FLOW CURVES AND FLUID LOSS OF WATER-BASED DRILLING FLUIDS

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ABSTRACT

A drilling fluid must fulfill numerous functions during well drilling, ranging from particle transport, lubrication, to wall stabilization. In that aim, the composition is carefully chosen by the drilling engineer for each well section according to the required properties such as density, rheological properties, chemical stability and fluid loss. In particular, fluid loss refers to the penetration of the liquid from the drilling fluid into the rock formation. It must be controlled and preferably avoided as it may reduce the permeability of the formation and change the fluid properties due to the depletion of the liquid. Fluids with low fluid loss have the ability to form an impermeable filter cake at the rock surface, i.e., a layer of accumulated particles on the wall of the well.

As interest in CO_2 storage has increased in the last decade, the need to design drilling fluids for CO_2 well drilling has arisen. Lots of knowledge is inherited from oil & gas wells, and still CO_2 wells pose new challenges. These wells should not be optimized for production (receiving fluids from the formation into the well), but for injection (injecting CO_2 from the well to the rock formation). Here, we present an experimental study aiming to optimize drilling fluids rheological properties and fluid loss for CO_2 wells. Flow curves are measured using a Couette cell in an Anton Paar rheometer. Fluid loss and filter cake formation are evaluated with a filterpress. We investigate the effect of the fluid components on the flow curve, the fluid loss and the filter cake mass.

INTRODUCTION

A drilling fluid must fulfill numerous functions during well drilling, ranging from particle transport, lubrication, to wall stabilization. In that aim, the composition is carefully chosen by the drilling engineer for each well section according to the required properties such as density, rheological properties, chemical stability and fluid loss. As interest in CO_2 storage has increased in the last decade, the need to design drilling fluids for CO_2 well drilling has arisen[1]. Lots of knowledge is inherited from oil & gas wells and still CO_2 wells pose new challenges. These wells should not be optimized for production (receiving fluids from the formation into the well), but for injection (injecting CO_2 from the well to the rock formation).

One of the important properties of the drilling fluids is their ability to reduce fluid loss, i.e., penetration of the liquid from the drilling fluid into the rock formation. Fluid loss is undesired as it may reduce the permeability of the formation and change the fluid properties due to the

depletion of the liquid. Fluid with low fluid loss have the ability to form an impermeable filter cake at the rock surface, i.e., a layer of accumulated particles on the wall of the well or in the outer layer of the rock. For CO_2 wells, it is essential that the filter cake does not hinder the injection of CO_2 in the reservoir. Since there is no flow from the formation into the well, there are no mechanisms from the formation to wash back the filter cake or clean out formation damage due to fluid loss.

In this paper, we investigate fluid loss and filter cake formation with different water-based drilling fluids. The paper is divided into two main parts: first, in the experimental part, we investigate the effect of testing conditions and fluid composition on their properties. Secondly, we present a model for the formation of the filter cake and compared it with the experimental data. This study is part of a larger project where we aim to provide methods and tools supporting the choice of drilling fluids for CO2 wells.

MATERIALS AND METHODS

Materials

The drilling fluids have been mixed with a OFITE high speed blender, at rotation velocity 11 500 rpm, first for 15 min for all the ingredients except barite particles, then another 15 min after the addition of barite. The composition for each of the studied drilling fluids are listed in **TABLE 1**. The density of the fluids is about 1200 kg/m^3.

