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Fiber Sweeps for Hole Cleaning

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Abstract

Cuttings transport in highly deviated wellbores is more challenging and critical than in vertical wells. In inclined wells, the fluid velocity has a reduced vertical component that may not be sufficient to transport all the cuttings to the surface. When cuttings returns do not appear to be sufficient for the drilling rate, hole cleaning sweeps are applied to clean the borehole or reduce cuttings bed thickness. Fiber-containing sweeps have been very effective in cleaning highly deviated and extended reach wells. In addition, substantial torque and drag reduction has been reported when fiber-containing drilling fluids are used in the field. Although field observations are encouraging, currently very little is known about flow behavior, hydraulics and cuttings transport efficiency of fiber sweeps.

There is a great need for understanding how fiber particles enhance the cleaning capabilities of fiber-containing sweeps. The interaction between fiber particles and drilling fluid is still not fully understood, although the improvement in cuttings and solids transport is attributed to the formation of a fiber mat/network that enhances the carrying capacity of drilling fluids.

This article presents results of experimental investigations conducted to study hole-cleaning performance of a fiber sweep. Flow loop experiments have been carried out to evaluate and compare sweep efficiencies of the fiber sweep (0.47% Xanthan Gum and 0.04% synthetic fiber) and the base fluid (0.47% Xanthan Gum). Equilibrium bed heights were measured at different sweep flow rates in horizontal and inclined configurations. Results from this study indicate that a fiber-containing sweep has better hole cleaning capabilities than the base fluid, even though these two sweep fluids have very similar rheological properties. Moreover, adding fiber slightly reduces annular pressure loss at the same average bed height.

1. Introduction

Inadequate hole cleaning can lead to costly drilling problems such as stuck pipe, premature bit wear, slow drilling rate, formation fracturing, and high torque and drag. A number of previous studies indicated that cuttings transport in directional wells is strongly dependent on wellbore inclination angle, rotary speed of the drill pipe, fluid rheology, flow rate, wellbore geometry and other drilling parameters. Over the years, various field procedures have been introduced to control the formation of cuttings beds. Most of these procedures involve addition of drilling fluid additives such as viscosifiers and weighting agents that enhance the cuttings transport ability of the drilling fluid. Unfortunately, these methods are inefficient in completely preventing the formation of a cuttings bed. At best they delay the buildup of cuttings beds but often cause additional problems. As a result, corrective methods such as drilling fluid sweeps are often applied in the field. In highly inclined and horizontal wells, drilling fluid sweeps can be applied to reduce cuttings bed thickness. Conventional drilling fluid sweeps are classified into: i) high-viscosity sweeps; ii) high-density sweeps; iii) low-viscosity sweeps; iv) combination sweeps; and v) tandem sweeps.[1]

A recent experimental study[2] with conventional sweeps indicates that in the absence of drill pipe rotation, high viscosity and high-density sweeps are found to be ineffective in a horizontal configuration. Although field observations indicate the effectiveness of fiber sweeps in cleaning highly deviated and extended reach wells, the mechanisms by which the fiber particles improve hole cleaning is not fully understood. Hence, investigating hole-cleaning performance of fiber sweeps can be useful to improve the understanding of these fluids and to establish a procedure for the design and application of fiber sweeps. In this study, flow loop tests were carried out to evaluate and compare the performance of fiber-containing sweeps. Experiments were performed in horizontal and inclined configurations.

Fiber containing suspensions are commonly used in many industrial applications. During drilling of oil and gas wells, fibrous lost circulation materials (LCM) are added to the drilling fluid. The fiber minimizes fluid loss by plugging pores in the rock at the surface of the wellbore. Recently, hole cleaning fibers made of synthetic material have been developed to enhance the cuttings transport capacity of drilling fluids. Hole cleaning fibers are flexible and have a large aspect ratio with typical dimensions of 10 mm length and 100 μm diameter. However, their application is limited to sweep fluids due to problems associated with the cuttings separation system at the surface. Fiber particles cannot easily pass through fine shaker screens; as a result, screen plugging often occurs when shale shakers are used with fiber-containing fluids. Prior to applying fiber sweeps, fine screens should be removed from the mud circulation line as they could get severely plugged with fibers. Hole cleaning fibers are designed to improve the performance of sweeps without considerable increase in viscosity. A very small quantity of fiber (i.e less than 0.1% by weight) is required to prepare a fiber-containing sweep fluid that has the desired cleaning performance. Adding a large quantity of fiber should be avoided because doing so can significantly increase the viscosity of the fluid and frictional pressure losses. In addition to the rheological property, fiber density plays a major role in the performance of fiber-containing sweeps. Currently available hole cleaning fibers have slightly lower density than water and they tend to float in the base fluid. In order to keep the fiber particles in suspension, the base fluid must have the desired rheology (viscosity and yield stress) under borehole conditions. Otherwise, during field applications, fiber particles can migrate to the high side of the wellbore and reduce the performance of the sweep. High temperature conditions in deep wells can affect the rheology of the base fluid and the performance of fiber sweep. Thus, in addition to having the desired rheological parameters, the base fluid rheology should not be sensitive to temperature to keep the fiber in suspension under borehole conditions.

The settling behavior of solids in fiber suspensions is very complex. When fiber is fully dispersed in the sweep fluid, it forms a stable network structure that tends to support cuttings due to fiber-fiber interactions. The origins of these interactions can be direct mechanical contact and/or hydrodynamic interference between fiber particles. Mechanical contact between fiber particles generates a strong friction force that hinders the settling of suspended drill cuttings. In addition the use of fiber improves the solids-carrying capacity of the fluid. Fiber sweeps have been very effective in transporting coarse cuttings. The sweeping process is very effective when cuttings remain in suspension and, at the same time, deposited cuttings are re-suspended. Different methods are applied in the field to re-suspend deposited cuttings. Increasing flow rate is one of the methods; however, increase in flow rate is limited by the equivalent circulation density (ECD). Excessive flow rate can result in a fractured formation and/or borehole erosion. Another approach is rotating the drilling string, which is very effective and often applied with fiber sweeps. In addition to these steps, the addition of fiber improves the re-suspension ability of the fluid. Shearing a fiber suspension gives rise to hydrodynamic and mechanical stresses at the interface between the sweep fluid and a cuttings bed that has formed on the low side of the wellbore. The mechanical stresses are generated due to friction between the fiber and cuttings at the surface of the bed. This friction helps to agitate the bed and facilitate re-suspension of the particles.

