 (Fluids 3, 6, 7 respectively), The rheological properties of these fluids were calculated and are shown in Table 4. Two different fluids with density of 10 and 13 ppg, Fluids 4 and 8, were prepared to study the effect of rheology and density on the bed erosion and cutting removal process.

The plot of sweep efficiency for Fluids 3, 6, 7, at a flow rate of 10 gpm without drillpipe rotation is shown in Figure 6. This figure indicates that the use of more "viscous" sweeps will increase the efficiency; i.e., "erode" the cuttings bed. This increment was recognized by comparing the change in rheological parameters alone from 12.8 to 60.9 lb/100ft^2. The idea behind these tests was to study the effect of a comparatively higher density to the lower density sweep on the bed erosion process. The higher density sweep Fluid 8 (13 ppg) is more effective than the lower density sweep Fluid 4 (10 ppg). Therefore, there was a significant increment in bed erosion by adding more barite to increase the density to 13 ppg. This result provides further evidence that increasing the density alone, or along with increasing viscosity does improve the erosion process.

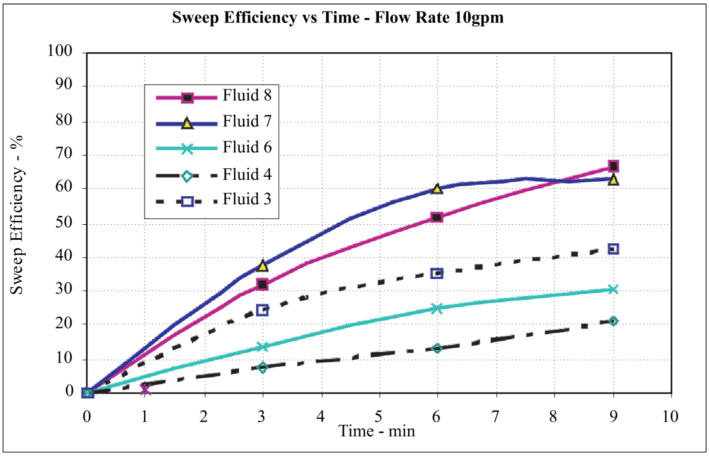

Fig. 6. Sweep Efficiency versus Time at 10 gpm and 0 rpm, *V* = 1.59 ft/s

Figure 6 also shows an increase of 20% sweep efficiency between Fluid 3 (1.5 PAC, 1.5 Xanthan Gum, Bingham Plastic YP 12.8 lb/100ft^2) and Fluid 7 (1.5 PAC, 1.5 Xanthan Gum, Bingham Plastic YP 60.9 lb/100ft^2) at a flow rate of 10 gpm. The sweep efficiency increments are 15, 25, 10% at 10, 15 and 20 gpm, respectively. There is an increase of 40% sweep efficiency between Fluid 4 (1.5 PAC, 1.0 Xanthan Gum, 10ppg) and Fluid 8 (1.5 PAC, 1.0 Xanthan Gum, 13 ppg).

The last group of tests was designed to study the influence of oil droplets attached to the surface of drilled cuttings with a chemical surfactant. The first stage of experimental work in this group was to perform tests under static conditions to prove the concept that the oil droplet can attach and lift the drilled cuttings to the surface. The next stage of this work was to run tests under dynamic condition to see whether the attachments still occur as well as to examine the effects of these fluids on bed erosion and sweep efficiency.

Figure 7 shows a significant reduction in the cuttings bed height. The difference between Fluid 5 (30% sodium chloride, 5% oil) and Fluid 5a (30% sodium chloride) is the 5% of mineral Oil in the composition of Fluid 5. By leaving out the oil from fluid Fluid 5 to create Fluid 5a we see improvement due to the increased density of the fluid. This difference made the performance of Fluid 5 less efficient than Fluid 5a at flow rate, 10gpm. However, both fluids have a significant ability to carry cuttings out of the pipe test section at 10 and 15 gpm. This may have been due to the turbulent flow regime of these fluids. The improved sweep efficiency of Fluid 5a could be explained by the absence of oil in its composition.

