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A Novel Experimental Setup for Testing Lost Circulation Material on a Large Scale for Geothermal Drilling Applications

Abdelmjeed Mohamed, Saeed Salehi, Ramadan Ahmed

Mewbourne School of Petroleum and Geological Engineering, University of Oklahoma, Norman, OK, USA

abdelmjeed@ou.edu

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ABSTRACT

Lost circulation is a common and challenging problem encountered while drilling oil, gas, water, and geothermal wells. It costs the industry enormous resources, nonproductive time (NPT), and effort. In the United States, 10 to 20% of the geothermal well cost is spent on lost circulation treatments. Using lost circulation material (LCM) is the commonly used treatment method to prevent and cure lost circulation events. There are different types of LCMs and are generally classified into three main categories; granular, flakey, and fibrous materials. Selecting the appropriate material and optimizing the mud formulation is essential in designing the treatment method. Therefore, LCMs should be evaluated first in laboratories before field implementation.

The LCM evaluation is always conducted using small-scale equipment in static or dynamic conditions such as plugging permeability apparatus. However, this small equipment does not fully represent the actual field conditions. It sometimes fails when the LCM particles block the tubes and valves opening, resulting in misleading findings and failure in field operations. This paper presents a novel experimental setup to evaluate lost circulation material in large-scale and high-temperature dynamic conditions (up to 350°F) to avoid the limitations of existing laboratory methods. The setup consists of a mud mixing and circulation system, heating system, pipe viscometer, main test section, and data acquisition system. In addition, several fractured discs were designed and 3D-printed using carbon fiber material to test the sealing efficiency of different LCMs. A detailed description of the experimental setup, 3D fractured discs, optimized operating procedure, and preliminary results are presented in this paper. The results showed promising findings and a novel testing procedure of different LCMs for geothermal drilling applications.

1. INTRODUCTION

Drilling fluids are introduced to the wellbore to fulfill many functions: mainly to control the well pressure, remove the drilled cuttings and transfer them to the surface while circulation and suspend the drilled cuttings while no circulation, maintain wellbore stability, reduce the torque on the drill pipe, and to lubricate and cool the drill bit (Caenn et al., 2017; Hossain and Al-Majed, 2015; Mohamed et al., 2020). Overbalanced drilling is a common technique for well control where the hydrostatic mud pressure is kept higher than the formation pressure. Consequently, the mud tends to invade the formation causing formation damage due to the solid particles and fluid filtrate interaction with the formation rocks and fluid (Mohamed et al., 2020). Therefore, fluid loss control additives are added to the mud formulation to minimize the damage (Vivas et al., 2020).

Loss circulation is a challenging phenomenon encountered while drilling, especially in depleted and high permeability zones (Alkinani et al., 2019). There are two types of loss circulation, partial or total loss. Loss circulation greatly impacts the cost of drilling operations and may lead to a severe loss of well control, causing a loss in lives and money (Magzoub et al., 2020). Many parameters affect the loss circulation, such as formation permeability, differential pressure, mud properties, and downhole hole conditions (Mohamed et al., 2021a). Loss circulation materials (LCM) are drilling fluid additives added to the drilling fluid formulation to prevent and mitigate loss circulation. Several additives are used as LCM, such as polymers, calcium carbonate, fiber, and graphite. Selecting and optimizing the LCM considering all the drilling parameters and downhole conditions is crucial to avoid the failure of the loss circulation prevention job (Vivas and Salehi, 2022).

Practically, loss prevention in the first place is more effective than lost circulation treatments. Loss prevention is achieved by adequately designing drilling muds, good hole cleaning, and optimized wellbore hydraulics. In addition, the prior knowledge of formation properties and advanced drilling technologies mitigate the consequences of lost circulation events (Magzoub et al., 2020). Therefore, a complete evaluation of the mud formulation, LCM, and drilled formation before field implementation is necessary to ensure more successful operations. Hence, a number of laboratory techniques and equipment were developed to evaluate the LCM sealing efficiency. These methods are conducted either 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 experimental methods are done on a small laboratory scale that does not account for the complexity of drilled formations. Moreover, these techniques are also limited with LCM size; the large LCM particles plug the tubes and connections, producing misleading results.