2. Literature Review

Hole cleaning in extended reach drilling (ERD) wells is a major issue. The increase in length of the annulus results in higher pressure loss and limits hole cleaning capabilities. ERD wells must be cleaned without inducing excessive ECD. Highly deviated portions of the wellbore are the most difficult to clean.[3] Moreover, the flow regime affects the intensity of hole cleaning in ERD wells. Turbulent flow conditions create very intensive eddy structures that enhance hole cleaning in horizontals well by maintaining the particles in suspension. On the other hand, turbulent flow reduces the formation of filter cake, resulting in increased level of filtrate invasion and formation damage. Mechanical agitation such as drillpipe rotation and reciprocation are effective in improving hole cleaning. The agitation resuspends cuttings particles and facilitates the removal of deposited cuttings. It is recommended to rotate the drill string while drilling even when a downhole motor is used.[3] The use of fiber sweeps under laminar flow conditions is often preferred in highly deviated and horizontal wells. World record extended reach drilling operations[3] show that certain fibrous lost circulation materials (LCM) have the ability to enhance hole cleaning and dramatically reduce torque and drag in highly inclined and horizontal wellbores. Applying fiber-containing sweeps with well-optimized drilling practices greatly improves drilling efficiency in extended reach wells. Particularly, an extended reach well was drilled in an environmentally-sensitive shallow marine area in offshore Abu Dhabi. Fiber sweeps were pumped to clean the hole prior to trips. The target depth was reached in significantly fewer drilling days. The fiber sweeps were effective in eroding the compacted cuttings beds on the low side of the hole. Applying the fiber sweeps with pipe rotation, it was possible to increase cuttings return to surface by up to 50% (Table 1). The fiber sweep not only helped clean cuttings from the low side of the hole, it also helped to control ECD, reduced torque and drag, and improved drilling rate considerably.

Table 1 Fiber Sweep Report Summary (Cameron et al.[3])

Date	Hole Size (Ins)	Depth (feet)	Hole Angle	Flow Rate (gpm)	Sweep Vol. (bbl)	MW (pcf)	Reason for pumping sweep	Result of Sweep
10/01/01	12.25	9462	63	883	40	95	Difficulty sliding	No cuttings increase
13/01/01	12.25	11597	62	888	50	95	Increased drag	No cuttings increase
14/01/01	12.25	12172	62	888	40	95	Clean hole for trip out	Slight cuttings increase
14/01/01	12.25	10800	62	916	40	95	Clean hole during trip	No cuttings increase
18/01/01	12.25	13800	64	842	80	95	Clean hole for trip out	Slight cuttings increase
18/01/01	12.25	12085	62	842	60	95	Clean hole during trip	50% cuttings increase
23/01/01	8.5	14000	64	595	40	75	ROP dropped to 4 fph	ROP increased to 10-15 fph
24/01/01	8.5	14460	61	600	40	75	ECD increased	50% cuttings increase
25/01/01	8.5	14620	57	600	40	75	Clean hole for new bit	15-20% cuttings increase
26/01/01	8.5	15300	57	600	40	76	ECD increase	10-20% cuttings increase
27/01/01	8.5	16050	33	600	30	76	ECD increase	50% cuttings increase
28/01/01	8.5	16412	30	600	40	76	Clean hole for trip out	30% cuttings increase
29/01/01	8.5	16442	30	600	30	76	Clean hole for new bit	50% cuttings increase
30/01/01	8.5	16720	26	600	40	76	ECD increase	50% cuttings increase
31/01/01	8.5	16914	24	600	30	76	Hole cleaning	10-20% cuttings increase
31/01/01	8.5	17007	21	600	40	76	Clean hole at connection	30% cuttings increase
31/01/01	8.5	17107	21	600	40	76	Clean hole at connection	50% cuttings increase
01/02/01	8.5	17198	21	500	30	76	Clean hole at connection	30% cuttings increase
01/02/01	8.5	17293	19	570	40	76	Clean hole at connection	30% cuttings increase
02/02/01	8.5	17525	18	600	50	76	Clean hole for trip out	10-20% cuttings increase

Fibre concentration in sweeps was 35-40 ppb.

Drilling sweeps have been essential for cleaning highly deviated and horizontal wellbores, and wellbore sections drilled with high rates of penetration (ROP). Cuttings transport efficiency of drilling sweeps can be improved by adding fibrous materials that are useful in eroding cuttings beds formed on the low-side of the wellbore.[4] In inclined wells, the drillpipe tends to lie on the low-side of the wellbore, resulting in the formation of stable cuttings beds. The cuttings bed formed in an eccentric wellbore is very difficult to clean because local fluid velocities close to the bed (narrow gap region) are extremely small. However, fiber particles suspended in the sweep fluid may have higher local velocities due to their interactions with the high-velocity fluid zone and fiber network. Recently, Bulgachev and Pouget[4] conducted a field-scale investigation on different types of sweep fluids. These included high-viscosity/high-density single sweeps, tandem sweeps, and sweeps with fiber additives. The best hole cleaning results were obtained with tandem sweeps that were performed by circulating low-viscosity fiber sweeps followed by a high-density sweep with or without fiber. Circulation of a low-viscosity fiber sweep resuspends the bed particles and exposes them for the high density sweep. Significant change in cuttings flow rate was observed at the surface when fiber-involving tandem sweeps were applied. Cleaning fine cuttings particles from deviated wellbores is more difficult than coarse cuttings. Field experiences[4] indicate that circulating a fibrous LCM with a weighted sweep can remove cuttings beds that are formed by fine cuttings.

One specific challenge associated during drilling of ERD wells is the ability to control torque and drag within manageable levels. The study conducted by Robertson et al.[5] indicated that the addition of certain loss circulation materials has a profound impact on torque and drag. The mechanism by which the LCM reduces the torque and drag is believed to be a combination of better hole cleaning and increased lubricity. The investigators presented one possible explanation for the enhancement of hole cleaning by considering the fiber particles of LCM as a fiber mat/network that scours the wellbore and drags the cuttings bed particles out of the well. The reductions in torque and drag are attributed to the decrease in wellbore friction. One possible explanation for this reduction is that fiber particles have a tendency to act as roller bearings when the drillstring rotates or moves axially in and out of the wellbore. Field experiments[5] that were conducted using fibrous lost circulation material showed reduction of the wellbore friction factor from 0.31 to 0.21. In addition, the presence of the LCM in the wellbore fluid system greatly reduced stick-slip phenomena. As a result, hookload and torque variations were significantly reduced when a liner was run.

A number of experimental and theoretical investigations have been conducted on fiber-containing fluids to study their rheological and sedimentation behavior. Introducing fiber particles can significantly alter the rheology of drilling fluids. Rajabian et al.[6] formulated a rheology model for fiber-polymer suspensions that takes into account the fiber-fiber and fiber-polymer interactions. Model predictions are in agreement with experimental measurements obtained from simple shear flows. Marti et al.[7] have studied the rheology of concentrated fiber suspensions both experimentally and theoretically. Experimental results[7] show that at relatively low fiber concentrations, the viscosity gradually increases as the fiber concentration increases. However, at higher concentrations, the viscosity becomes extremely sensitive to the fiber concentration and excessive thickening can occur with the addition of fiber.