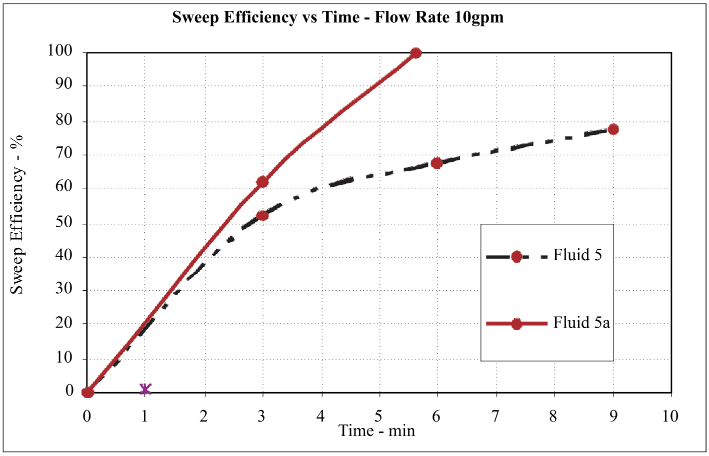

Fig. 7. Sweep Efficiency versus Time at 10 gpm and 0 rpm, $V = 1.59$ ft/s

Sweep Efficiency Comparison of Group I, II and III

There are several “sweep” formulation options available for improving hole cleaning performance, but often little consideration is given to what will be the most appropriate “sweep” for a given set of conditions. Factors that need to be considered when selecting “sweeps” include, fluid density, fluid viscosity, cuttings diameter, drill pipe rotation, etc. The three groups of fluids can help to give an overall of view in determining the efficiency of the “sweeps.” Plots of sweep efficiency versus time for all the test fluids are presented in Figure 8. The sweep efficiency of Fluid 5 (enhanced fluid, 30% sodium chloride, 5% oil, 9.65 ppg) and Fluid 5a (30% sodium chloride, 9.65 ppg) were the best performing , while Fluid 2 (low viscosity, 0.5PAC, 0.5 Xanthan Gum) and Fluid 4 (density 10 ppg) performed poorly. The excellent performance of Fluids 5a and 5 is due to the increase in density from 8.3 to 9.65 ppg by adding 30% concentration sodium chloride. The primary purpose of sodium chloride is to help increase the density of the fluids and buoyancy force of drilled cuttings connected to oil droplets. This force increases as the concentration of sodium chloride increases. Note that although no attachment was actually observed during the dynamic tests, the static tests indicate that such attachments do exist and probably exist in the dynamic experiments, as well, at least in the initial stages of the tests. The flow behavior may show that the viscous fluids are in laminar flow as compared to Fluids 5 and 5a, which are in turbulent flow.

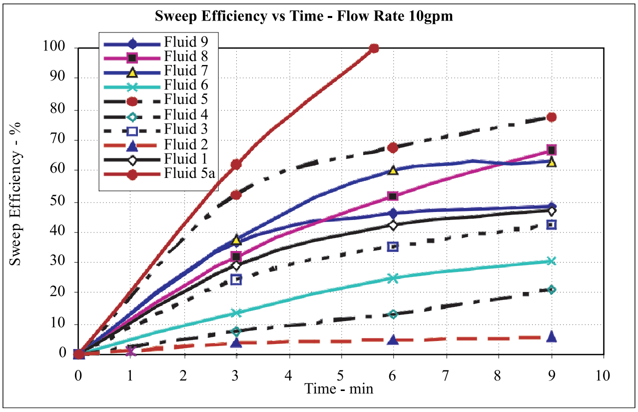

Fig. 8. Sweep Efficiency versus Time at 10 gpm and 0 rpm, $V = 1.59$ ft/s

Effect of Flow Rate

All the tests conducted in this study involving change in flow rate show that there is a considerable improvement in sweep efficiency with increase in flow rate. The results of the "sweeps" are presented in three different groups:

Group I: The effects of flow rate on the sweep efficiency for Group I (low viscosity fluids) are presented in Figures 9, 10 and 11 for Fluids 1, 2 and 9, respectively. These tests were run at flow rates of 5, 10, 15 and 20 gpm.

Group II: The effects of flow rate on the sweep efficiency for Group II (high viscosity, high density fluids) are presented in the Figures 12–16 for Fluids 3, 4, 6, 7 and 8, respectively. These figures are plots of sweep efficiency versus time at flow rates of 5, 10, 15 and 20 gpm.

Group III: Figures 17 and 18, are plots of sweep efficiency for Fluids 5 and 5a at flow rates of 5, 10, and 15 gpm.

All the figures mentioned above show that increasing the flow rate from 5 to 20 gpm increases the sweep efficiency in the absence of drill pipe rotation.

Figure 17 indicates a significant improvement in sweep efficiency of Fluid 5 when increasing sweep rate from 5 gpm to 15 gpm. Sweep efficiency increased from 10% at 5 gpm to 80% at 10 gpm. There was also a great improvement in removing cuttings using Fluid 5a (Fig. 18) upon increasing the flow rate. Upon changing from 5 to 10 gpm, sweep efficiency increased from 8% to 100%. For all ten fluids used in this study, Fluid 5a was the only one to reach 100% sweep efficiency within 6 minutes of test time at a flow rate of 10 gpm.

