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The Effect of Shear Rate on the Static and Dynamic Fluid-Loss Behavior of Drilling Fluids Across Aloxite Disks

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Abstract

Filtercakes are formed under both static and dynamic conditions. As such, neither a static fluid loss test nor a dynamic fluid loss test accurately depicts a drilling fluid's performance in the well bore. However, the characteristics of a mud under both conditions should be considered for a complete evaluation.

This paper reports the results of an experimental study undertaken on a wide variety of drilling fluids (three water-based and two synthetic oil-based drilling fluids) at dynamic (OFI Dynamic Filter Press) and static fluid loss conditions. In addition to the common API practice of static HTHP measurement, the fluid loss was measured across five-micron aloxite disks for a period of 24 hours at both static and dynamic conditions.

The experiments showed the shear-rate dependence of fluid loss. The fluid loss depends on the shear that is exerted on the filtercake and depends on the type of drilling fluid. While the water-based drilling fluids' fluid loss showed little to no effect at the applied shear rate, two different synthetic oil-based drilling fluid systems showed a surprisingly strong dependence of fluid loss behavior to shear rates. It is speculated that the cause for this behavior lies in the different mechanisms of filtercake formation in the two mud systems (oil-based vs. water-based). These effects can be important to the field observations of formation damage and differential sticking using synthetic-based drilling fluid.

Introduction

Past studies have shown that standard API high temperature/high pressure (HTHP) tests do not sufficiently simulate the conditions a mud is subjected to in the well bore.[1-4]

When the drilling fluid is circulated, a dynamic filtercake forms. At any given flow rate an equilibrium between the drag force of the drilling fluid across the surface of the filtercake and newly deposited particles on the surface of the filter cake is established. When the circulation is stopped, a static filtercake is deposited. In a static condition, the filtercake grows as long as there is a supply of drilling fluid and a pressure drop across the filtercake. Under dynamic conditions the filtercake grows, but is constantly eroded.

The measured fluid loss at dynamic condition can differ significantly from a static fluid loss. As such, neither a static fluid loss test nor a dynamic fluid loss test accurately depicts a mud's performance in the well bore. The characteristics of a mud under both conditions must be considered during its evaluation.

Dynamic fluid loss measurements are not part of the standard API test procedure. The challenge in designing a dynamic filter condition is to achieve a uniform flow condition across the filtercake. Past publications on dynamic fluid loss have described a variety of test designs for evaluating fracturing fluids and drilling fluids.

Examples of experimental setups are modified static filtration cells with a stirrer.[1,2] The disadvantage is that even a carefully designed system has a nonuniform shear rate across the filtercake. The shear increases with increasing radius. Zamora *et al*.[1] describe the use of a such modified static fluid loss cell. The stirring unit (described as "a four-blade mixer resembling the two door hinges welded together") of the cell was designed to promote an even shear across the filtercake and to avoid undesirable vortices. Zarmora *et al*[1] observed increasing fluid loss with higher shear rates (although the exact shear rates could not be determined in the setup).

Designs that are closer to well conditions are described by Wyant *et al.*[3] and Warren *et al.*[4] A centralized cylindrical core (artificial and sandstone) was used as a filtration medium. Warren *et al*.[4] describe simulated well conditions (including circulation, pipe movement and fluid displacement) with the duration of the dynamic tests up to five days. Four water-based drilling fluids with little fluid loss control were tested (Freshwater Bentonite, Potassium Chloride, Nondispersed Gyp, Potassium Acetate). They observed in all the tests an increase in the filtration rate upon an increase in the circulation rate.

Wyant *et al*.[3] observed a correlation of the static fluid loss and the dynamic fluid loss: a low static HTHP fluid loss also showed a low dynamic fluid loss. The dynamic fluid loss increased with increasing shear rate.