When a suspension of fiber-containing fluid is subjected to a flow field, the fiber particles interact with one another mechanically and/or hydro-dynamically. The fiber-fiber interaction significantly affects the rheological properties of the fluid. In addition to fiber concentration, fiber properties also affect the rheology of its suspensions. Recently, the relationship between fiber shape and relative viscosity of a fiber suspension was explored[8] using a numerical simulator. Fiber curvature was found to contribute to a large increase in suspension viscosity. Hence, the viscosity of a fiber suspension is highly dependent on the shape of fiber particles and their degree of entanglement. Usually, fiber particles in suspension form three-dimensional networks that display yield stress as a result of mechanical entanglement.[9] Rheological measurements show the

presence of critical strain that marks the onset of structural breakdown of the fiber network. Moreover, the presence of fiber particles in viscoelastic polymer suspensions affects the rheological properties of the fluid due to fiber-polymer coupling.[10]

The presence of fiber particles in the suspension will affect the velocity profile and other flow characteristics. Under turbulent flow conditions, fiber particles have a tendency to reduce turbulence intensity and thus reduce turbulent momentum transfer. However, fibers in suspension also have a tendency to form fiber networks, which increase the viscous momentum transfer.[11] Xu and Aidun[11] measured the velocity profile of fiber suspensions flowing in a rectangular channel using a pulsed ultrasonic Doppler velocimeter. The effects of fiber concentration and Reynolds number on the shape of the velocity profile was investigated. Five types of flow behavior are observed when fiber concentration increases or flow rate decreases progressively. At low fiber concentrations (Fig. 1a), as Reynolds number increases, the shape of the velocity profile changes from laminar to turbulent. For fully turbulent flow conditions (i.e. Re ≥ 37,000), the presence of fiber particles has a negligible effect on the flow. As a result, the velocity profiles of fiber suspensions are similar to that of single-phase flow. However, at high fiber concentrations (Fig. 1b), the presence of fiber particles has a significant effect on the flow. In this case, the fiber suspension velocity profiles do not follow the velocity profile pattern of a single-phase flow. The velocity profile of the fiber suspension strongly depends on the Reynolds number. The discrepancies between the velocity profiles of single-phase flow and fiber suspension flow are very high at low Reynolds numbers. At high Reynolds numbers these discrepancies are minimal.

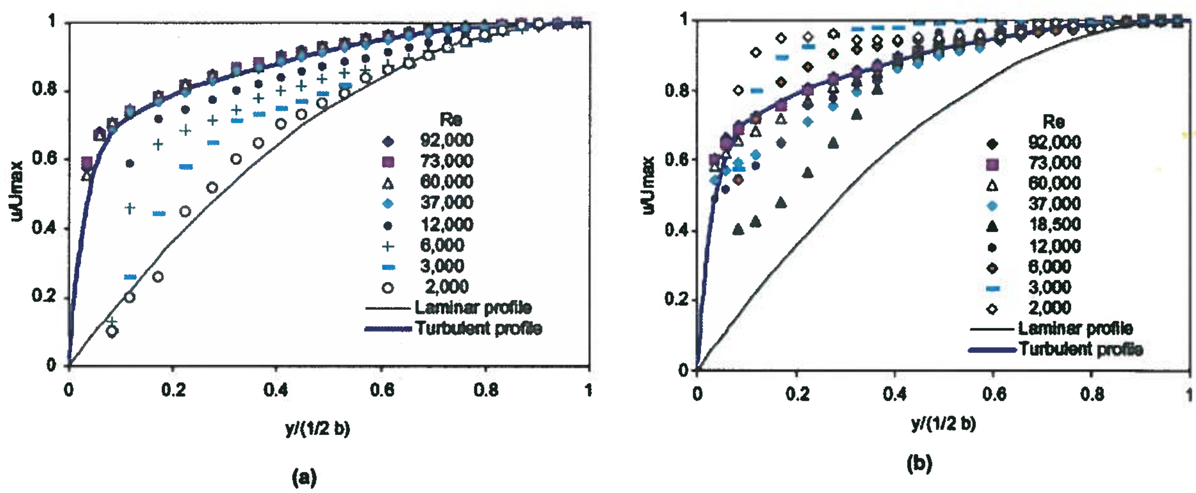


Fig. 1 Changes of velocity profile with Reynolds Number for fiber suspension at different concentrations: a) low fiber concentration; and b) high fiber concentration (Xu and Aidun[11])

At low Reynolds number (Re = 2000 and 3000), an important characteristic of fiber suspension flow is that the addition of fiber considerably increases the local velocities close to the wall. For instance, if we consider Re = 2000 and dimensionless distance from the wall, y/0.5b = 0.1, the measured local velocity for the fiber suspension is more than five times the theoretical local velocity of a laminar flow. An increase in the local velocity can be a strong indication of better sweep efficiency with fiber-containing fluids.

A linear stability analysis[12] of channel flow in the presence of fiber suspensions indicates that the fiber additives can effectively damp the instability of the flow and may increase the critical Reynolds number. In addition, a recent study[13] on proppant-transport suggests that fiber additives could enhance the proppant-transport capabilities of fracturing fluids. Adding fiber particles to a polymer suspension dramatically alters the solids particle settling behavior of the fluid.

3. Mechanisms of Hole Cleaning and Friction Reduction

Understanding the mechanisms of hole cleaning in inclined wells is important in the development of more efficient sweep fluids. These mechanisms often involve transport phenomena such as deposition (settling), re-suspension (lifting), and rolling and sliding of particles. For a given set of operating conditions, one of these phenomena may dominate over the others. The mechanisms are highly dependent on the location of cuttings particles in the flow stream. From a mechanistic point of view, the deposition, re-suspension, and rolling and sliding of solid particles begin when the net force or net moment acting on the particle becomes positive or negative. In a conventional sweep fluid, if we consider a protruding bed particle at the surface of the bed, as presented in Fig. 2, the dominant forces acting on the bed particle during the sweeping process are: gravity (W),

buoyancy (F_b), hydrodynamic drag (F_d) and lift (F_L), and plastic force (F_p).[14] When fiber is added to the fluid, the fiber particles form a mat/network in which fiber particles tend to move together due to fiber entanglement and fiber-fiber interaction. As a result, fiber particles don't have the same local velocity as the fluid. Very close to the bed, fiber particles can have a higher velocity than the local fluid velocity, which is very small. The fiber particles that are moving close to the bed at higher velocities can transfer a substantial amount of momentum to the bed particle due to a fiber-cutting interaction force (F_f). Rolling is the dominant transport mechanism in highly inclined configurations. The cause of cuttings particle rolling motion can be seen by considering net torque (Γ_P) acting on the particle at point P (Fig. 2). If we assume a spherical bed particle is under threshold conditions, then the net torque can be expressed as:

$$\Gamma_P = \frac{d_P}{2}\left[F_f \sin(\beta+\phi) + F_d \sin\phi + F_L \cos\phi - F_P \cos\phi - (W - F_b)\sin(\alpha+\phi)\right], \quad \text{... (1)}$$

where ϕ and d_p represent the angle of repose and particle diameter, respectively. Angle β is the angle between the interaction force and x-axis. Rolling of the particles occurs when the torque becomes positive. The addition of fiber can significantly increase the torque, depending on the level of the interaction force and the values of β and ϕ. The increase in torque disrupts the mechanical equilibrium to initiate particle movement and facilitates the sweep process. Once the movement is initiated, some of the particles may re-suspend and others may roll on the surface of the bed. The sweeping process becomes efficient if the re-suspended particles remain in suspension for a long time. One of the benefits of adding fiber is that it decreases the settling velocity of suspended particles substantially.[13] The reduction in the settling velocity is attributable to a fiber network structure that provides strong support for suspended cuttings particles.