TABLE 1: Drilling fluids used in this paper

	DF_base	DF_cellulose	DF_MEG	DF_PEEK
Tap water (g)	465	465	450	465
Xanthan gum (g)	2.00	2.00	2.00	-
Sulfonated PEEK (sPEEK) (g)	-	-	-	2.00
Soda ash (g)	1.00	1.00	1.00	1.00
KCl (g)	33.0	33.0	33.0	33.0
Cellulose (g)	-	10.0	10.0	10.0
Mono-ethylene glycol (MEG) (g)	-	-	20.0	-
Barite (g)	140	140	140	140

The composition of DF_base is similar to commercial KCl-based drilling fluids. DF_cellulose has the same composition except for the addition of cellulose fibers. In DF_MEG, water is partially replaced by monoethylene glycol (MEG), a common component in drilling fluids to avoid hydrate formation. The MEG content is chosen so that the total volume of liquids is the same in all the drilling fluids (MEG density is 1350 kg/m^3). Finally, in DF_PEEK, we replace Xanthan gum polymer by sulfonated PEEK (sPEEK). Functionalization of PEEK (Polyether ether ketone) is performed in our lab prior to the experiments. This step is necessary to make the polymer hydrophilic and soluble in water. In a typical procedure, 5.5 g of commercial PEEK (Fumion® E 600-PEEK from Fumatech) was dissolved in 75 ml of 97% H_2SO_4 and heated at 80°C for 7 days. After the reaction, the solution was poured in ice cold water, neutralized with sodium hydroxide and used further for preparing water-based fluid.

Hot rolling (HR)

In the field, fluids are reused after being circulated in the well as long as their properties do not change too much. In the well, the fluids are exposed to higher temperature, pressure and mechanical stirring. To check whether these conditions may affect the properties of the drilling fluids, we perform hot rolling where the fluids are placed in a 500 mL cylindrical cell and kept in an oven at 90°C with rotation at 20 rpm for one night. In addition, in some cases, we placed a steel rod in the cell to induce additional shear on the fluids. This procedure is inspired by, and further described in, the work of Klungtvedt and Saasen[2].

Filter press measurements

The filter press experiments are performed with an OFITE HTHP static filtration cell. A schematic drawing of the tests can be seen in **FIGURE 1**. 50 mL of drilling fluid is placed in the chamber on a 11-µm sized filter paper supported by a porous disk with pore size much larger than 11 µm. The top of the chamber is connected to a nitrogen bottle to impose a pressure of 35 bar. The test starts when the bottom or the cell is opened, and the fluid coming out of the drilling fluid (filtrate) is collected. The filtrate volume (fluid loss) is monitored during 30 min, after which the test is stopped. The test leads to the forming of a filter cake, i.e., an agglomeration of particles on the top of the filter paper. After the test, the cell is opened and the remaining fluid at the top of the filter cake is poured out. The filter cake is weighted before (wet mass) and after (dry mass) drying for one night in an oven at 66°C.

The cell is placed in a heating jacket: For the results presented in this paper, tests are performed at room temperature and 50°C.

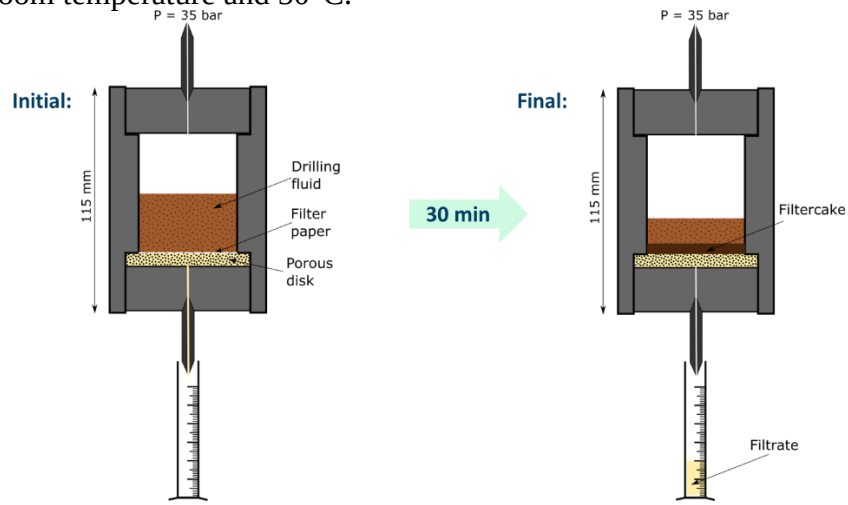

FIGURE 1: Schematic drawing of filter press experiments

Rheology

The rheological properties are derived from tests performed in Anton Paar 102 MRC equipped with a smooth Couette cell. The measuring gap is 1.13 mm, and the rotating cylinder has a diameter of 26.66 mm and a height of 40 mm. The cell is equipped with a Peltier system to control the temperature.