The mathematical description of static-and dynamic fluid loss is well documented[6] and briefly described here:

Static Filtration

For a static filter cake, flow of the filtrate through the filter cake is governed by Darcy's law[6]:

With

dVf/dt	as the filtration rate
k	the filter cake permeability
A	the surface area of the filter (paper, aloxite disk)
Δp	the pressure drop across the filter cake
μ	the filtrate viscosity
h_{mc}	the thickness of the filtercake
f_{sc}	volume fraction of solids in the cake
f_{sm}	volume fraction of solids in the mud

$$V_f = \sqrt{2k\Delta p\left(\frac{f_{sc}}{f_{sm}}-1\right)}A\frac{\sqrt{t}}{\sqrt{m}} \qquad \text{Eq. (1)}$$

The above equation indicates that for static filtration the fluid loss is proportional to $\sqrt{t}$.[6]

Dynamic Filtration

In case of a dynamic filtration the filtercake does not grow indefinetly, rather the filtercake forms and grows until the shear stress applied by the circulating fluid on the surface of the filtercake is equal to the strength of the cake at the surface. Then the cake is eroded as fast as it is deposited. A dynamically deposited filtercake is usually thinner than a static filtercake. Thus the observed dynamic filtration rates are usually higher than static filtration.[1] With constant cake thickness we can integrate Darcy's law and find the filtrate volume is proportional to t

$$V_f = \frac{kA\Delta pt}{mh_{mc}}$$

This work attempts to gain a better understanding of the differences between static and dynamic filtration, tests were run at both conditions for five drilling fluids: three water-based muds and two synthetic-based muds.

Experimental Setup

Static HTHP fluid loss tests were performed using a standard HTHP OFI fluid loss test machine. The dynamic HTHP fluid loss cell (OFI) is similar to the static fluid loss cell: The cells' endcaps had been modified to accept 5 micron-permeable aloxite disks. The stirrer of the dynamic fluid loss cell had been modified to make the flow across the filter cake more uniform (i.e. have a uniform shear rate across the filtercake) and to minimize secondary flows (eddies)[5]. The stirrer had the shape of a cone with a blunt tip and was located within an inch of the aloxite disk. The filtercakes that were generated appeared uniform across the diameter, with a small hill at the center where the shear stress is zero. A schematic of the cell is shown in Figure 1. Both static and dynamic cells are placed in heating wells and the system is heated to 150° F. The pressure drop across the filter medium (5-micron aloxite disks) was 500 psi. The fluid loss was tested at static conditions, 300 RPM, 600 RPM, and 1000 RPM. Some selected experiments were also performed at 700 RPM and 800 RPM. No attempt was made to correlate the stirring to actual shear stress or shear rate across the filter cake. The filtrate was collected for 24 hours.

Results

Three water-based drilling fluids: NaCl/PHPA; lime/salt and silicate mud at 12 ppg and two SBM based on internal olefins and linear alpha olefins (12.0 and 12.5 ppg, respectively) were tested. None of the mud formulation had been optimized for rheology or fluid loss prior to the investigation. The salt/polymer mud is a standard mud formulation in the Gulf of Mexico. The silicate mud, too, is a common formulation provided by a drilling fluid vendor. The lime/salt mud was an experimental formulation. The SBMs have internal olefins (IOs) and linear alpha olefin (LAO) as base oils. The mud properties are shown in Table 1.

The 24-hour static fluid loss is shown in Figure 2. Not surprisingly, in the static test the oil-based fluids exhibit the lowest fluid loss, and the salt/polymer mud has the highest fluid loss.

Figure 3 is the summary figure of all the dynamic tests. The salt/polymer mud has kept its high level of fluid loss, compared to the other mud systems. The fluid loss is independent of the shear rate across the filter cake. The silicate drilling fluid behaves similarly. The filtrate volume of the lime/salt drilling fluid increases at the higher shear rate. However, the behavior of the synthetic-based drilling fluids is markedly different. The initial low fluid loss at the low shear rates increases significantly at higher shear rates. A more-detailed view of this behavior is shown in Fig. 4 for the IO-based fluid and Fig. 5 for the LAO-based fluid. Some additional fluid-loss tests at intermediate shear rates with the internal olefin based fluid were included to define the transition to the higher fluid-loss behavior. The cumulative fluid loss of the SBM drilling fluid remains almost unchanged up to 700 RPM. A sharp increase in the fluid loss can be observed at 800 RPM shear rate.