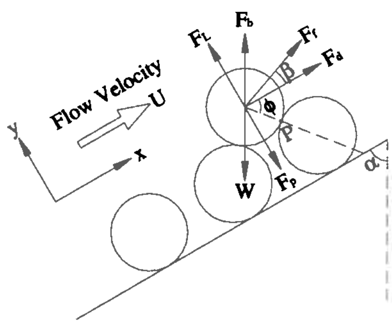


Fig. 2 Forces acting protruding bed particle

In addition to direct sweep efficiency enhancement, adding fiber tends to decrease pressure loss under turbulent flow conditions.[14] The reduction in pressure loss permits drillers to increase the sweep flow rate, which means it indirectly improves the sweep efficiency at the same level of ECD. A number of studies[15,16] have been conducted on the drag reduction process involving fibers. One of the mechanisms presented to explain this phenomenon involves the formation of a fiber network in the base fluid that suppresses the generation of turbulence by damping hydrodynamic instabilities. This results in reduction of turbulent intensity and viscous losses.

4. Experimental Investigations

The current investigation involves experimental studies conducted on hydraulics and hole cleaning performance of fiber containing sweeps. A flow loop (Fig. 3) that has a fully eccentric annular test section (2" × 1") was used to carry out the sweep experiments. The flow loop is equipped with a pipe viscometer section (ID = 0.65") to perform rheology and hydraulic investigations. The aim of this investigation is to separately study the effect of fiber on the sweep efficiency of fiber containing sweep fluids. Hence, except fiber concentration, test parameters were maintained the same during the sweep experiments. Two test fluids (fiber sweep and base fluid) with similar flow curves (Fig. 4) were selected after extensive screening tests. Compositions and rheological parameters of test fluids are presented in Table 2. The fiber is a specially processed 100% virgin synthetic monofilament fiber that is designed to increase the lifting, carrying, and suspension characteristics of drilling fluids. During the experiments, the flow rate was varied from 4 gpm to 33 gpm.

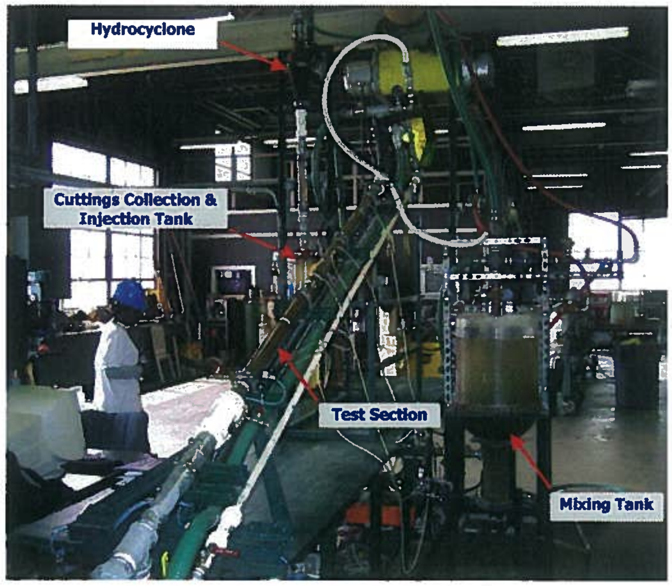


Fig. 3 Small-scale sweep flow loop

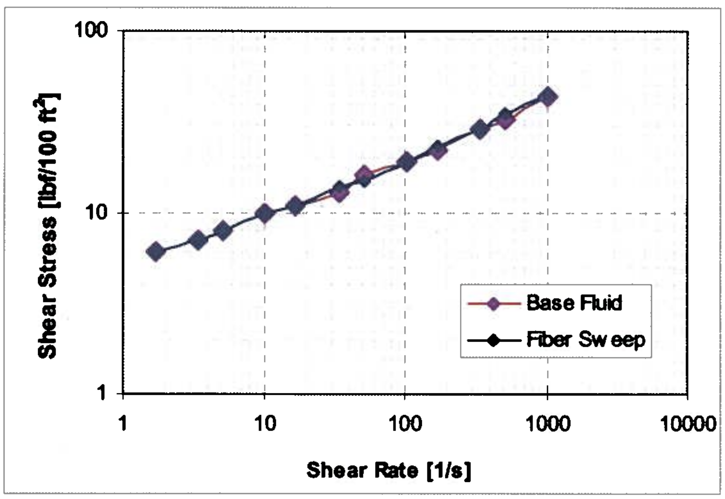


Fig. 4 Rotational viscometer data for fiber sweep and base fluid

Table 2 Composition and Rheological Parameters of Test Fluids

Fluid	Composition [w/w]		Rheological Parameters for Yield Power-law Model		
	XG	Fiber	k [$lbfs^m/100ft^2$]	m	τ_y [lbf/100ft2]
Base fluid	0.47%	0.00%	2.62	0.41	3.35
Fiber Sweep	0.47%	0.04%	2.75	0.52	3.56

Fluid Screening Tests

The purpose of fluid screening tests was to select different pairs of fluids (base fluid and fiber sweep) that have very similar rheological properties. These tests were completed before the flow loop experiments began. Fluids with different concentrations of fiber and polymer were prepared and the rheology of each fluid was measured using a rotational viscometer. The results show the presence of two physical phenomena: i) fiber separation at low polymer concentration; and ii) excessive thickening due to fiber addition that occurs at high polymer concentrations. Since the density of the fiber is slightly less than that of water, the fiber particles tend to float/separate due to buoyancy. Thus, in order to keep fiber particles in suspension, the fluid must have sufficient yield stress. Fluids with low Xanthan Gum (XG) concentration (i.e. less than

0.4%) showed significant fiber separation. Adding 0.04% fiber into the fluids with high XG concentration (i.e. greater than 0.5%) significantly affects the rheologies of the fluids. Only slight rheological change is observed when 0.04% fiber is added to test fluids with intermediate XG concentration (i.e. 0.4% to 0.5%). Further screening tests with suspensions that have intermediate XG concentration were carried out to determine the optimum XG concentration; i.e., the concentration that minimizes the effect of fiber on the rheology of the fluid. The minimum fiber effect is achieved with XG concentration of 0.47%. Hence, the sweep experiments were conducted using 0.47% XG as the base fluid. Adding 0.04% fiber to this fluid has an insignificant effect on the rheology and density of the fluid.

Experimental Setup

Sweep experiments were carried out in a unique small-scale flow loop that has a transparent 12-ft-long annular section. The annular section is made of a 2-inch Polycarbonate tube and a 1-inch, fully eccentric inner pipe made of stainless steel. A simplified schematic of the flow loop is shown in Fig. 5. Together with a test procedure that is presented in the next section, the schematic illustrates how the sweep tests are performed, and how the desired bed thickness and liquid circulation rates are maintained. All tests were conducted at ambient temperature conditions. A centrifugal pump with maximum capacity of 33 gpm is used to circulate fluid (test fluid/fiber sweep) in the flow loop. The pump flow rate is automatically controlled by varying the motor speed. A magnetic flow meter (F1) placed downstream of the centrifugal pump measures the flow rate. A test section bypass line was constructed in parallel with the test section. After accumulating the desired quantity of cuttings (river sand with mean particle diameter of 0.12 in (3.0 mm)) in the test section, the bypass line is opened while closing flow through the test section using a three-way valve installed at the inlet. The bypass line is used for flushing out cuttings deposited in the piping.

