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Evaluate the Sealing Efficiency of Lost Circulation Material on a Large Scale for High-Temperature Drilling Applications

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Abstract

Lost circulation is a severe problem encountered while drilling operations. Huge resources, efforts, and time are spent treating fluid losses worldwide. Treatment methods vary depending on the loss amount and severity, such as using conventional lost circulation material (LCM), smart LCMs, LCM pills, cement, and advanced drilling operations. However, adding LCMs to drilling fluid formulations is the commonly used method in the field to prevent and treat mud losses. Evaluating LCM and other mud additives is essential in designing the treatment formulation. Therefore, laboratory studies are performed to assess the sealing efficiency in the lab scale before field implementation. The LCM evaluation relies on using small-scale equipment such as plugging permeability apparatus. However, the LCM particles may block the tubes and valves opening, resulting in misleading findings. This paper evaluates different lost circulation materials on large-scale and high-temperature dynamic conditions.

A novel experimental setup was developed to evaluate the LCMs and avoid the limitations of existing laboratory methods. Many fractured discs were designed and created with various sizes and complexity using a 3D printer. Carbon fiber material was used to print the discs to withstand the high testing temperature (up to 320°F). Several drilling mud samples were prepared in the mixing tank and tested on the new setup using different lost circulation materials. The used LCMs are calcium carbonate, cedar fiber, walnut, and shape memory polymer. The plugging process was evaluated by observing the differential pressure and flow rate change resulting from each LCM.

Calcium carbonate was ineffective in sealing the fracture due to its fine particle size. Cedar fiber and walnut performed better than calcium carbonate. They successfully plugged the 2000-micron fracture but failed to seal the 3000-micron and complex fractures completely. The shape memory polymer outperformed other LCMs and instantly sealed all fracture sizes used in this study with a lower filtrate volume and higher differential pressure than other LCMs.

Introduction

High temperatures cause formidable challenges to the drilling operation, such as degradation of drilling mud and cement, damage to casing and cement sheath, and failure of downhole tools (Mohamed et al. 2021a). In addition, lost circulation is a challenging event faced during drilling operations (Alkinani et al. 2019). For instance, between 1993 and 2003, more than 10% of the nonproductive time in the Gulf of Mexico was due to lost circulation. In the United States, 10 to 20% of the geothermal well cost results from lost circulation treatments (Lavrov 2016). Moreover, lost circulation causes well control problems in severe cases, leading to a loss in lives and resources (Magzoub 2021).

Practically, loss prevention in the first place is more effective than treating the losses (Magzoub et al. 2020). Loss prevention is achieved by adequately designing drilling muds, good hole cleaning, and optimized wellbore hydraulics (Mohamed et al. 2021a). The prior knowledge of formation properties and advanced drilling technologies mitigate the consequences of lost circulation events (Magzoub et al. 2020). However, lost circulation events in weak and fractured formations are inevitable because controlling wellbore pressure is challenging. In such cases, drilling engineers should promptly cure the losses and regain well control. The appropriate treatment method is selected and designed based on the loss severity: seepage, severe, or complete loss.

Many lost circulation materials are used to treat fluid losses in geothermal, oil, and gas wells. LCMs are added to the drilling mud in various concentrations, depending on the loss severity and downhole conditions. Therefore, selecting and optimizing the LCM mud formulation is vital for optimal treatment results. Mohamed et al. (2021a) summarized the lost circulation materials commonly used in drilling operations. LCMs can be classified based on the particle shape into three main groups: granular, flakey, and fibrous materials. Several studies were carried out to study the sealing performance of common LCMs under different testing conditions (Akhtarmanesh et al. 2016, Ezeakacha et al. 2017).

Many laboratory techniques and equipment were developed to evaluate the LCM sealing efficiency. These methods are performed in static or dynamic conditions such as low-pressure low-temperature (LPLT) static filtration, high-pressure high-temperature (HPHT) static filtration, permeability plugging apparatus (PPA), and dynamic linear and radial filtration.

However, these experiments are conducted in small-scale laboratory equipment that does not account for the complexity of drilled formations. The techniques are also limited with LCM size; the large LCM particles plug the tubes and connections, producing misleading results. Moreover, various flow loops have been used to evaluate lost circulation materials' filtration and sealing performance in a large-scale setup and under dynamic conditions. Thus, this paper evaluates different lost circulation materials on large-scale and high-temperature dynamic conditions. A novel experimental setup has been developed to avoid the limitations of existing laboratory methods. The material and methods used in this study are described in detail in the subsequent sections. Then, experimental results are interpreted and discussed, and some conclusions are drawn.