In contrast to the SBM behavior, the tests for the salt/PHPA and silicate mud show little shear dependence (Figs. 6,7). The lime/salt water-based system has an elevated fluid loss at 1000 RPM, but to a lesser extent than the SBM.

Further insight is gained by looking at the fluid loss rates over the twenty-four hour period for the mud systems (Figs. 9-11). At the low shear rates the rate of fluid loss has dropped below 4 ml/hr within 90-150 minutes, even for the higher fluid loss of the NaCl/PHPA drilling fluid. The two SBM maintain a very low rate of fluid loss. At the much higher shear rates, the equilibration time is more than twice as long (260 minutes and 450 minutes, respectively) for the SBM, while the equilibration time of the WBM has increased, but not by as much. The NaCl/PHPA and silicate-based drilling fluid maintained the most consistent performance of rate of fluid loss over time.

Discussion

Dynamic and static fluid loss tests similar to the above observations have been published previously.[1-4]

The trends outlined by our experiments show a lower fluid loss for the SBM than for the WBM under static conditions. When the filtercakes of the SBM are subjected to high shear rates, the fluid loss is higher than for the WBM. In this study we found that the critical shear rate in this particular set up and this specific permeable medium was 700-800 RPM for the SBM. At shear rates higher than 700-800 RPM, the fluid loss increased sharply. Accordingly, the filtercake must have been very thin or widely eroded to allow the high fluid loss. This conclusion is counter-intuitive to the presumed prevalent mechanism of OBM filer cake (i.e. primarily through internal plugging). Apparently the mechanisms surrounding the WBM and the SBM external filtercake are important for an effective fluid loss control at high shear rates. A correlation of the pore-size distribution of the aloxite disk to the particle-size distribution and emulsion globule-size distribution has not been performed.

In general, we observed the rates of fluid loss remain much higher longer for the higher shear rates. The high shear rates appear to prolong the time required to form a low-permeable filtercake.

It is reasonable to assume that the underlying reasons for this behavior are the different responses of the filtercakes to shear. Visual observations of the individual filtercakes after the tests showed that the filtercakes of the WBM became thinner with shear rate, but the already thin SBM filtercake remained relatively thin (no measurements of the filtercake thickness had been carried out).

Looking back at this and other published studies, the mechanisms surrounding filter cake deposition, including their contribution to an optimized fluid loss behavior have not been sufficiently investigated. For example, SBM/OBM and WBM filtration properties are thought of being governed by different mechanisms when forming a filtercake: A WBM forms an external filtercake and the particles and particle-size distribution of the solids in the drilling fluid are important to form a dense, low-permeable filtercake. This is also reported and recognized in the ceramics industry: a certain particle-size distribution must be attained for the best and densest packing[8].

For SBM or OBM the pore plugging and impairment of filtration is assumed to be through a so-called internal filtercake (emulsion globules). The globules blocking the pore throats and pore bodies are thought to be the dominating mechanism in the fluid loss behavior. The contribution of the external filtercake to fluid loss control are thought to be not as important as for WBM.

Chesser *et al.*[2] discuss the effects of the filtercake on the fluid loss. Particle-size distribution, cake compressibility, cake lubricity, state of flocculation and cake thickness are cited as the most important properties of the filtercake. They argue that under dynamic conditions the filtercake is formed by optimum-sized particles only, and the cake has a lower permeability than under static conditions. The filtration rate per unit thickness should therefore be lower. The experiments used to support their statement were 120 minute-long static and dynamic tests. These showed that the filtration rate of OBM is much lower under dynamic conditions. This is in contrast to the observations of the tests described in this paper. However, the shear rates used in those experiments were not reported, thus making a comparison difficult.