For such reasons, various flow loops were introduced to evaluate drilling fluids' filtration and sealing performance and lost circulation materials. The flow loop setups allow testing the mud filtration performance under dynamic HPHT conditions with few limitations on LCM size. For instance, Magzoub et al. (2021) built a high-temperature flow loop that evaluates the mud filtration in a 14-inch rock sample with different fracture sizes. They used actual granite core samples to simulate the natural geothermal formations. The flow loop setup consists of a filtration cell, pump, mud tank, and collection system. In addition, a mud pump was installed on the system to circulate mud under the testing conditions. The test can be conducted at a pressure up to 2000 psi and a temperature up to 350°F. However, this setup is still small compared to the field scale. Thus, this paper describes a novel experimental setup to evaluate lost circulation material in large-scale and high-temperature dynamic conditions (up to 350°F) to avoid the limitations of existing laboratory methods. The subsequent sections present a detailed description of the setup design, components, experimental methods, limitations, and some preliminary results to address the experimental capabilities of the introduced setup.

2. EXPERIMENTAL SETUP DESCRIPTION

The flow loop setup is developed to evaluate the performance of lost circulation material under high-temperature conditions. The setup consists of five main sections: a mud mixing and circulation system, heating system, pipe viscometer, main test section, and data acquisition system. Each system serves specific functions, and all systems are described in the subsequent sections in detail. The schematic design and setup components are illustrated in Figure 1.

2.1 Mud Preparation and Circulation System

This system is designed to prepare drilling fluid samples and circulate fluid samples through the flow loop setup. The setup has a stainless-steel mud tank with the capacity of 10.5-gal for preparing and circulating fluid. The mud tank has a variable-speed agitator installed on the top to mix the drilling fluid and keep the fluid homogeneous throughout the experiments. The circulations system also consists of a lobe mud pump to circulate the fluid sample through the whole experimental setup at various flow rates, ranging from 0 to 36 gpm, with a differential pressure of up to 150 psi. The mud pump can withstand solid particles of up to 18 mm at a maximum concentration of 40 wt.%. 2-inch stainless-steel flexible pipes connect the flow loop components and allow mud circulation. Additionally, control valves are used to control the flow direction and help operate and clean the system, while relief valves are installed for safety to protect the main flow loop components. All flow loop parts are temperature and pressure rated up to at least 350°F and 150 psi.

2.2 Heating System

The function of the heating system is to maintain the desired testing temperature throughout the experiments. The heating system mainly consists of:

- 7-gal stainless-steel oil tank to contain the heating oil with a maximum temperature of 650°F and pressure of 200 psi.
- Relief valve installed on the top of the oil tank to avoid overpressure while heating.
- Control valve installed at the bottom of the oil tank to control the oil flow.
- Pump to circulate the heating oil at various flow rates (maximum of 85 gpm) and temperature of 650°F.
- Circulation heater with a power of 6000 W and maximum temperature of 550°F.
- Stainless-steel coil installed inside the mud tank to circulate the hot oil and increase the mud temperature to the desired level.
- Pressure and temperature sensors distributed along the flow loop to monitor the fluid pressure and temperature.

The heating system is a closed system, where the oil is circulated through the oil tank, heater, and stainless-steel coil using the pump. During circulation, the heat is transferred from the oil to the mud. Afterward, the oil will return to the tank at a lower temperature. The heating rate is optimized by controlling the heater temperature and oil circulation rate. All the flow loop components are thermally insulated to improve the heating efficiency and minimize the heat losses across the whole system.

2.3 Rheology Measurement System

The primary function of this system is to evaluate the flow characteristics of different drilling fluid samples and study the impact of lost circulation material on mud rheological properties under different conditions. The measured flow characteristics are also used to obtain the wellbore hydraulic parameters and interpret the findings of LCM transportation experiments. The rheology measurement system mainly consists of a 1-inch stainless-steel pipe viscometer with a length of 9 ft. A differential pressure transmitter (DP cell) is connected to the pipe viscometer through two capillary lines. The DP cell measures the differential pressure across the pipe viscometer. The capillary lines are 3 ft apart from each other with 3 to 4 ft distance from the viscometer's upstream and downstream to eliminate the end effects. The capillary lines are installed precisely at the same level and distance from the DP cell to ensure accurate pressure readings. The DP cell can measure differential pressure in the range of -5 to 5 kPa with an accuracy of ±0.05%. A flow meter is also used in this system to measure the exact flow rate provided by the mud pump. The differential pressure values corresponding to various flow rates are used to obtain the fluid flow characteristics and rheological properties. The detailed methods are discussed in Section 3.2.