Material and Methods

Materials

Several water-based drilling fluid samples were prepared in the mixing tank of the flow loop with a total volume of 10.5 gal. A synthetic hectorite clay (THERMA-VIS) developed by a service company was added as a viscosifier to suspend and carry LCM particles with a 3 lb/bbl concentration. It activates and builds viscosity at a temperature above 300°F, with a thermal resistance of up to 700°F (Baroid 2012). It was selected because of its high thermal resistance and high shear-thinning behavior (Mohamed et al. 2021b, 2021c, 2021a). A smart polymer and other conventional LCMs were added to the drilling fluid, with a concentration of 1.0 wt.%, and tested using the experimental setup. The smart LCM is a shape memory polymer (SMP) designed to activate at 300°F. After activation, the SMP particle size increases to seal the large fractures with minimal risk of plugging downhole tools (Mohamed et al. 2021d). The conventional LCMs are calcium carbonate, cedar fiber, and walnut. These commercial LCMs were obtained from a service company. LCM properties are shown in Table 1. Different fractured discs were designed and created using a 3D printer. The discs were printed using carbon fiber to withstand the high testing temperature, up to 350°F (Figure 1).

Methods

The experimental setup is a high-temperature (HT) flow loop mainly consists of: i) Frame designed to mount the components of the flow loop; ii) Main test section to simulate and visualize the annular mud flow; iii) Cylindrical mud tank with a capacity of around 10.5 gal to prepare the mud; iv) Heating system to increase the mud temperature to the desired testing conditions; v) Mud pump to circulate the mud at various flow rates; vi) Flowmeter to measure the liquid flow rate; vii) Pipe viscometer with a differential pressure cell to measure the viscosity of the mud; viii) Pressure and temperature transmitters to monitor the pressure and temperature in the whole system; ix) Control and relief valves; and x) Data acquisition system to obtain and record the measured data. Figure 2 illustrates the schematic of the experimental design.

Initially, the main test section was designed to simulate the annular flow of drilling fluids to study the LCM transportation under different parameters. Recently, we have done a slight modification on the main test section to study the sealing efficiency of various LCMs. The test section has two viewports to visualize the plugging process. A differential pressure cell was connected to both sides of the test section to measure the pressure buildup throughout the plugging process. In addition, the designed fractured disc is mounted inside the viewport to visualize the sealing process. The schematic of the modified test section and the fractured disc is shown in Figure 3.

The modified flow loop was used to conduct the fracture sealing experiments at 320°F. The experiments were performed using the following steps:

Step 1. The base fluid was prepared in the mixing tank by adding the viscosifier to the water and mixing it for around one hour to ensure complete dispersion.

Step 2. The base fluid was left for 20-24 hrs to hydrate and yield optimal and consistent rheological performance.

Step 3. The fluid sample was heated and circulated in the flow loop to ensure homogenous fluid temperature. The circulation was stopped when the desired temperature was attained and 1.0 wt. % LCM was added to the tank and mixed for 30 min to ensure better LCM dispersion in the fluids.

Step 4. The experiment started by circulating the LCM mud at a flow rate of about 6 gpm. The differential pressure across the fracture, flow rate, and videos were recorded during the experiment to capture the plugging process.

Step 5. The plugging was confirmed by the increase in differential pressure, decrease in flow rate, and the captured videos.

Step 6. The sealing experiments were conducted using different fracture sizes and complexities to evaluate and compare the sealing performance of the different LCMs. The used fractures were 2000 microns, 3000 microns, and complex fracture. The experimental parameters are summarized in Table 2.

Results and Discussions

Calcium Carbonate

Calcium carbonate was tested using the three fracture sizes. As all LCMs, calcium carbonate particles were added after reaching the testing temperature (320°F). Figure 4 shows the change in differential pressure across the fracture over time. As shown in Figure 4, the differential pressure did not increase significantly, indicating that calcium carbonate was ineffective in sealing all the fractures. Although some spikes in the pressure were observed with calcium carbonate due to the particles bridging, the bridging was not strong enough to seal the fracture. The fracture reopens as the pressure builds up, resulting in differential pressure drops. It can also be seen that the calcium carbonate performed slightly better in the 2000-micron fracture than in 3000-microns and complex fracture as higher spikes were detected with the 2000-micron fracture. This poor performance observed with calcium carbonate is attributed to its small particle size.