The applied test sequence is as follows. The fluid is presheared for 1 min at 1000 s^{-1}, then left to rest for 10 s. Then, we apply a ramp of increasing shear rates from 0.01 s^{-1} to 1000 s^{-1}, before a decreasing ramp from 100 s^{-1} to 0.01 s^{-1}. The curves shown in this paper are obtained during the decreasing shear rate ramp.

EXPERIMENTAL RESULTS

Effect of hot rolling and test temperature

We have first studied for DF_base the effect of hot rolling and test temperature on the properties for the drilling fluid (see **FIGURE 2**).

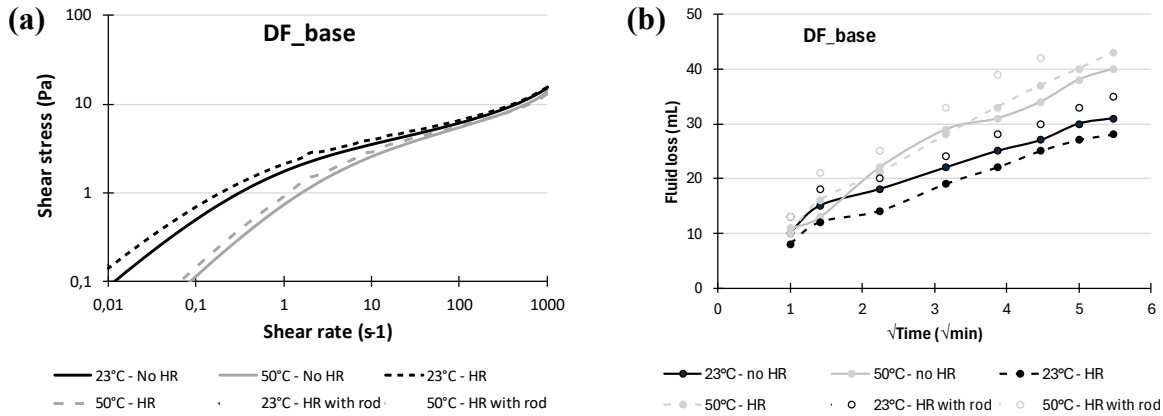

FIGURE 2: Effect of hot rolling (with and without rod) and test temperature on the properties of DF_base. (a) Flow curves (b) Fluid loss curves.

The hot rolling, with or without rod, did not have a major impact on the rheological properties of the drilling fluids, showing that the DF_base composition is adapted to be used in wells at high temperature (see **FIGURE 2** (a)). The temperature in the tests affects the viscosity of the fluids. The viscosity decreases with the test temperature. This is a common observation for water-based drilling fluids. Regarding the fluid loss properties (**FIGURE 2** (b)), hot rolling has a limited effect, while increasing the test temperature increases the fluid loss.

Besides, the test temperature and hot rolling does not seem to have a major effect on the filter cake dry mass, as the values obtained for all the tests are between 9.0 and 13.1 g, with an average of 11.3 g.

Effect of cellulose

Next, we study the effect of cellulose by comparing the flow curves and fluid loss curves of DF_base and DF_cellulose. These results can be seen in FIGURE 3. The cellulose fibers have a major effect on the flow curves of the drilling fluid; it increases the effective viscosity at high shear rate ($> 10\ s^{-1}$) and decreases the effective viscosity at low shear rates ($< 10\ s^{-1}$). Hot rolling has limited effect on the flow curves of the fluids.