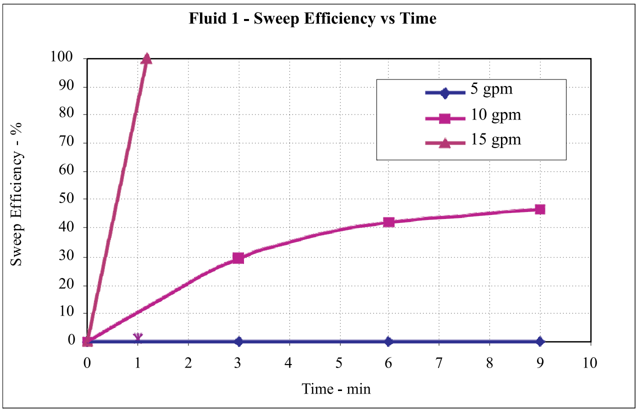

Fig. 9. Sweep Efficiency versus Time at 5, 10, 15 gpm and 0 rpm

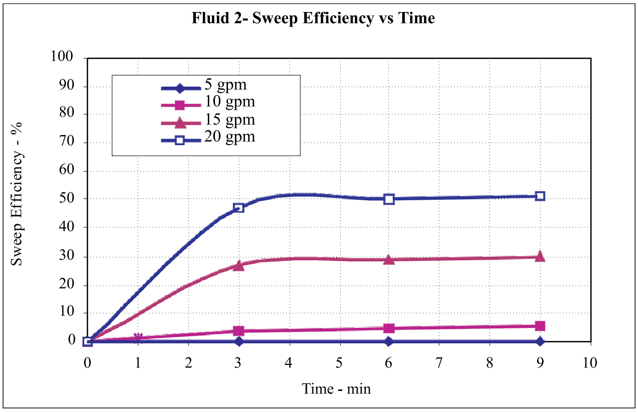

Fig. 10. Sweep Efficiency versus Time

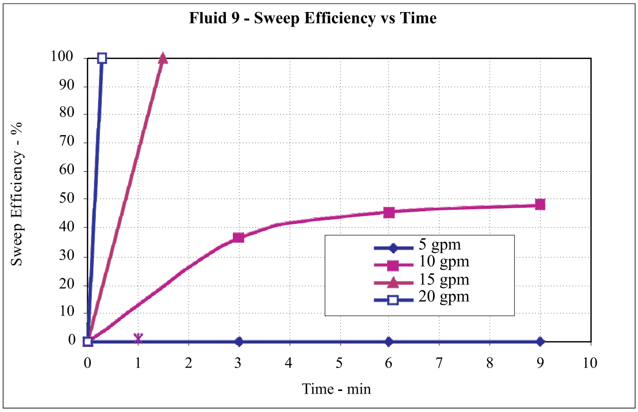

Fig. 11. Sweep Efficiency versus Time at 5, 10, 15 gpm and 0 rpm

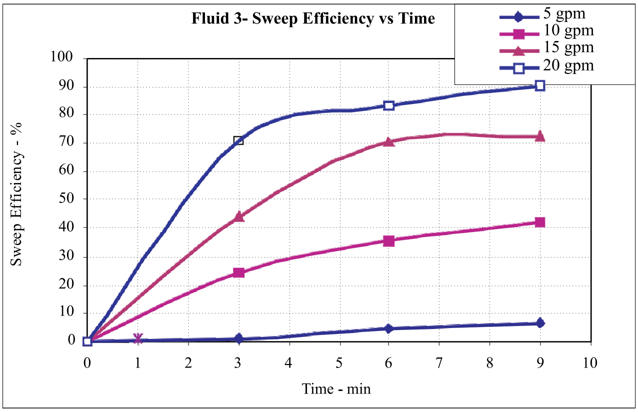

Fig. 12. Sweep Efficiency versus Time at 5, 10, 15, 20 gpm and 0 rpm

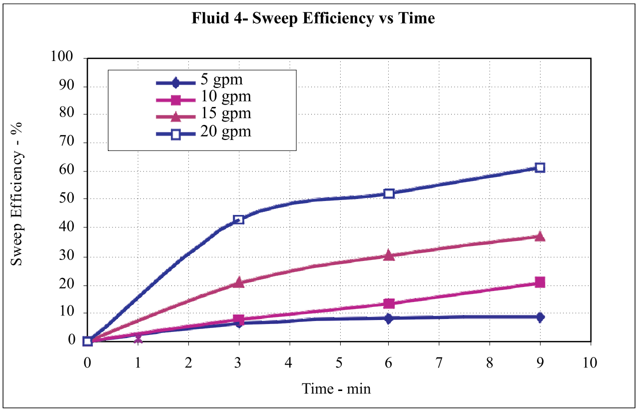

Fig. 13. Sweep Efficiency versus Time at 5, 10, 15, 20 gpm and 0 rpm

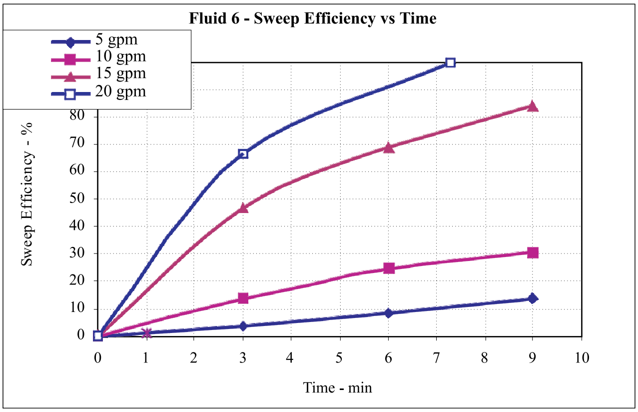

Fig. 14. Sweep Efficiency versus Time at 5, 10, 15 and 20 gpm and 0 rpm

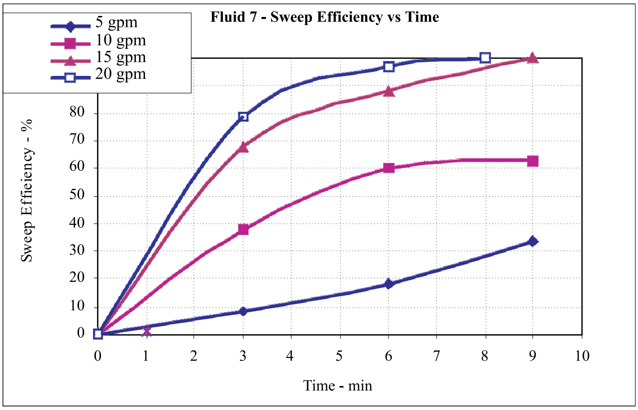

Fig. 15. Sweep Efficiency versus Time at 5, 10, 15, 20 gpm and 0rpm

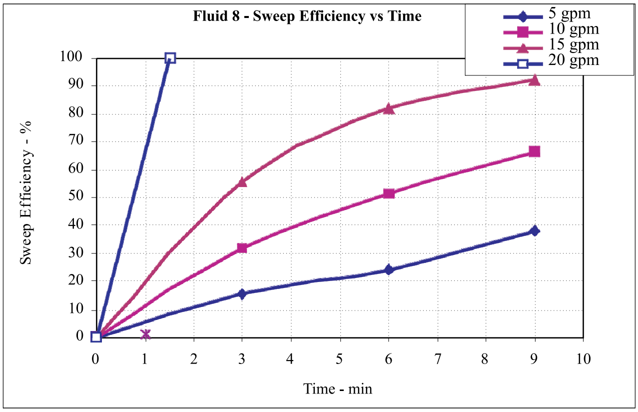

Fig. 16. Sweep Efficiency versus Time at 5, 10, 15, 20 gpm and 0 rpm

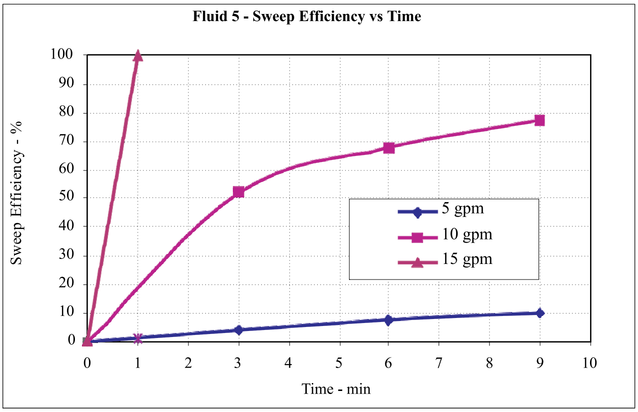

Fig. 17. Sweep Efficiency versus Time at 5, 10 and 15 gpm and 0 rpm

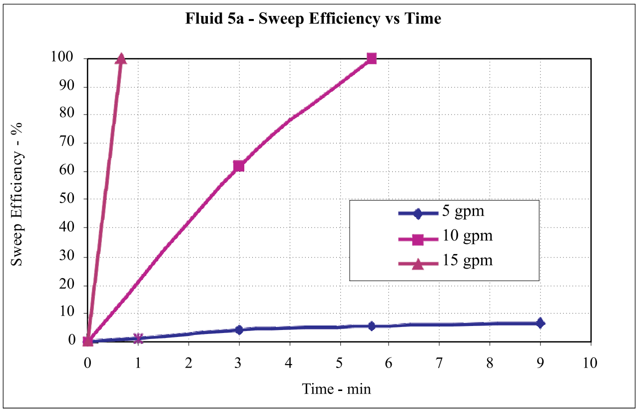

Fig. 18. Sweep Efficiency versus Time at 5, 10 and 15 gpm and 0 rpm

Effect of Drill Pipe Rotation

In order to study the effect of drill pipe rotation, a constant flow rate of 10 gpm was used to test all the fluids. Rotational speeds of 60 and 120 rpm were investigated. Bed erosion at 10 gpm and 0 RPM with all the test fluids is shown in Figure 8. In preliminary tests with Fluid 1 (water) as the drilling fluid, the bed erosion tests with drill pipe rotation yielded good results. Drill pipe rotation at 60 and 120 rpm has a significant effect on hole cleaning for all the tests conducted. Most of