Conclusions

- An increasing fluid loss with increasing shear rate was observed primarily in SBM.
- This effect was also observed, albeit to a lesser degree, in WBM.
- The measured static fluid loss for a given fluid correlates to dynamic fluid loss at low shear rates (i.e. a low fluid loss at static conditions also has a low fluid loss at dynamic conditions). At higher shear rates, different trends in fluid loss behavior may be observed.
- The initial rate of filtration is much higher for high shear rates and may last two- to three times longer. The high shear rates appear to prolong the time required to form a low-permeable filtercake.
- Particle deposition under static and dynamic filtration conditions dominate the fluid loss behavior of drilling fluids.
- A greater number of different drilling fluids need to be tested to confirm that OBM/SBM indeed respond differently to shear than WBM.
- If confirmed, this observation may be important in reviewing occurrences of differential sticking and formation impairment.

Acknowledgments

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	NaCl/PHPA	Lime	Silicate	SBM: IO based	SBM: LAO based
After 16 hr hot rolling					
Mud weight [ppg]	12.0	12.0	12.0	12.5	12.0
600 RPM	89	66	103	56	43
300 RPM	58	45	72	36	26
200 RPM	46	36	58	28	19
100 RPM	31	25	41	19	12
6 RPM	9	11	16	8	5
3 RPM	8	11	14	7	4
PV [cP]	31	21	31	20	17
YP [lb/100 ft^2]	27	24	41	16	9
10 sec/10 min	8/18	15/30	14/16	8/9	4/6

Table 1. Summery of fluid properties.

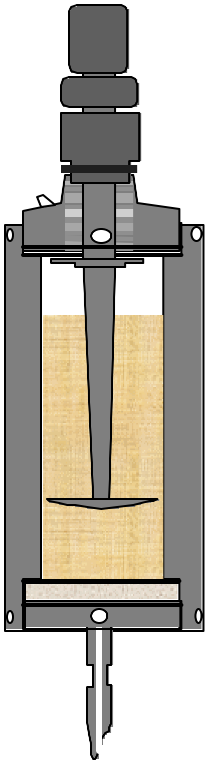

Figure 1- Schematic of dynamic fluid loss cell.

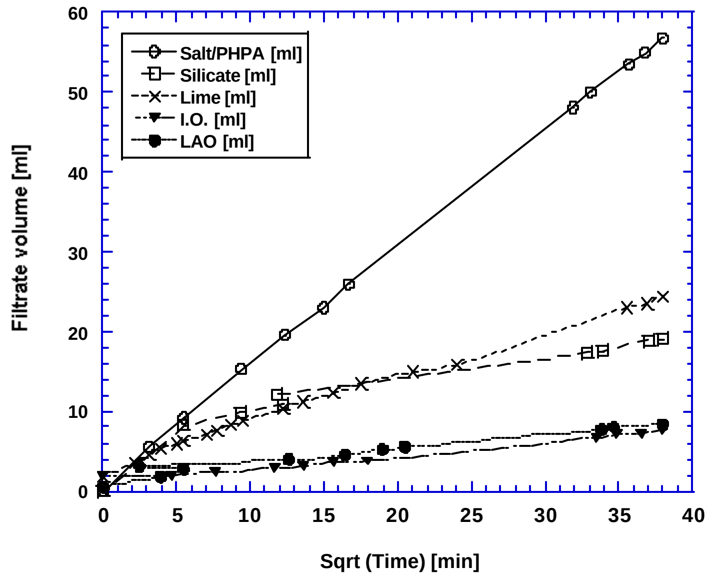

Figure 2. Static fluid loss across a 5 micron aloxite disk in 24 hours.

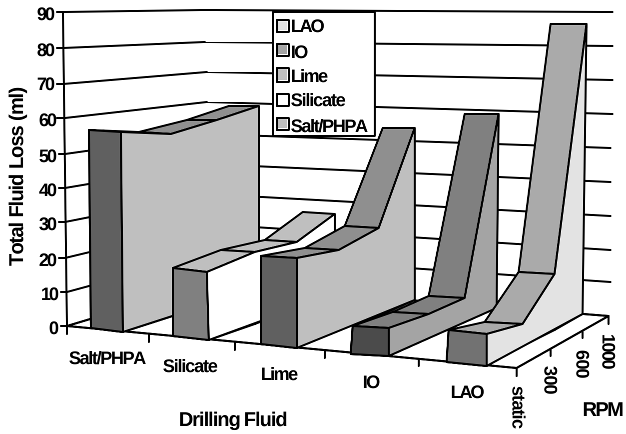

Figure 3. Summary of the cumulative fluid loss of all measured drilling fluids.