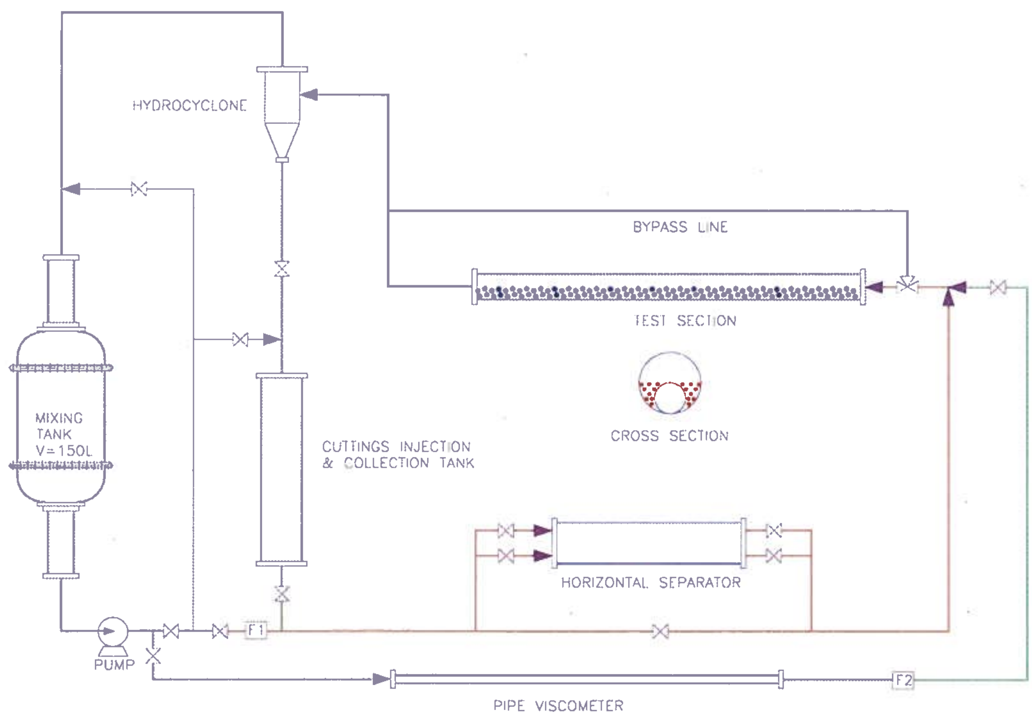


Fig. 5 Schematic of small-scale sweep flow loop

A 4-inch diameter polyurethane hydrocyclone and a horizontal separator are used to recover cuttings from the test fluid. A cuttings injection/collection tank is placed at the bottom of the hydrocyclone to collect separated cuttings or inject cuttings into the flow line. A pipe that connects the flow line and the bottom of the collection tank is installed to inject cuttings. The cuttings injection is controlled using a ball valve installed at the bottom of the cuttings injection/collection tank. The quantity of cuttings in the test section is determined by measuring the cuttings bed thickness at different locations. A pipe viscometer section is connected to the flow loop to conduct rheological and hydraulics investigations. The flow rate through the viscometer is measured using a Coriolis flow meter placed downstream of the viscometer. A 20-gallon mixing tank is used to prepare and circulate the test fluid. Inside the mixing tank, a high-speed agitator is installed to prepare a homogeneous test fluid by mixing water, polymer and fiber. Two differential pressure transducers measure pressure loss in the annular test section and pipe viscometer, respectively.

Test Procedure
Sweep experiments with base fluid and fiber sweeps involve the following five major steps:

Step I. **Preparation of Base Fluid:** A sweep experiment begins by blending water and Xanthan Gum (0.47% w/w) in the mixing tank while the test fluid is being circulated using the centrifugal pump. After a sufficient time of mixing, a homogeneous suspension (base fluid) forms in the system. A rheology test (using a rotational viscometer) with the base fluid should be performed before starting cuttings injection. Viscosity of the base fluid is adjusted by adding water or polymer while mixing and circulating.

Step II. **Building Cuttings Bed:** Divert flow to the bypass line of the horizontal separator as needed to avoid cuttings accumulation in the separator. Circulate the base fluid through the test section to build a cuttings bed. The ball valve placed at the bottom of the collection tank is partially opened to begin injection of cuttings into the system. As cuttings injection proceeds, the cuttings bed builds in the piping and test section. The injection of cuttings and fluid circulation is stopped when the desired quantity of cuttings is accumulated in the test section.

Step III. **Flushing Cuttings Accumulated in the Piping:** Divert flow from the test section to the bypass line using the three-way valve. Close the bypass line of the horizontal separator and divert flow through the horizontal separator. Start the centrifugal pump and flush the cuttings that are deposited in the piping using high flow rates. After sufficient cleaning, cuttings accumulation in the collection tank stabilizes, indicating that cuttings have been swept out of the piping.

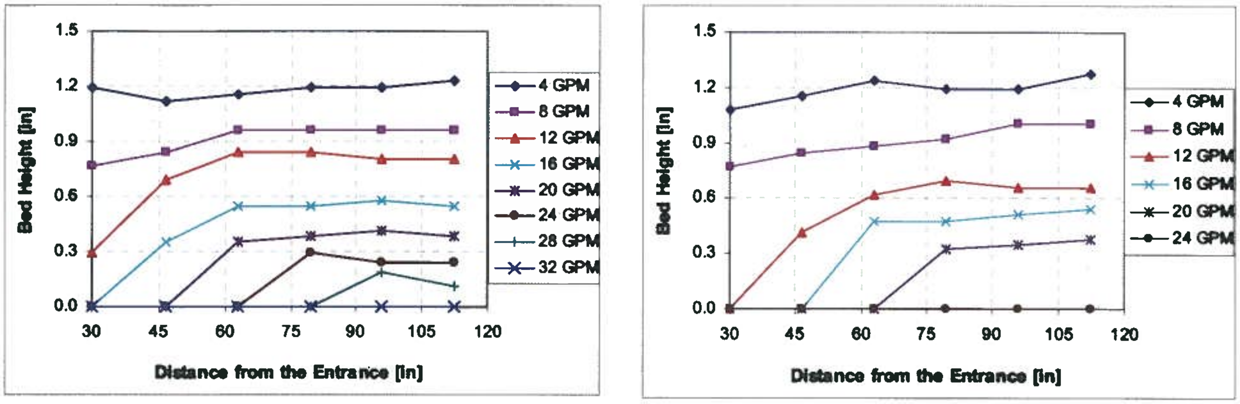
Step IV. **Preparation of Fiber Sweep Fluid:** This step is only required for fiber sweep experiments. The fiber sweep fluid is prepared by adding the desired quantity of fiber (0.04% w/w) to the base fluid in the mixing tank. The mixer is turned on to disperse fiber particles while the pump circulates test fluid through the test-section bypass line. After sufficient mixing, a homogeneous fiber suspension forms. The rheology of the fiber sweep is measured and adjusted (by adding water or polymer) before starting the sweep test.