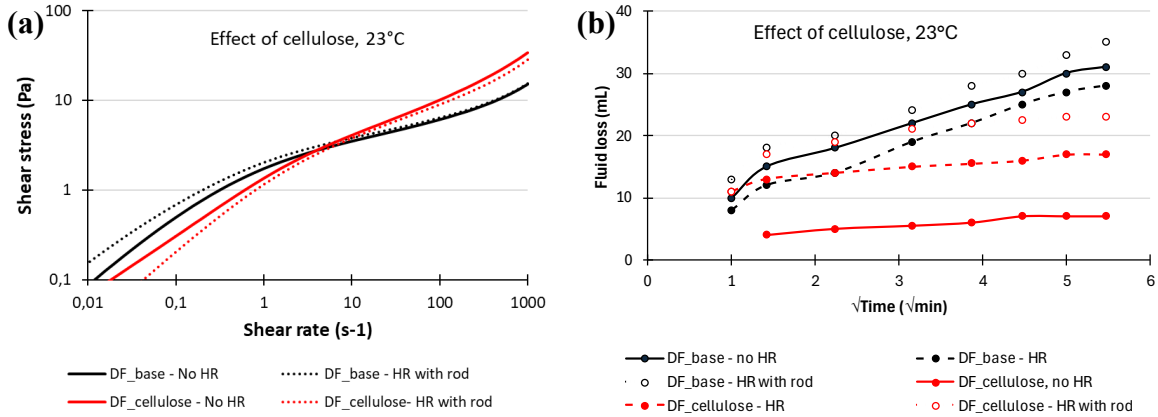

FIGURE 3: Effect of cellulose on (a) the flow curve and (b) the fluid loss curve of the drilling fluids, at 23°C.

The cellulose fibers also have a major impact on the fluid loss curves. It is known that the addition of fibers in a drilling fluids reduces the fluid loss and makes it easier to close the large pores in the rock formation[3,4]. This effect can clearly be seen in **FIGURE 3** (b), where the fluid loss is about 30 mL without cellulose after 30 min, while it is no more than 8 mL with cellulose. We can note that the hot rolling and mechanical shear with rod both reduce the efficiency of cellulose fibers. The fluid loss reaches 23 mL for DF_cellulose after hot rolling with rod. This shows that high temperature and mechanical shear damage the cellulose fibers. This observation is in accordance with previous tests which investigated the crack sealing ability of drilling fluids[2], where the sealing ability decreased when hot rolling was performed with a rod compared to hot rolling without rod. Experiments with DF_cellulose performed at 50°C showed no difference in fluid loss without hot rolling, but fluid loss much higher than DF_base in the case of hot rolling (results not shown here). This confirms that the cellulose fibers tend to be damaged by high temperature.

The mass of the filter cakes obtained from DF-cellulose were consistently lower than the filter cakes obtained from DF_base, on average 7,9 g. A large variation could however be observed in the dry mass of filter cakes obtained with cellulose. For instance, the experiment at 23°C without hot rolling, gave a filter cake dry mass of 4.3 g.

Effect of glycol

In **FIGURE 4** we investigate how MEG affects the fluid properties. Both DF_cellulose and DF_MEG contain cellulose. The difference in composition is that in DF_MEG, water is partially replaced by monoethylene glycol. Just one set of experiments has been performed, without hot rolling and with test temperature 50°C. Both flow curves and fluid loss curves show no difference between the fluids. This shows that MEG has no effect on these properties.