2.4 Main Test Section

The main test section consists of two concentric stainless-steel pipes with a diameter of 1" and 2" to simulate the drilling mud annular flow during circulation. The inner pipe serves as a drill pipe and is attached to a motor to simulate the drill pipe rotation (0 to 150 RPM), while the outer pipe represents the drilled hole. Two viewports are connected to the outer pipe, and two high-speed cameras are mounted to visualize the fluid flow. The sight glass can withstand a maximum pressure and temperature of 115 psi and 450°F, respectively. The total length of the main test section is around 10 ft, and it is mounted on the moving part of the flow loop frame. The main test inclination can vary from 45˚ up to 90˚ (from vertical) to simulate inclined and horizontal wells. The inclination is changed by lifting the downstream side of the moving part using an overhead crane, and safety pins are added to the setup to secure the test section at the desired inclination angle. The recorded videos and images are analyzed to study the LCM transportation, change in LCMs, and mud flocculation under different parameters.

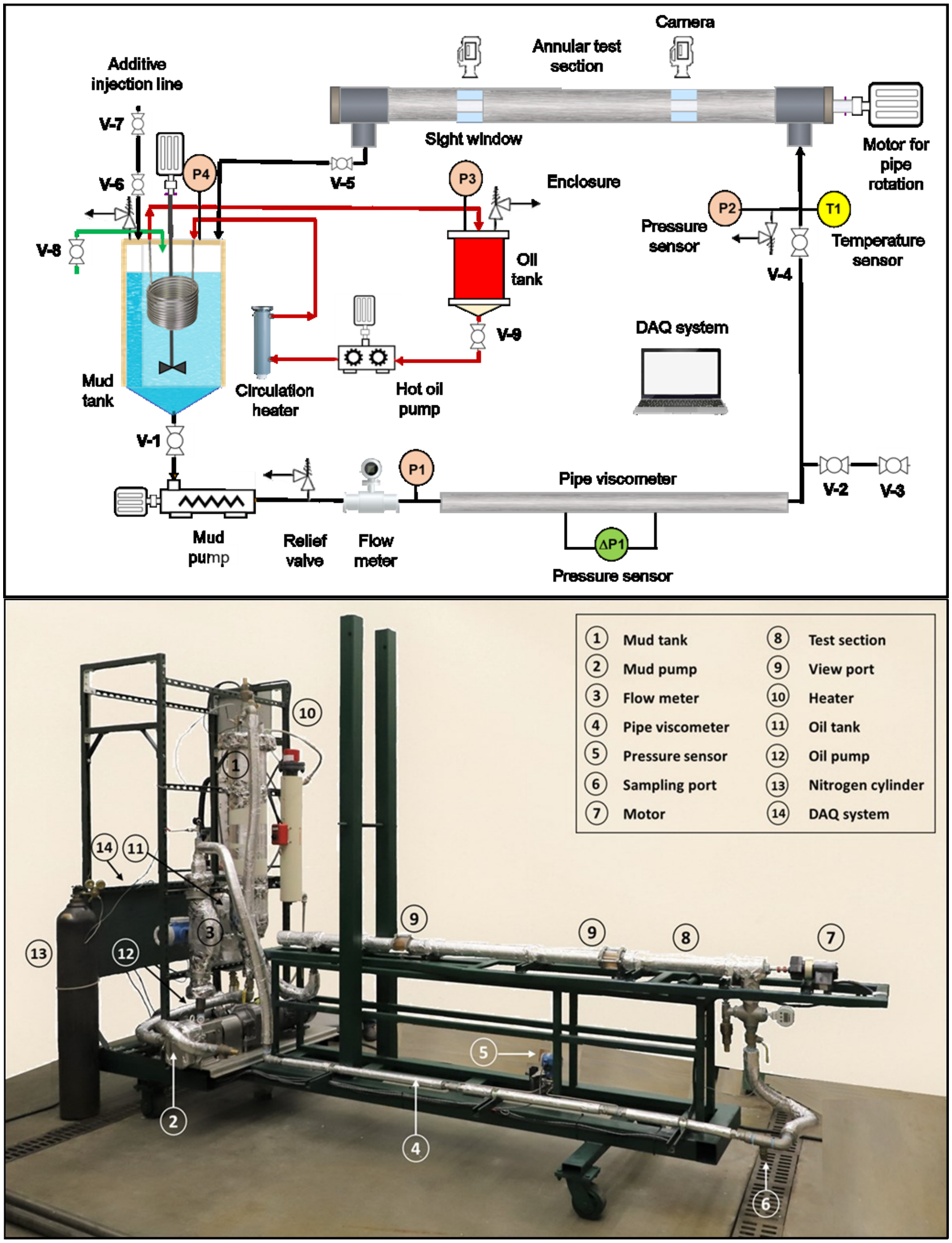

Figure 1: Schematic design and Components of the high-temperature flow loop.

Moreover, the flow loop design is modified to perform the fracture sealing experiments to evaluate the sealing performance of different LCMs. Mainly the test section is modified by removing the inner pipe from the system to install the fractured disc. The fractured disc is installed inside the viewport to enable real-time visualization of the plugging process. Different fractured discs were designed using the Tinker Cad platform. The fracture disc is designed as a hollow cylinder that contains a fractured disc in the middle perpendicular to the flow direction. The design has openings at the sides to allow flow visualization and detect the plugging process. The fractured disc has an outer diameter of 6.63 cm to fit inside the viewport. It also has lips at both ends to help secure the disc in the viewport and make sure it does not move