the tests indicate that increasing the rpm also improves the sweep efficiency, however there were a few tests in which increases RPM from 60 to 120 did not have any noticeable effect on the bed height. Pipe rotation helps in mechanical agitation provided by the relatively eccentric drill pipe. Pipe rotation changes the cuttings accumulation in the annulus. The direction in which pipe is rotating forces cuttings toward that side of the annulus. The cuttings height results in dunes formation. The effect of pipe rotation is presented in three different groups, as structured before.

Group I: Figures 19–21 are the plots of sweep efficiency for fluids with low viscosity at flow rates of 10 gpm pipe rotation speeds of 0, 60 and 120 rpm. These Figures show a considerable effect on the sweep efficiency at 60 rpm and indicate that increase of rpm increases the sweep efficiency.

Group II: Figures 22–26 are plots of sweep efficiency for fluids with high density and high viscosity at flow rates of 10 gpm pipe rotation speeds of 0, 60 and 120 rpm. These Figures show a significant effect on the sweep efficiency at 60 rpm especially for high viscosity fluids. Increasing rpm from 0 to 60 (Fig. 24) increases the sweep efficiency from 45 to 100%. It was observed that cuttings that lie on the lower side of the hole are forced under the rotating drill pipe. As the height of cuttings on the other side of the pipe (in the direction of pipe rotation) decreases, cuttings are able to move out from underneath the pipe. Thus, pipe rotation plays an important role in cuttings transport in a horizontal annulus.