Step V. **Circulation of Sweep Fluid:** The original bed thicknesses in the test section are measured before starting the sweep fluid circulation. Flow through the bypass line must be diverted to the test section using the three-way valve. Circulation of the sweep fluid is started at lower flow rates and increased to the desired level gradually to minimize acceleration effects. The sweep fluid erodes the cuttings bed gradually at constant flow rate until an equilibrium condition is established. At this point the sweep circulation is stopped and equilibrium bed thicknesses are measured at six different locations. The measured equilibrium bed thicknesses are used to determine the average equilibrium bed height that corresponds to a given flow rate.

5. Results and Discussions

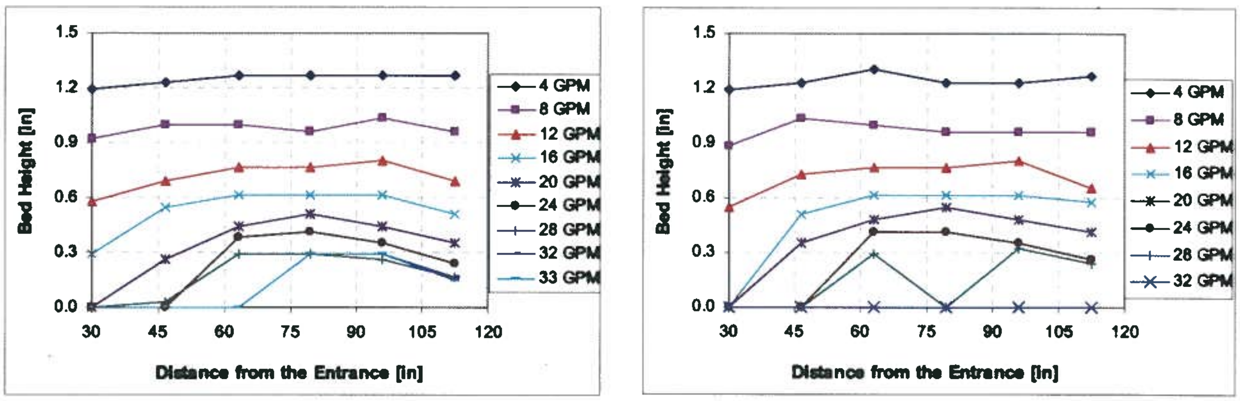
Sweep Experiments
Flow loop tests were conducted to investigate the effect of fiber on the sweep efficiencies of polymer-based drilling fluids at different inclination angles. Before running the main experiments, preliminary tests were conducted in the horizontal configuration using water and base fluid to check repeatability of the measurements. The sweep efficiency is evaluated in terms of the amount of cuttings removed from a stationary cuttings bed formed in the test section using the base fluid as a drilling fluid. Tests were conducted in horizontal (90°) and inclined (70° and 55°) configurations without inner pipe rotation.

Figures 6 through 8 show measured equilibrium bed heights at different locations in the test section. For the horizontal configuration, the base fluid (Fig. 6a) can not completely clean the test section at 28 gpm while the fiber sweep (Fig 6b) is able to completely clean it at 24 gpm. Similar results are obtained for other inclination angles. The fiber sweep shows better hole-cleaning efficiency than the base fluid. For all inclinations, the fiber sweep is able to clean the test section completely. At 55° inclination, the fiber sweep completely cleaned the test section at a lower flow rate than the base fluid.



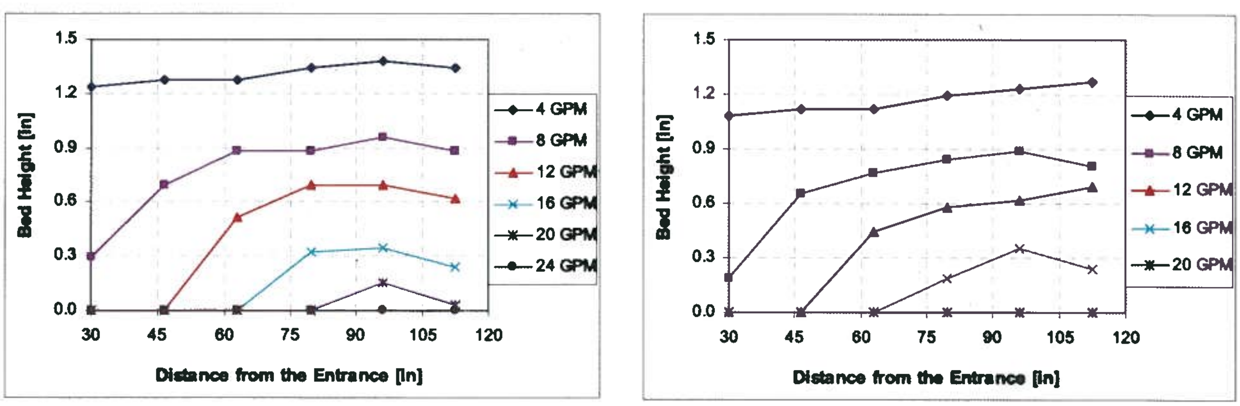
(a) (b)

Fig. 6 Equilibrium bed heights at different locations in the test section for horizontal configuration: a) Base fluid; and b) Fiber Sweep



(a) (b)

Fig. 7 Equilibrium bed heights at different locations in the test section for 70° inclination: a) Base fluid; and b) Fiber Sweep

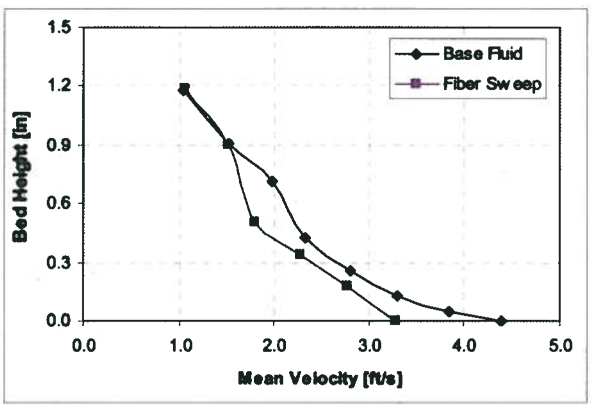


(a) (b)

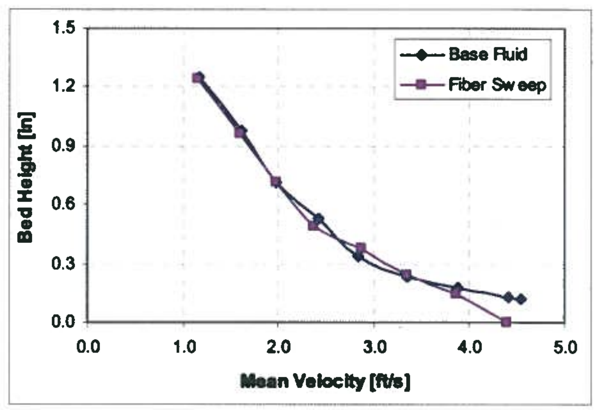
Fig. 8 Equilibrium bed heights at different locations in the test section for 55° inclination: a) Base fluid; and b) Fiber Sweep

Figures 9a, 9b and 9c present average equilibrium bed heights as a function of mean flow velocity (i.e. the ratio of flow rate to the average flow cross-sectional area) of base fluid and fiber sweep. Although the test fluids have very similar rheological properties (Fig. 4), results generally indicate improved hole-cleaning efficiency when using the fiber sweep. Especially in the horizontal configuration, hole-cleaning performance of the fiber sweep is significantly better than that of the base fluid. At 55° inclination, the fiber sweep shows better efficiency at high and low bed heights (greater than 30% and less than 10%).