during the experiments. Different disc designs were created by changing the fracture width and complexity to evaluate the sealing efficiency at different fracture sizes. These sizes are 2000 and 3000 microns, and the third disc was designed to contain a complex fracture network with 2000 microns width. The fractured discs were created by a 3D printer using carbon fiber material to withstand the high testing temperature. A differential pressure cell is also added to the main test section to detect fracture plugging by monitoring the pressure change throughout the plugging process. The two capillary lines of the DP cell are installed at the inlet and outlet of the main test section. The DP cell has a high-pressure range that can measure a differential pressure up to 30 psi. The schematic design of the fractured disc and modified test section are illustrated in Figure 2.

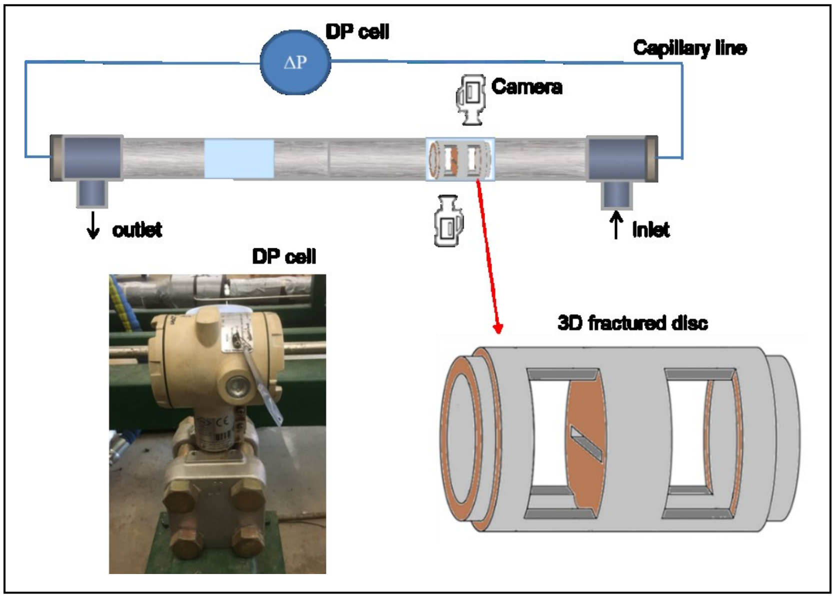

Figure 2: Modified schematic design of the main test section for fracture sealing experiments.

2.5 Data Acquisition and Control System

The data acquisition and control system is used to start and end the experiments, control the experimental parameters, and process and record all the obtained data throughout the flow loop experiments, such as pressure, temperature, flow rate, density, photos, and videos. The data acquisition computer is equipped with a multi-channel data acquisition card (DAQ). All instruments are connected to the DAQ card. The measured data is converted into digital numeric values then sent to, processed, and displayed on the PC monitor. Visual basic-based software is developed to process and record the obtained data. The software also starts and ends the experiments and controls the pumps' flow rate by sending specific voltage to the variable frequency drives (VFD) through the DAQ card. Some safety features are also added to the software to stop the oil pump and heater when the temperature exceeds the testing temperature by a specific margin. Based on the full system description, the range and limitations of experimental parameters are listed in Table 1.