Cedar Fiber

Cedar fiber performed better than calcium carbonate, where the differential pressure increased with time, confirming the plugging process. In all fractures, the pressure started to increase after around 3 min. We observed that cedar fiber performed better in the small fracture (2000 microns), and the differential pressure increased up to 22 psi compared to 17 psi in the 3000-micron fracture. Conversely, we observed some sudden drops and spikes in the differential pressure in the complex fracture (Figure 5). These sudden changes are attributed to the fact that the bridging was not strong enough to hold the pressure. However, in all fractures, cedar fiber did not plug the fracture completely; as a result, filtrate flow was observed until the end of the experiments, which indicates the partial plugging of the fractures and the formation of permeable bridge. Blending fiber with other LCMs or introducing smaller particles are required to seal the pore space between fiber particles and improve the cedar fiber performance.

Walnut

Walnut particles showed a good plugging performance in the 2000-micron fracture, where the differential pressure started to increase after 2 min to reach up to 25 psi (Figure 6). In contrast, walnut particles failed to seal the 3000-micron and complex fractures. The differential pressure slightly increased to reach around 12 psi and remained constant until the end of the experiments. This low differential pressure confirmed that the walnut particles partially plugged the fractures without forming a solid bridge on the fracture opening. Filtrate flow was also observed until the end of the experiments.

Shape Memory Polymer (SMP)

As shown in Figure 7, SMP outperformed all other LCMs with a higher sealing pressure, and the fractures started to seal in a shorter time (around 1.5 min). SMP showed almost the same performance with the 2000-micron and 3000-micron fractured disc with slightly lower pressure for the 3000-micron fracture. Similarly, SMP was effective in sealing the complex fracture with a slight delay in the sealing; the fracture started to seal after 3 min to reach a differential pressure of 27 psi at the end of the experiments. The longer it takes to seal the fracture, the more fluid will be lost to the formation; therefore, more cost for the lost fluid and more formation damage to the producing formation (Adebayo and Bageri 2020, Marx and Rahman 2007). The captured videos and flowmeter readings showed that the filtrate flow stopped entirely after the fractures were sealed. The flow rate dropped down to zero, indicating the high sealing efficiency with SMP. Figure 8 clearly shows the seal created on the fractured discs by SMP particles. The excellent sealing performance of SMP with large and complex fractures can be attributed to the increase in particle size due to the thermal activation of SMP. Moreover, the wide range of SMP particle sizes improved the sealing efficiency. The large particles create the bridge on the fracture mouth, while the small particles plug the pore space between large particles and the fracture wall (Magzoub 2021).

Blend of Shape Memory Polymer and Cedar Fiber

To improve the performance of cedar fiber, it was mixed with SMP in a ratio of 25% to 75%. The SMP and cedar fiber blend was tested on the 3000-micron and complex fractures. The SMP-fiber combination showed the best sealing integrity and efficiency (Figure 9). The differential pressure started to shoot up after around 2 min to reach the maximum differential pressure detected with the differential pressure transmitter, 30 psi. The maximum differential pressure was maintained with both fractures until they were plugged entirely and the flow rate dropped to zero. This phenomenal performance is attributed to the complementary effects of the LCMs. The variety in sizes and irregular shape of SMP and long and thin particles of cedar fiber helped plug the fracture by forming a robust bridge of LCMs inside the fracture (Figure 10). Therefore, cedar fiber and SMP blends have a high potential to seal large and complex fractures in high-temperature and geothermal formations. However, more experimental studies are required to optimize the ratio of SMP to cedar fiber depending on the fracture size and shape to ensure optimal results in the field operations. These results also confirmed the findings of the previous study conducted by Magzoub et al. (2021a, 2021b).

Conclusions

An experimental study was performed to evaluate the sealing efficiency of different LCMs at high-temperature conditions using a large-scale flow loop. Several discs were created using a 3D printer to simulate the formation fractures. The experiments were conducted by varying LCM type, fracture size, and fracture complexity. The LCMs used in this study are calcium carbonate, cedar fiber, shape memory polymer, and walnut. Based on the obtained results, the following conclusions can be drawn:

- Calcium carbonate was ineffective for treating fluid losses in large fractures due to its fine particle size.
- Cedar fiber and walnut performed better than calcium carbonate. They successfully plugged the 2000-micron fracture. However, when the fracture size was increased to 3000 microns, they partially sealed the fracture and failed to block the complex fracture.
- The shape memory polymer outperformed other LCMs in terms of sealing efficiency. SMP efficiently plugged all fracture sizes used in this study with a lower filtrate volume and higher differential pressure than other LCMs.
- Cedar fiber and SMP blends showed a good potential to seal large and complex fractures. As a result, higher differential pressure and lower filtrate volume were observed with the blend than other fluid formulations. However, more experimental studies are required to optimize the ratio of SMP to cedar fiber to ensure better results in the field operations.