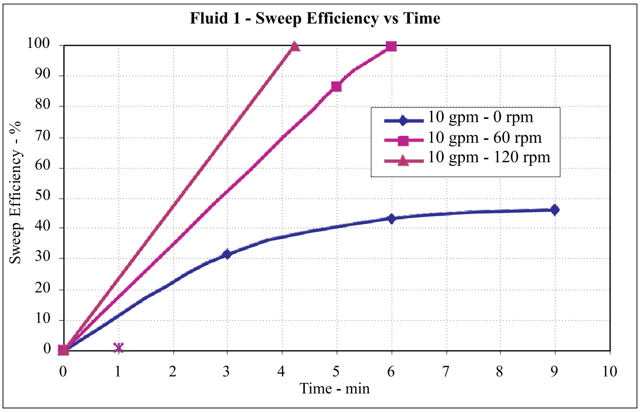

Fig. 19. Sweep Efficiency versus Time at 10 gpm and 0, 60, 120 rpm

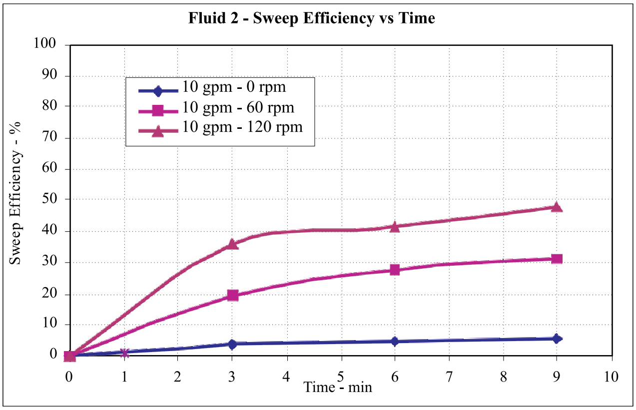

Fig. 20. Sweep Efficiency versus Time at 10 gpm and 0, 60, 120 rpm

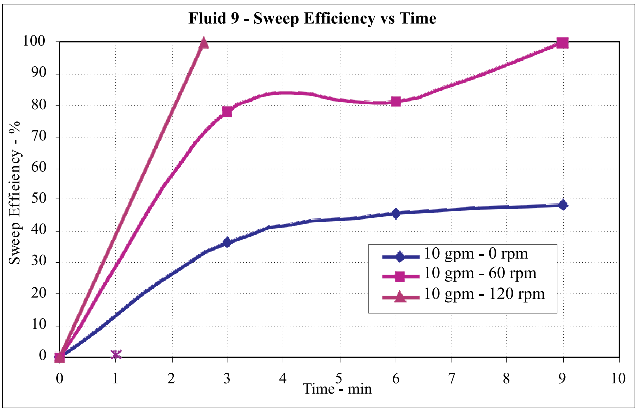

Fig. 21. Sweep Efficiency versus Time at 10 gpm and 0, 60, 120 rpm

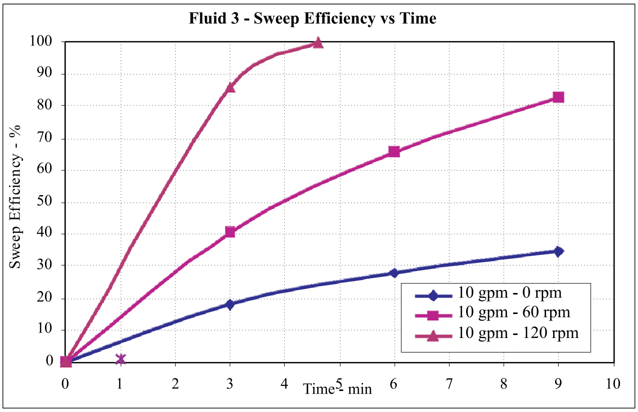

Fig. 22. Sweep Efficiency versus Time at 10 gpm and 0, 60, 120 rpm

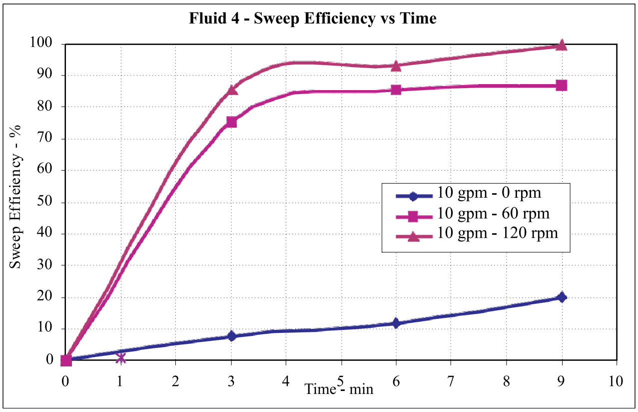

Fig. 23. Sweep Efficiency versus Time at 10 gpm and 0, 60, 120 rpm

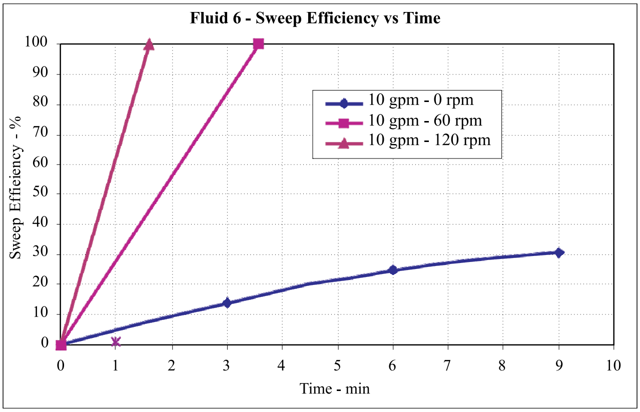

Fig. 24. Sweep Efficiency versus Time at 10 gpm and 0, 60, 120 rpm

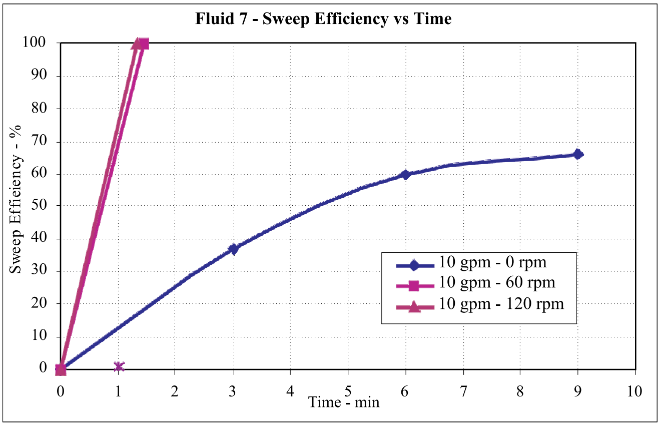

Fig. 25. Sweep Efficiency versus Time at 10 gpm and 0, 60, 120 rpm