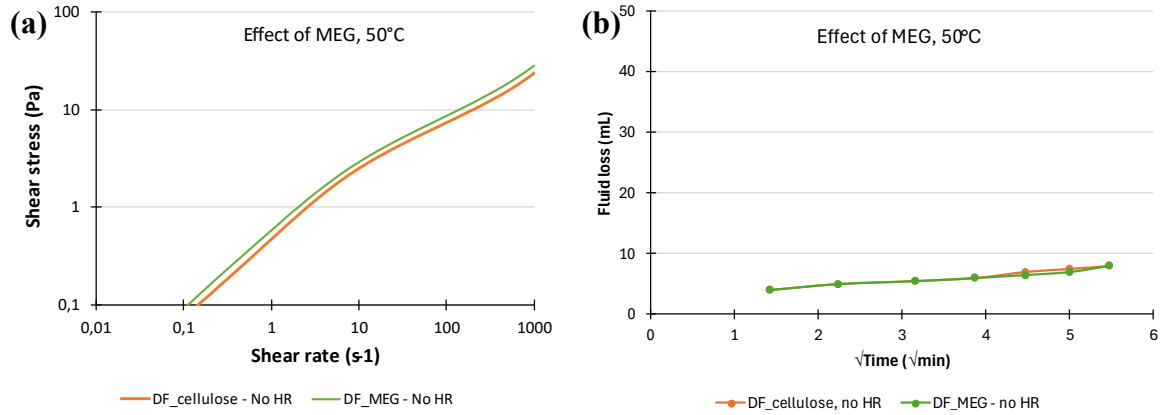

FIGURE 4: Effect of MEG on (a) the flow curve and (b) the fluid loss curve of the drilling fluids, at 50°C.

Replacement of Xanthan gum by PEEK

Finally, we investigate the effect of the polymer on the measured fluid properties (with cellulose). Xanthan gum is a common polymer used in water-based drilling fluids. PEEK, on the other hand, is not commonly used in drilling fluids. We have performed experiments to investigate whether it could be used to replace Xanthan gum for CO2 well applications.

The flow curves in **FIGURE 5** (a) show that the sulfonated PEEK results in drilling fluids with much lower viscosity than the xanthan gum. Note that this may reduce the fluid's ability to suspend and transport particles (weight particles and cuttings). This effect is not the object of this study.

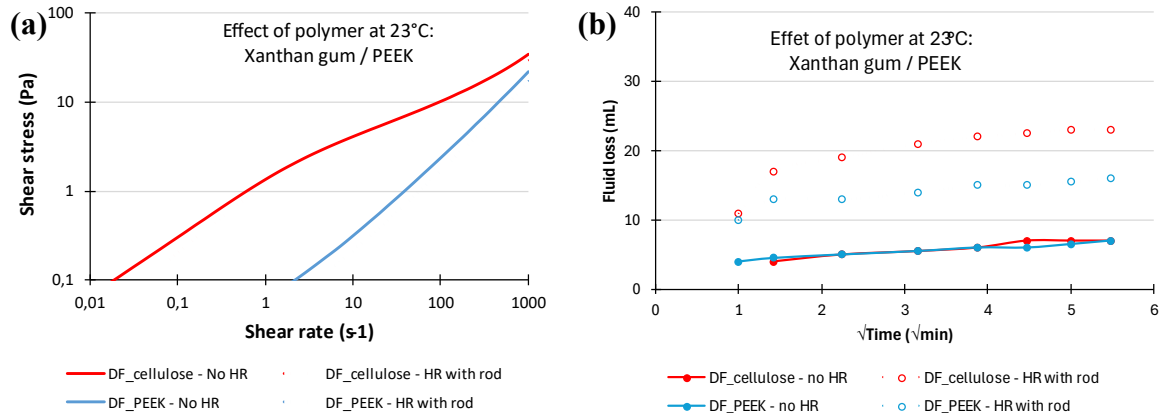

FIGURE 5: Comparison of (a) flow curves and (b) fluid loss curves for drilling fluids prepared from two different polymers.

On the other hand, fluid loss curves are very similar between the fluid with Xanthan gum (DF_cellulose) and the fluid with PEEK (DF_PEEK) without hot rolling. After rot rolling with rod, DF_PEEK had a lower fluid loss, which may indicate a good temperature stability of the PEEK. This should be confirmed by further experiments.