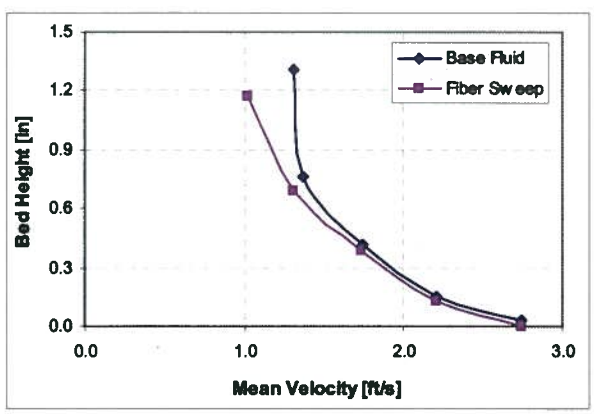
However, at 70° inclination, the base fluid and fiber sweep have approximately the same effectiveness in reducing the bed thickness, except at low bed thicknesses (i.e. less than 15% bed height). Fiber sweeps applied in the field did not show good cleaning performance in this range of inclination angles. For instance, most of the field measurements (Table 1) for inclination angle between 62° and 64° did not show significant increase in cuttings return when the fiber sweep was used. Analysis of forces acting on a single bed particle shows the presence of a critical inclination angle, which is close to 70°.[14] At the critical angle, a bed particle requires the highest flow velocity to reach the threshold conditions for rolling of the particle on the surface of the bed. The critical inclination angle appears to remain the same even after the addition of fiber. This can be deduced by analyzing Eq. (1). Accordingly, when the angle of inclination varies from 0° (vertical) to 90° (horizontal), the net torque (Eq. 1), attains its minimum value at $\alpha = 90 - \phi$. The critical angle at which a bed particle requires the highest flow velocity is $90 - \phi$. The critical angle is a function of angle of repose and is not affected by the addition of fiber particles. The angle of repose for wet sand ranges from 12° to 19°.[17] Hence, the critical angle for a cuttings bed formed by sand particles is expected to be in the range of 71° to 78°. The existence of a critical angle close to 70° has been documented.[18-20] Further analysis of Eq. (1) shows that the value of the gravity term, $(W - F_b)\sin(\alpha + \phi)$, increases as the inclination angle approaches the critical angle. This term significantly diminishes the net torque when the angle approaches the critical angle. Under this situation adding fibers may not improve the sweep efficiency of the fluid unless a strong fiber-cutting interaction force is created to compensate for the reduction in the net torque.



(a)



(b)



(c)

Fig. 9 Average equilibrium bed heights as the function of mean velocity:
a) horizontal configuration; b) 70° inclination angle; and c) 55° inclination angle

In addition to sweep efficiency, frictional pressure loss in the test section is measured during sweep experiments. Generally, results indicate approximately the same frictional pressure loss for base fluid and fiber sweep. However, for the same flow rate and average bed height (i.e. the same annular mean velocity; for instance, the first three data points in Fig. 9b), the fiber sweep exhibits slightly lower pressure loss. Figures 10a through 10c present measured pressure losses as a function of time for different flow rates. Similar results were obtained for other flow rates when comparisons are made to data with the same level of average bed height. Experiments were conducted at different flow rates, which covered a wide range of Reynolds

numbers (from 40 to 830). Apparently, the Reynolds numbers indicate the prevalence of laminar flow conditions in the test section. The slight decreases in pressure loss may not be a regular drag reduction that occurs under turbulent flow conditions. Possible explanations for the decrease could be differences in cuttings bed profiles or mode of cuttings transport. In horizontal and inclined configurations, the cuttings bed forms different bed profiles, including dunes, ripples and flat bed profiles. A flat bed profile reduces the pressure loss at the same level of average bed height. The mode of cuttings transport can be moving bed type or suspension form. In the moving bed mode, bed particles are transported in a thin layer of a highly concentrated slurry moving on the surface of the bed. When the transport occurs in the suspension mode, the bed particles fully disperse in the fluid, forming a low-concentration slurry that flows over the surface of the bed. The suspension mode tends to minimize pressure loss by reducing the wall shear stresses between the low concentration slurry and the cuttings bed.