Table 1: Rang of experimental parameters of the flow loop setup

Parameter	Range
Temperature	70-350°F
Pressure	15-150 psi
Inclination angle (from vertical)	45-90˚
Mud circulation rate	0-36 gpm
Pipe rotational speed	0-150 RPM
Solid concentration	40 wt.%
Solid particle size	18 mm

3. EXPERIMENTAL METHODS

3.1 Mud Preparation

A total fluid volume of 10.5 gal is mixed and prepared in the mud tank for every experiment. During mud preparation, the mud tank is isolated from the setup by closing the valve at the bottom of the tank to ensure homogenous mixing and consistent results. The mud additives are added separately to the tank, starting with the base fluid. Each additive is added slowly and mixed for a specific time, depending on the fluid formulation. The mud agitator is running throughout the mixing process and experiments to maintain the fluid homogeneity. After the fluid is prepared and before starting the experiment, the tank is connected to the system by opening the control valve at the bottom of the tank to allow mud circulation. The additive injection line remains closed during the experiment.

3.2 Rheology and Wellbore Hydraulics

Rheology experiments are performed using the pipe viscometer by ramping the mud circulation rate and measuring the corresponding differential pressure across the pipe. Each rate is kept for a few minutes to ensure stable and accurate readings. The recorded flow rate and differential pressure measurement are used to obtain the flow curve for each fluid sample as follows:

i. The flow rate (Q) and differential pressure (ΔP) data, obtained from the flow meter and pipe viscometer, are converted from gallon per minute (gpm) and inch water (in H_2O) to cubic meter per second (m^3/s) and pascal (Pa).

ii. Q and ΔP data are converted to wall shear stress (τ_w) and nominal Newtonian wall shear rate ($\dot{\gamma}_{nom}$), using the viscometer diameter (D) and length (L) by applying Equations 1 & 2.

$$\tau_w = \frac{D\ \Delta P}{4\ L} \tag{1}$$

$$\dot{\gamma}_{nom} = \frac{32\ Q}{\pi\ D^3} \tag{2}$$

iii. τ_w and $\dot{\gamma}_{nom}$ data are plotted to determine the fluid type and obtain the flow curve. For instance, for Power-law fluids, τ_w and $\dot{\gamma}_{nom}$ data gives a straight line in a full logarithmic scale. Then, the consistency (K) and flow index (n) can be obtained from the curve fitting techniques after excluding the turbulent flow data.

iv. Determining flow parameters, the rheological properties and wellbore hydraulic parameters can be obtained.

3.3 LCM Transportation

This part of the experiment studies the annular flow of different LCM muds to evaluate the LCM suspension under different conditions. These experiments consider a broad range of experimental parameters such as fluid and LCM type, LCM concentration, temperature, inclination angle, mud circulation rate, and pipe rotational speed. The primary function of these experiments is to optimize the lost circulation treatment parameters to avoid any LCM accumulation that may impact the LCM sealing efficiency or complicate the drilling operations. The high-speed cameras are installed on the main test section to visualize the fluid flow through the viewports. After setting the experimental parameters and starting the experiments, live videos are recorded with time. Afterward, the captured videos are frame-by-frame processed using video processing techniques. The frame-by-frame image analysis is very useful for obtaining the height of accumulated solids, detecting LCM change over time, and observing any mud flocculation or instability issues. Figure 3 shows some examples of the processed images for cedar fiber transportation. More experimental results are presented in previous publications (Mohamed et al., 2021a, 2021b).