MODELLING OF FILTER CAKE FORMATION

During drilling a filter cake builds up on the inner cylindrical surface of the borehole wall as particles deposit on the surface while fluid (termed filtrate) flows into the porous formation. At the same time, the axial flow of drilling fluid circulating in the well causes erosion of the filter cake. This process is therefore a dynamic, radial filter cake buildup. If there is no axial flow the process is termed static, and if the geometry is planar, as in a laboratory filterpress, the process is termed linear. The latter is also a suitable approximation if the thickness of the filter cake is small relative to the wellbore radius. Civan[5] presents models for this process with both constant pressure difference and constant rate conditions. Here we use the model for static, linear filter cake buildup at constant Δp to analyze some of the results presented above from filterpress experiments with water-based drilling fluid. Civan presented this model as

$$Q(t) = \frac{q_0}{\hat{A}u_0^2}\left[\sqrt{1+2\hat{A}u_0^2 t}-1\right] = \frac{a}{\hat{A}u_0}\left[\sqrt{1+2\hat{A}u_0^2 t}-1\right] \tag{1}$$

where $Q(t)$ is the cumulative filtrate volume versus time t, a is the effective area of the porous disk, q_0 = a*u_0 is the initial volumetric filtrate flow rate and $\hat{A}$ is given by

$$\hat{A} = \frac{K_f k_d c_p}{\rho_p\left(1-\phi_c\right)K_c u_0 L_f} \tag{2}$$

Here, K_f and K_c are the permeabilities of the porous disk and the filter cake, respectively, k_d is a dimensionless constant of order unity representing the particle deposition rate of particles onto the filter cake, c_p is the mass concentration of particles in the drilling fluid, ρ_p is the mass density of these particles, ϕ_c is the filter cake porosity and L_f is the thickness of the porous disk. See **TABLE 2** for list of symbols.

While we do not know the permeability of the porous disk, it can be estimated using the Kozeny-Carman relation, given by [6]

$$K_f = \frac{\phi_f^3 d_f^2}{180\left(1-\phi_f\right)^2} \tag{3}$$

This gives a permeability of 3.65 darcy. The effective area a of the porous disk is

$$a = \frac{\pi D_{f,eff}^2}{4} \tag{4}$$

The model presented above neglects the spurt loss volume. We account for this ad hoc by neglecting the flow time for this volume. The resulting model is thus

$$Q(t) = \frac{a}{\hat{A}u_0}\left[\sqrt{1+2\hat{A}u_0^2 t}-1\right] + Q_{sl} \tag{5}$$

At short times, i.e. for

$$t << \tau \equiv \frac{1}{2\hat{A}u_0^2} \tag{6}$$

we have

$$\lim_{t\to 0}\frac{Q(t)-Q_{sl}}{t} = au_0 = q_0 = \frac{\Delta p a K_f}{\mu L_f} \tag{7}$$

where we have assumed flow according to Darcy's law. Assuming (or defining) $Q(t=0) = Q_{sl}$ we can estimate q_0 as

$$q_0 = \frac{Q(t_1) - Q_{sl}}{t_1} \tag{8}$$

Asymptotically at large times $t >> \tau$ we have

$$Q(t) - Q_{sl} = \frac{a}{\hat{A}u_0}\left[\sqrt{1 + 2\hat{A}u_0^2 t} - 1\right] \approx \frac{a}{\hat{A}u_0}\sqrt{2\hat{A}u_0^2 t} = a\sqrt{\frac{2}{\hat{A}}}\sqrt{t} \tag{9}$$

Thus, the model predicts that Q plotted versus the square root of time should produce straight lines asymptotically at large times, and from this slope we can calculate the filter cake permeability.