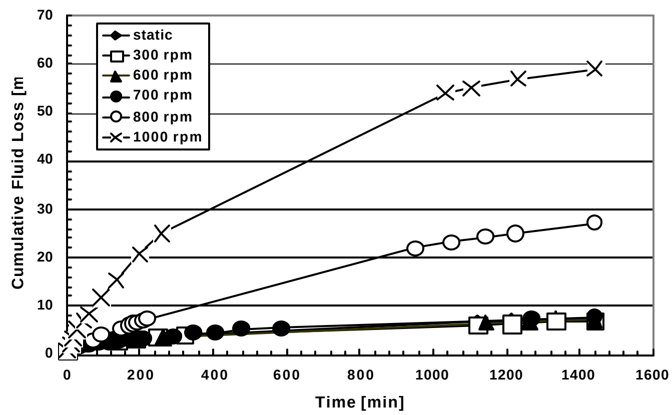

Figure 4. Effect of shear rate on the 24-hr fluid loss in a SBM with internal olefins as base.

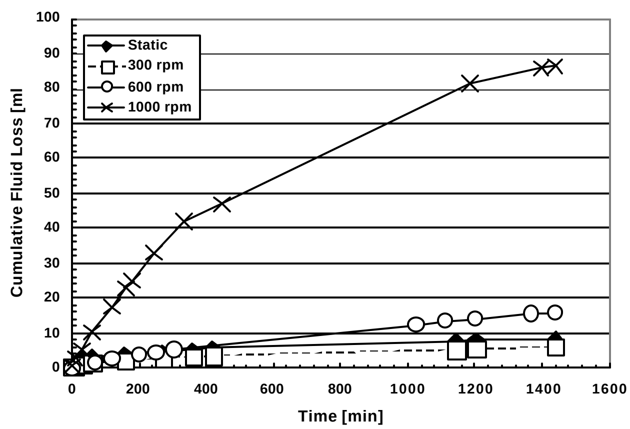

Figure 5. Effect of shear rate on the 24-hr fluid loss in a SBM with LAO as base.

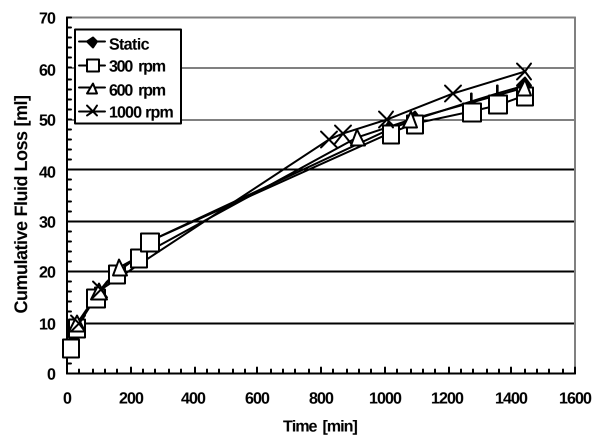

Figure 6. Effect of shear rate on the 24-hr fluid loss in a NaCl/PHPA drilling fluid.

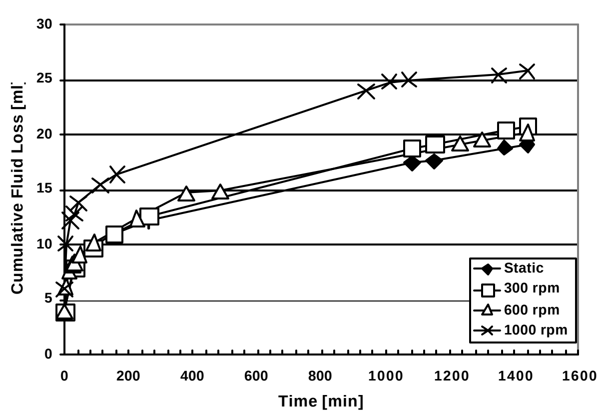

Figure 7. Effect of shear rate on the 24-hr fluid loss in a silicate drilling fluid.