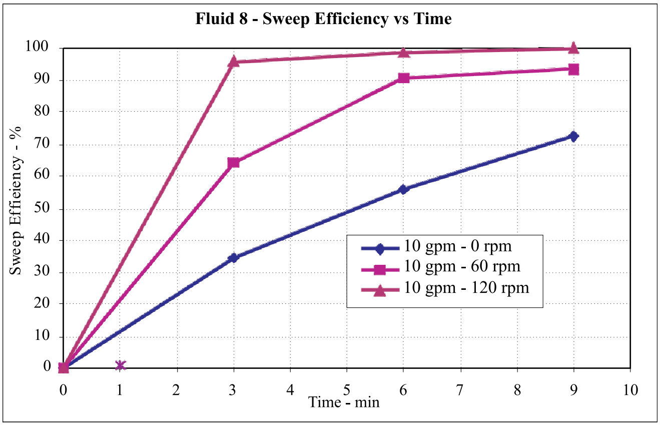

Fig. 26. Sweep Efficiency versus Time at 10 gpm and 0, 60, 120 rpm

Figure 25 does not show any noticeable change of sweep efficiency at the rotary speed 60 and 120 rpm, increasing pipe rotation from 0 to 60 rpm was more significant than from 60 to 120 rpm. However, rotary speed of 60 rpm shows greater improvement in sweep efficiency for the higher viscosity fluids tested. This was true for the polymer fluid systems. It is again believed that the most enhancement in hole cleaning due to pipe rotation is a result of the mechanical agitation of cuttings on the low side of the well bore and also the fact that the pipe lifts off from the low side to the high side as it rotates.