The following approximations are made:

1. Instantaneous spurt loss volume
2. Incompressible mudcake
3. No deposition of particles inside permeable disk
4. No deposition of particles inside filter cake
5. Darcy flow

The validity of the first of these assumptions can be discussed by analyzing the initial part of the curve $Q(t)$. Assumption #2 can be questioned due to the large pressure difference over the filter cake. Qualitatively, we expect that compression of the filter cake will reduce the porosity and thus the permeability of the filter cake and thus that the filtrate flow volume will increase more slowly than indicated by eq. (1). Since the permeable disk is covered by a filter paper with small pore size (11 μm), assumption #3 appears reasonable. Assumption #4 can be argued valid provided that the particles are of uniform size. In the base fluid (DF base) this is the case. For the other fluids the validity of this assumption can be questioned due to the presence of cellulose fibers. The validity of Darcy flow can be checked by calculating the Reynolds number based on the initial flow velocity u_0, viscosity μ, porosity ϕ_f, and pore size d_f of the porous disk. The viscosity is here the effective viscosity of the filtrate at representative shear rate for flow inside the porous disk. Thus, the viscosity cannot generally be inferred from the flow curves presented above, since the filtrate by assumption does not contain particles. In addition, we expect that some of the polymers are retained by the filter cake. However, we can still estimate the viscosity from eq. (7) once the initial flow rate q_0 is determined.

We apply the model presented above to the fluid DF base. It contains only one species of particles (barite) and is most likely to adhere to the assumptions presented above.

By regression using the model presented above we can in principle estimate values for initial filtrate flow velocity u_0, effective viscosity μ, and filter cake permeability K_c. Since the time resolution of the experimental data for $Q(t)$ is relatively coarse, the application to experimental data here is mainly to illustrate the principles.

We determine the parameters u_0, μ, and K_c using three different methods:

1. Asymptotic analysis, first using eqs. (7)-(9) neglecting the spurt loss and then calculating the spurt loss Q_{sl} as the difference between the experimental and modelled filtrate volume at the first non-zero time step.
2. By least square non-linear regression of eq. (5) using u_0, $\hat{A}u_0$, and Q_{sl} as fitting parameters
3. Subtract the spurt loss Q_{sl} calculated from method 1, and then apply least square non-linear regression of eq. (5) using u_0 and $\hat{A}u_0$ as fitting parameters.

Results from the regression analysis are shown in **TABLE 3**. We notice that there is a significant difference between the results from Method 1 (using asymptotic analysis) on the one side and Methods 2&3 (using least square fit) on the other side, for all results except the spurt loss. For all the models the viscosity μ is given by the velocity u_0 by eq. (7). We can argue which combination of μ and u_0 is most correct by considering the flow curve for this fluid, see **FIGURE 2**. The shear rate in the porous disk can be estimated as

$$\gamma = \frac{u_0 / \phi_f}{d_f} \tag{10}$$

From method 1 we obtain $\gamma = 2.5$ s^{-1} for method 1 and 1600-1700 for methods 2 and 3.
The actual viscosity of the filtrate is expected to be lower than indicated by **FIGURE 2** due to loss of particles and possibly also polymers. However, from **FIGURE 2** we obtain a viscosity of about 1.0 Pa*s at $\gamma = 2.5$ s^{-1} and 0.015 Pa*s at $\gamma = 1000$ s^{-1} (highest shear rate measured). Since the viscosity values of the filtrate should be lower than this, we conclude that all three methods overestimate the viscosity. This in turn means that the permeability K_f of the porous disk most likely is overestimated. From eq. (2) we see that then also the filter cake permeability is overestimated in this static linear model. To be able to conclude on which of the methods used here produce the most correct results, one would need more accurate experimental data on spurt loss volume and the corresponding time when this volume has been produced (spurt loss time t_{sl}). The three methods give t_{sl} = 40 s, 0.07 s, and 0.06 s, respectively.
Overall, we note that the cumulative filtrate volume is roughly linear in square root of time at large times, indicating the validity of the model. However, the time resolution is too low, in particular at short times, to produce more reliable data. Also, the accuracy of the filtrate volume is relatively low, on the order of 1 ml.
For all three methods we find that the filter cake permeability is much lower than the permeability of the porous disk and is of order 0.025 to 5.0E^{-5} darcy.