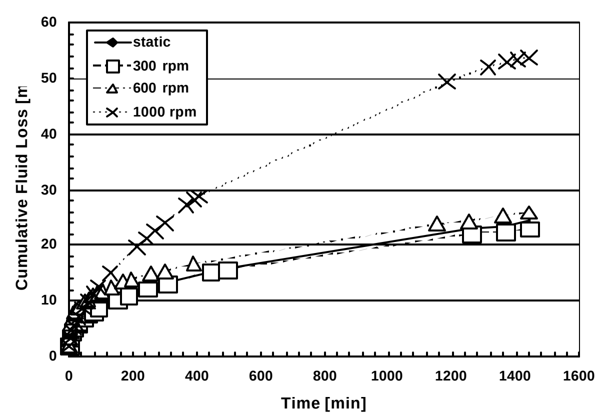

Figure 8. Effect of shear rate on the 24-hr fluid loss in a lime/salt drilling fluid.

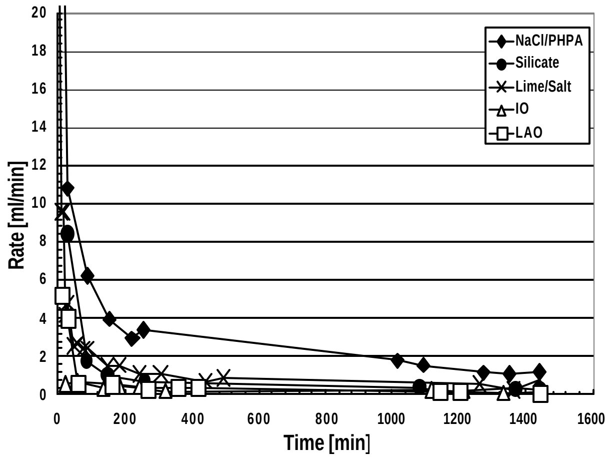

Figure 9. Rate of fluid loss over 24 hours at static conditions.

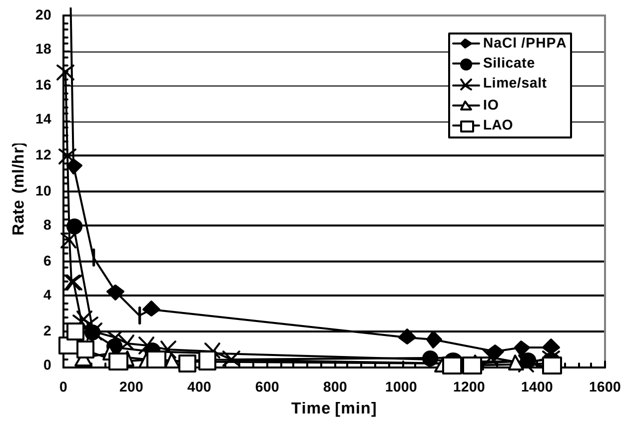

Figure 10. Rate of fluid loss over 24 hours at 300 RPM.

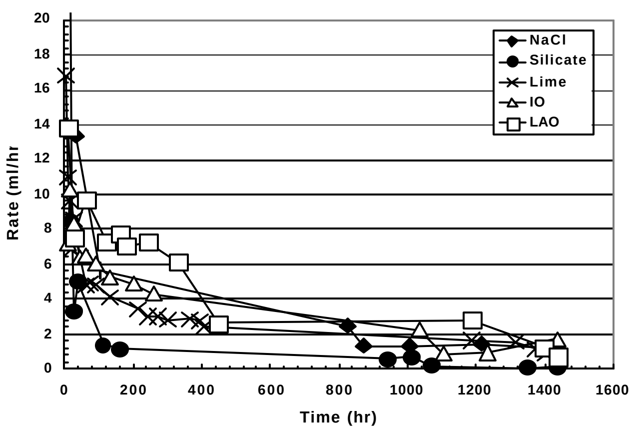

Figure 11. Rate of fluid loss over 24 hours at 1000 RPM.