Group III: Figure 27–28 are plots of sweep efficiency versus time for Fluids 5 and 5a at flow rates of 10gpm and pipe rotation of 0, 60, 120 rpm. Increasing of the rotary speed from 0 to 60 rpm does have an effect on the sweep efficiency of either Fluid 5 or 5a. However, increasing the rotary speed from 60 to 120 gpm does have an effect on Fluid 5.

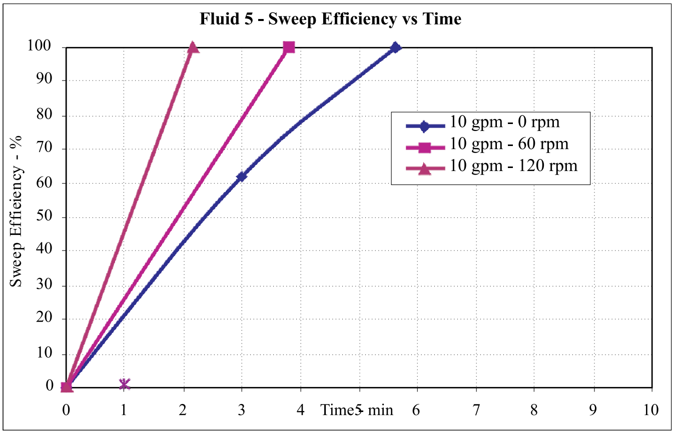

Fig. 27. Sweep Efficiency versus Time at 10 gpm and 0, 60, 120 rpm

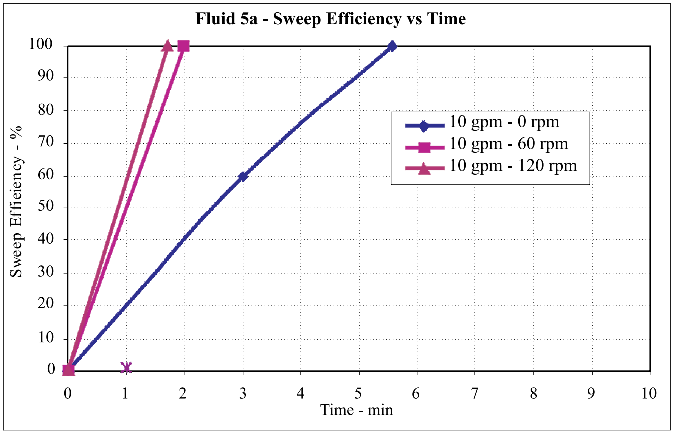

Fig. 28. Sweep Efficiency versus Time at 10 gpm and 0, 60, 120 rpm

The level of improvement in hole cleaning as a result of drill pipe rotation can vary from moderate to significant depending on fluid rheology and drill string rotary speed. In Figure 23, rotating the pipe at 120 rpm can result in as much as an 80% increase in the sweep efficiency of Fluid 4. Consequently, drill pipe rotation has a major effect on hole cleaning. At low flow rates, the annular velocities are not high enough to sweep 100% of the cuttings bed. A residual concentration was generally left when the pipe was not rotating. However, when the pipe was rotating at 120 rpm, in most of the tests, it was possible to clean the annulus completely. Also, the time it takes to clean the hole can be reduced even with the lower rotary speeds of 60 rpm.