TABLE 2. List of symbols for filter cake formation modelling

Symbol	Description	Typical or default value
c_p	Mass concentration of particles in slurry	263 kg/m^3
d_f	Pore size in porous disk	90 µm
D_f	Diameter of porous disk	63.5 mm
$D_{f,eff}$	Effective diameter of porous disk (in contact with fluid)	53 mm
K_c	Permeability of filter cake	
k_d	Particle deposition rate coefficient	1
K_f	Permeability of porous disk	3.65 darcy
L_f	Length (thickness) of porous disk	6.5 mm
Q	Cumulative filtrate volume	
Q_{sl}	Spurt loss	
q_0	Initial filtrate flow rate	
Δp	Applied pressure difference	35 bar
ϕ_c	Porosity of filter cake	
ϕ_f	Porosity of porous disk	0.33
ρ_p	Mass density of particles in slurry	4200 kg/m3

TABLE 3. Results from regression analysis of filter cake model for fluid DF_base, no hot rolling, 23 °C.

Method	u_0	μ	Q_{sl}	K_c
	m/s	Pa*s	ml	darcy
1	7.6E-5	25.7	6.7	0.025
2	0.048	0.041	7.5	5.0E-5
3	0.053	0.037	6.7	4.5E-5

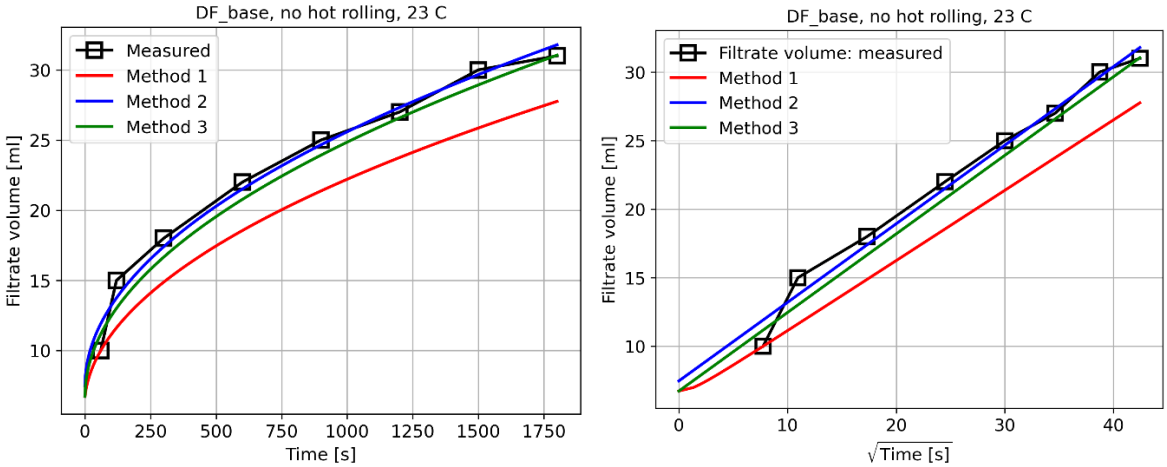

FIGURE 6. Measured and modelled filtrate volume as function of time (left) and square root of time (right) for fluid DF_base (no hot rolling, 23 °C).

CONCLUSIONS

We have measured experimentally the rheological and fluid loss properties of different water-based drilling fluids. We have also compared the fluid loss data with a static linear model and estimated physical parameters including filter cake permeability. The following observations have been made:

- The cellulose fibers increased the high shear rate viscosity and decreased the low shear rate viscosity of the drilling fluid. They reduced efficiently the fluid loss at room temperature but were easily damaged by mechanical shear and high temperatures.
- Replacement of a small quantity (3%) of water by monoethylene glycol (MEG) did neither affect the flow curve nor the fluid loss properties.
- Replacement of Xanthan gum by sulfonated PEEK strongly reduced the effective viscosity but seems slightly beneficial to fluid loss properties.
- The cumulative filtrate volume increases as the square root of time, indicating the validity of the static, linear filter cake buildup model for the setup used here.
- The permeability of the filter cake is significantly lower than the permeability of the porous disk.

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