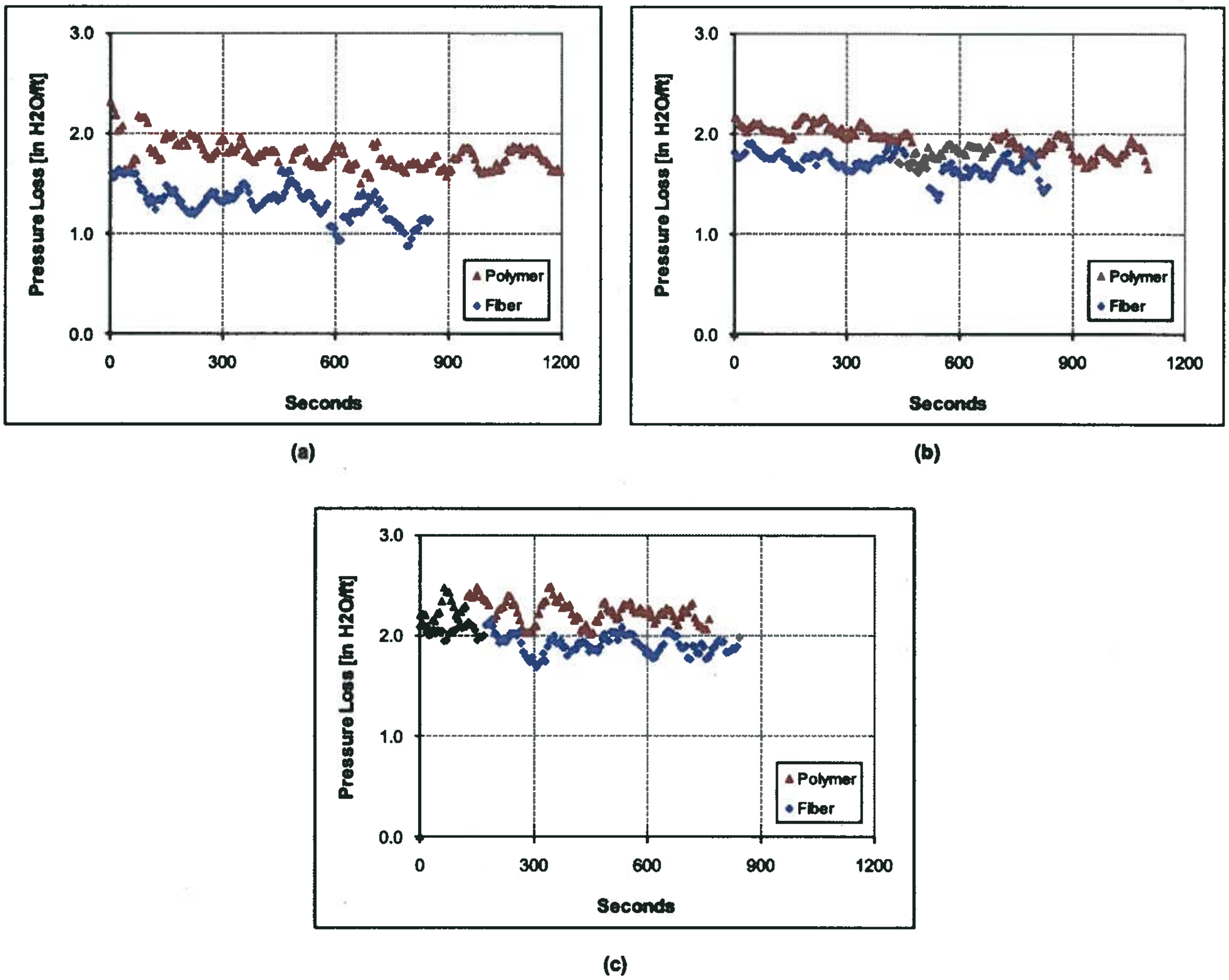


Fig. 10 Measured pressure losses at 70° inclination angle: a) 4 gpm (Re=70); 8 gpm (Re=132); and c) 12 gpm (Re=197)

It is important to note that the fiber sweep shows better cleaning performance than the base fluid, even though it exhibits lower pressure loss. Since the test fluids have very similar rheological properties, higher wall shear stress in the base fluid is expected to result in a higher velocity gradient and higher local fluid velocities at a given flow rate. The increases in local fluid velocities enhance the removal of cuttings from the bed. Despite this, the fiber sweep shows better sweep efficiency than the base fluid. This indicates the presence of other possible mechanisms that can improve the removal of cuttings particles from the bed when the fiber sweep is used. One of these mechanisms is a mechanical effect that agitates (brushes) cuttings bed particles. Mechanical agitation of cuttings bed particles by fiber particles that form a network structure (fiber mat) due to the entanglement of fiber particles can improve the sweep efficiency of fiber-containing fluids.

Pipe Viscometer Test

Pipe viscometer tests were carried out to compare flow curves of the base fluid and sweep fluid, to determine the effect of fiber on the critical Reynolds number for the transition from laminar to turbulent flow and to study drag reduction behavior of the fiber suspensions under turbulent flow conditions. Measured pressure loss in the viscometer is presented as a function of flow rate in Fig. 11. At low flow rates (laminar flow conditions), pressure loss measurements are the same for base fluid and fiber sweep. A previous study[11] on the flow characteristics of fiber-containing fluids indicates that addition of a small quantity of fiber does not substantially influence the velocity profile. Our measurements are in agreement with these findings; viscometeric results show similar flow curves for the base fluid and sweep fluid under laminar flow conditions. Figure 12 presents friction factor as a function of generalized Reynolds number. As the flow rate increases, a flow regime change occurs when the generalized Reynolds number is approximately 2,700 (Fig. 12). Under turbulent flow conditions, the addition of fiber results in slight reduction of the frictional pressure loss. Drag reduction behavior of fiber sweeps may be useful to control ECD within the operating window during sweep applications.

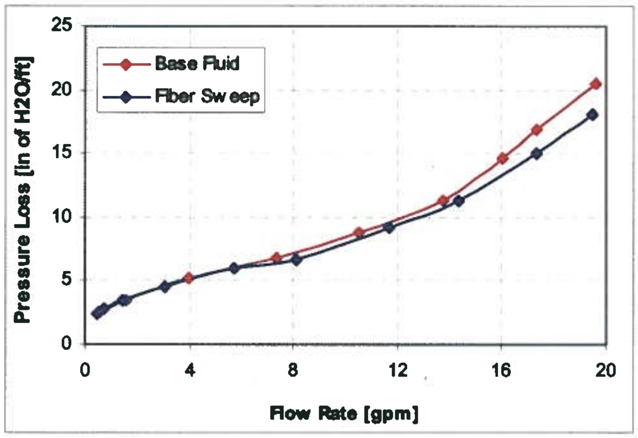


Fig. 11 Measured pressure losses as a function of flow rate

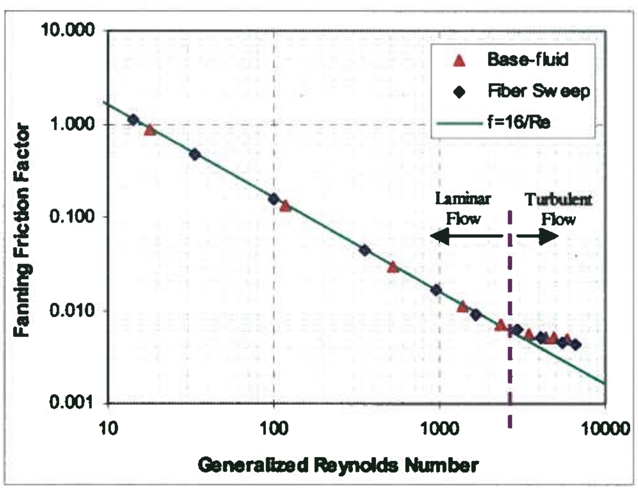


Fig. 12 Friction factor versus generalized Reynolds Number

6. Conclusions

This study was conducted to investigate hole-cleaning performance and hydraulics of fiber-containing fluids. Sweep experiments were performed to measure the equilibrium bed height at different flow rates in horizontal and inclined configurations. All experiments involving cuttings transport were performed without drillpipe rotation. Viscometer tests were carried out with the test fluids. From these investigations, the following conclusions can be drawn:

- Adding fiber materials into drilling sweeps significantly improves sweep efficiency of the fluid in fully eccentric annuli, especially in the horizontal configuration. Fiber-containing sweeps cleaned the test section predominantly better than the base fluid. The present study was conducted at ambient temperature. For field applications in deep or

other high-temperature wells, consideration should be given to use of base fluids whose rheologies are not sensitive to temperature increases, such as synthetic (invert emulsion) fluids;

- The effect of fiber is minimal at 70° configuration. Analysis of forces acting on the particle indicates that a strong fiber-cutting interaction force is required to observe the effect of fiber at this inclination angle.

- Addition of fiber slightly reduces annular pressure losses, even under laminar flow conditions, This phenomena is attributed to the differences in cuttings bed profiles and modes of cuttings transport;

- Results from the pipe viscometer show similar hydraulic characteristics under laminar flow conditions for the tested fluids (base fluid and fiber sweep). However, under turbulent flow conditions, adding fiber to the sweep fluid slightly reduces pressure loss.

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Nomenclature

d_p = Particle diameter, m
F_b = Buoyancy force, N
F_d = Hydrodynamic drag, N
F_f = Fiber-particle interaction force, N
F_L = Hydrodynamic lift, N
F_p = Plastic force, N
Re = Reynolds number
U = Mean flow velocity, m/s
W = Gravity force, N

Greek Letters

α = Inclination angle from vertical
β = Angle between the interaction force and x-axis
ϕ = Angle of repose
Γ_p = Net torque acting on the particle at point P, N·m

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