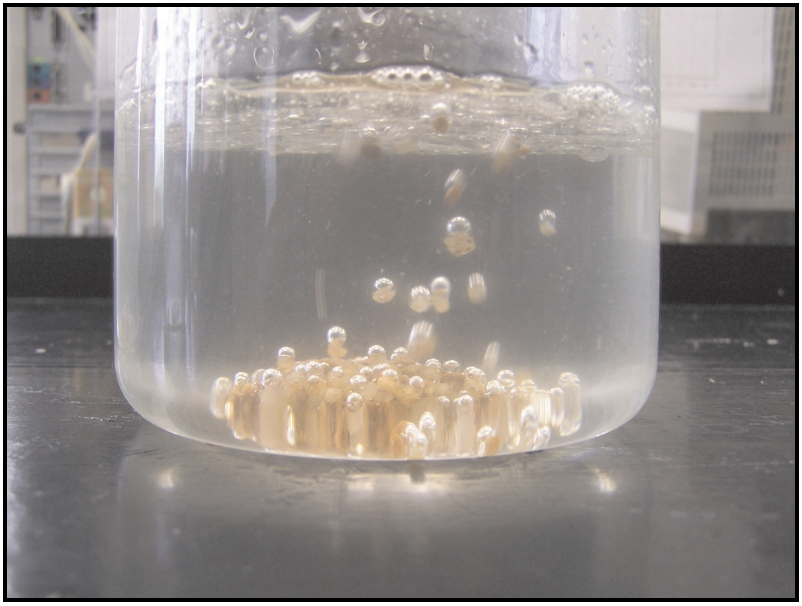

Fig. 29. Oil droplets attached to the cuttings size 3 mm from Test 35
400 ml Water, 100 g of Sodium Chloride, 10 ml Oil

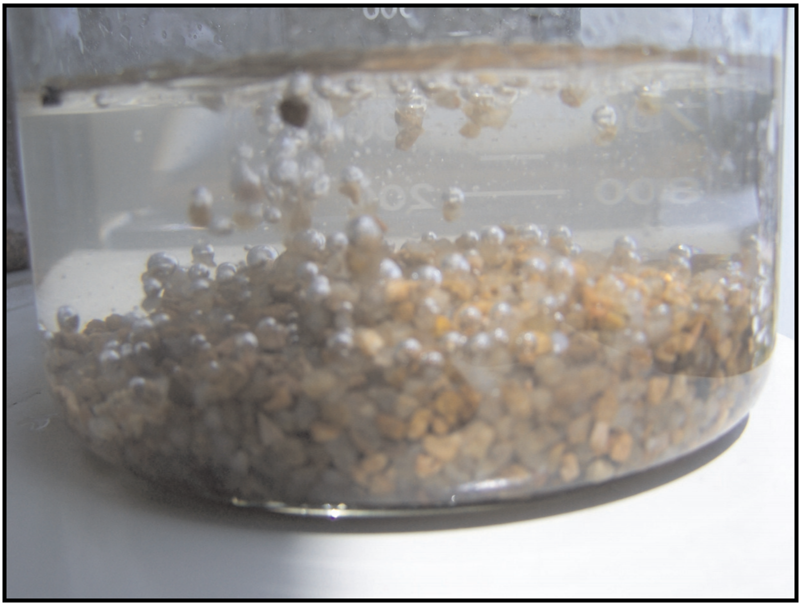

Fig. 30. Oil droplets attached to the cuttings size 2.83 mm Test 36
400 ml Water, 120 g of Sodium Chloride, 10 ml Oil

7. CONCLUSIONS

1. Upon further exploration Fluid 5 and Fluid 5a appear to give the best results in terms of reduction in bed height, amount of cuttings removed sweep efficiency (Fig. 8).
2. Fluids 7 and 8 (high viscosity, high density) do perform well in horizontal wellbores at low velocity 0.79 ft/s (5 gpm), while Fluid 2 (low viscosity) performed poorly.
3. With or without pipe rotation, increasing the flow rate (5–10–15–20 gpm) will increase the sweep efficiency. With pipe rotation, this factor plays a very important role in increasing cleaning capacity in the annulus, and this occurred for all the test fluids (see Figs. 19–28). Increasing rpm gives a significant improvement in cleaning out cuttings, especially for high viscosity fluid. This effect is not obvious with water and low viscosity fluids. However, with pipe rotation there is an additional improvement in cuttings removal.
4. In general, there is an increase in pressure loss with increasing the flow rate. Pressure drop generally decreases during the sweep tests.
5. Higher weight fluids (e.g., Fluid 8, 13 ppg) have better hole cleaning than lower weight fluids (e.g., Fluid 4, 10 ppg) with or without drill pipe rotation. There is a significant increase in bed erosion by adding more barite to increase the fluid density to 13 ppg. This gives further proof that increasing the density alone does improve the erosion process.

8. RECOMMENDATIONS

Based on experimental observations:

1. Fluid 2 (0.5 PAC, 0.5 Xanthan Gum) is not recommended.
2. High Density (13 ppg), High Viscosity (3 PAC, 3 Xanthan Gum) fluids are recommended at low flow rates.
3. High Viscosity fluids with pipe rotation (60–120 rpm) are recommended at any flow rates.
4. Fluid 5 and 5a (water, sodium chloride) are recommended, however attention should be given to corrosive effects.
5. Higher flow rates plus pipe rotation is recommended for practical applications.

Nomenclature

K	*Consistency Index*
LPAT	*Low pressure Ambient Temperature*
n	*Flow Behavior Index*
F	*Temperature, Fahrenheit*
YP	*Yield Point, lb/100 ft^2*
Ty	*Yield Stress, lb/100 ft^2*
GPM	*Flow Rate, gallons per minutes*
RPM	*Drill pipe rotation, revolution per minutes*

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