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Nomenclature

HPHT = *High-pressure high-temperature*
HT = *High-temperature*
LCM = *Lost circulation material*
LPLT = *Low-pressure low-temperature*
PPA = *Permeability plugging apparatus*
SMP = *Shape memory polymer*

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Table 1: Properties of used lost circulation materials

Material	Appearance	Specific gravity	Particle size
Calcium carbonate	Granular	2.71	Average of 88.2 µm
Cedar fiber	Fibrous	1.7	53-2360 µm (Average of 550 µm)
Shape memory polymer (SMP)	Granular	0.95	840-2360 µm (Average of ~1400 µm)
Walnut	Granular	1.3	840-2360 µm (Average of ~1400 µm)

Table 2: Experimental parameters of fracture sealing experiments

Parameter	Description
LCM concentration	1.0 wt.%
Temperature	320°F
Pressure	40 psi
Flow rate	6 gpm
Inclination angle	Horizontal (90˚)

Figure 1 – 3D fractured discs used in this study: a) complex fracture, b) 3000 microns, and c) 2000 microns.

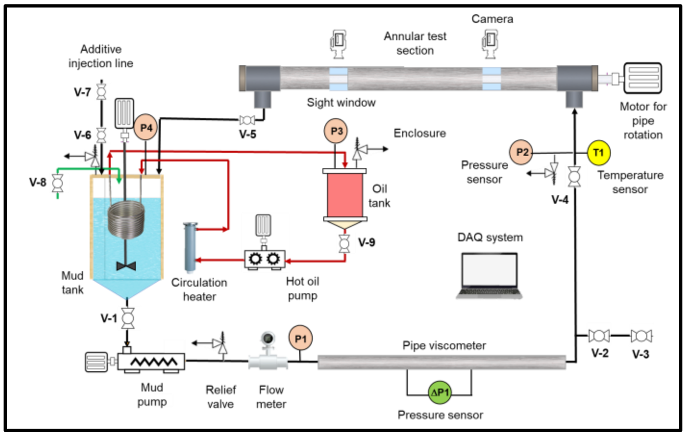

Figure 2 – Schematic design of the high-temperature flow loop setup.

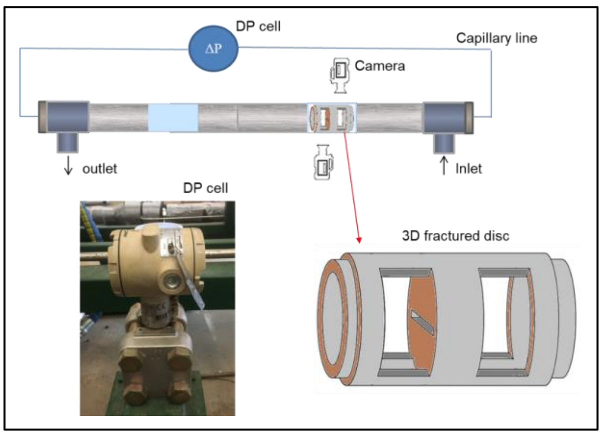

Figure 3 – Modified schematic design of the main test section.

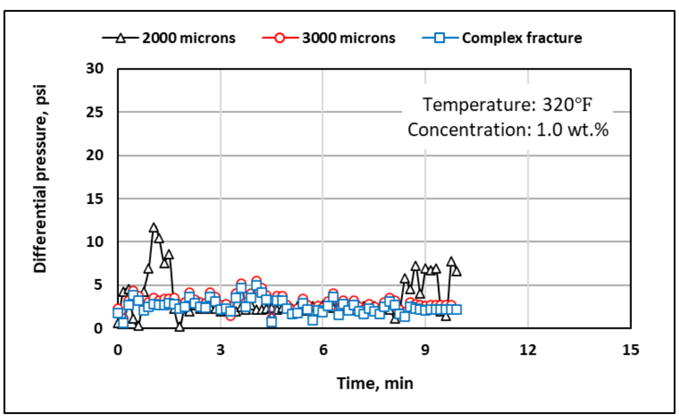

Figure 4 – Sealing performance of calcium carbonate at different fracture sizes.

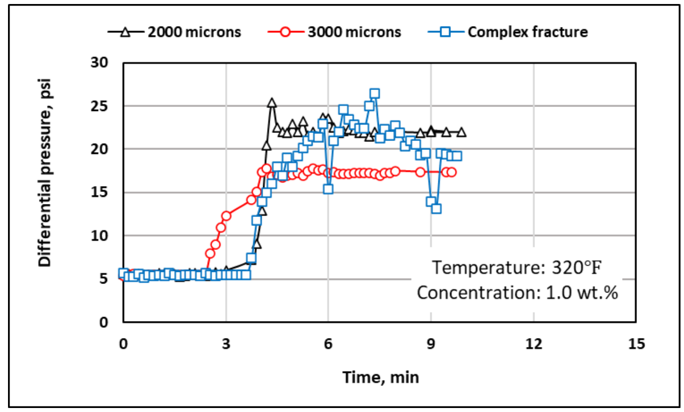

Figure 5 – Sealing performance of cedar fiber at different fracture sizes.

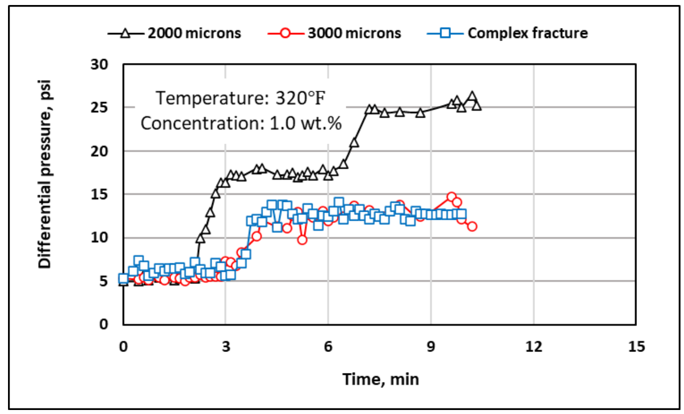

Figure 6 – Sealing performance of walnut at different fracture sizes.

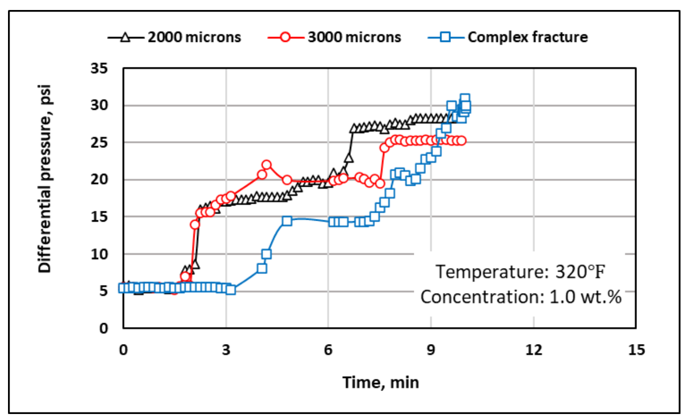

Figure 7 – Sealing performance of shape memory polymer at different fracture sizes

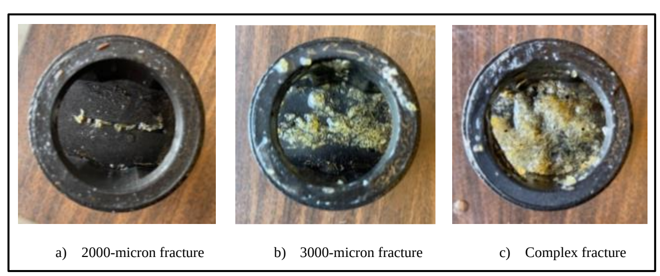

Figure 8 – Fractured discs after the experiments with shape memory polymer.

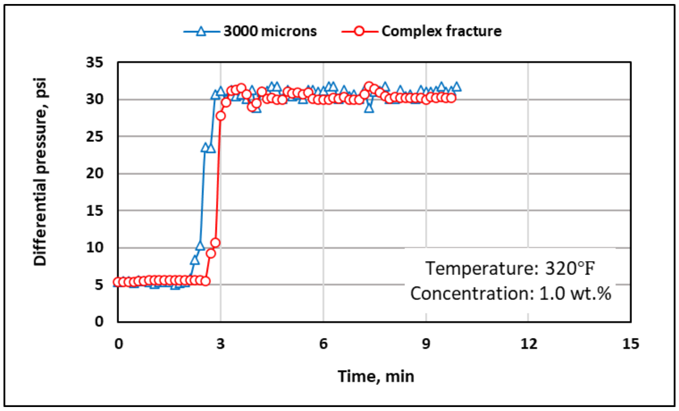

Figure 9 – Sealing performance of SMP-fiber blend at different fracture sizes.

a) 3000-micron fracture b) Complex fracture

Figure 10 – Fractured discs after the experiments with SMP-fiber blend.