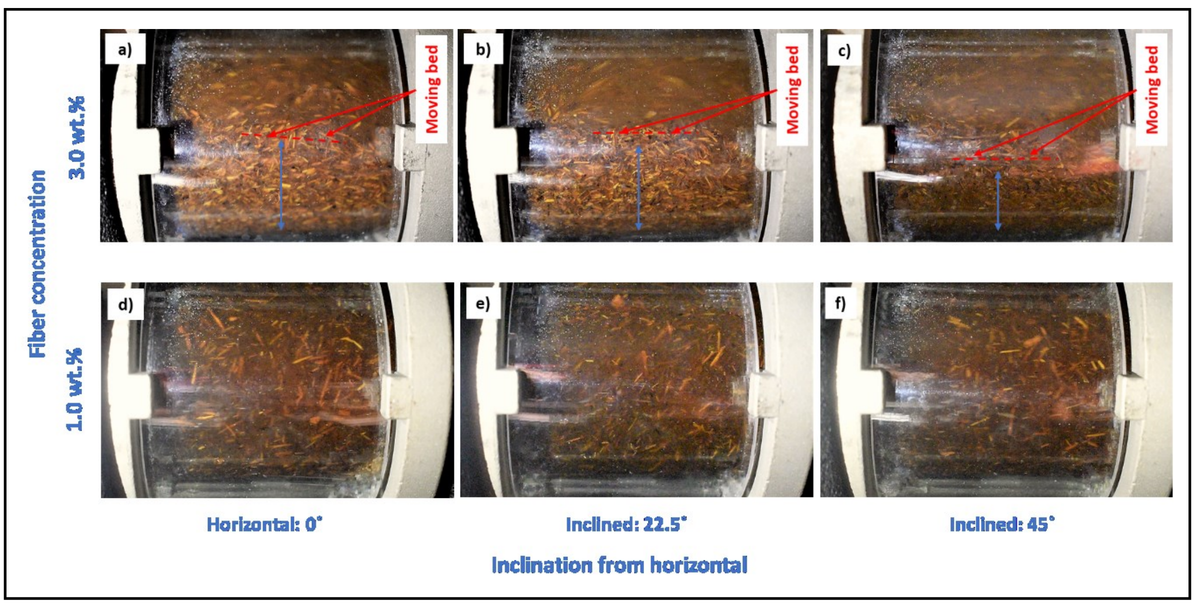

Figure 3: Inclination angel and concentration effect on cedar fiber transportation (350°F).

3.4 Fracture Sealing

Fracture sealing experiments are performed to study the plugging process and evaluate the LCM sealing efficiency. The sealing efficiency is assessed by how rapidly the differential pressure increases over time and the magnitude of differential pressure. The main parameters considered in these experiments are mud and LCM type, LCM concentration, fracture size, and fracture geometry. The fracture sealing experiments were conducted using the following steps:

i. The base fluid is prepared in the mud tank by adding mud additives individually and mixing them properly.

iii. Fluid is heated and circulated in the flow loop to ensure homogenous fluid temperature. When the testing temperature is reached, the circulation is stopped, and LCM is added to the mud tank with the desired concentration and mixed for 30 min. The agitator in the tank is kept rotating to ensure better LCM dispersion throughout the experiment.

iv. The experiment starts by circulating the LCM mud at a flow rate of about 6 gpm. The differential pressure, flow rate, and videos are recorded to capture the plugging process throughout the experiment.

v. The plugging is confirmed by the increase in differential pressure, decrease in flow rate, and the captured videos.
vi. The sealing experiments are conducted using different fracture sizes and complexities to evaluate and compare the sealing performance of the different LCMs.

4. TESTING AND CALIBRATION

4.1 Heating and Pressure Testing

Pressure testing was performed to ensure that the experimental setup worked efficiently without any leakage. The pressure test was conducted in two stages; 1) Test the heating system lines and tank using nitrogen and heating oil, and 2) Test the mud tank, test section, pipe viscometer, and flowlines using water and nitrogen. The test was performed in two stages because the setup is divided into two separate systems. First, the heating system was tested with nitrogen starting with the oil tank. The tank was isolated from the other system components by closing the valves. The tank was tested until 100 psi, and the pressure was monitored for more than 10 hrs using the data acquisition system and pressure gauges. Then the test was conducted on the whole heating system by following the same procedure. After the heating system passed the pressure test with nitrogen, the tank was filled and pressure tested with heating oil. Oil was circulated throughout the heating system at different flow rates using the oil pump, and no leakage was observed in the heating system. Afterward, the pressure test was performed on the mud tank and test section using nitrogen gas, following the same procedure. The pressure test was repeated with water by running the mud pump at different flow rates. The flow loop system passed the pressure testing successfully, and no leakage was observed.

The heating system was then tested by running different experiments with water to check the heating efficiency and optimize the insulation. The heating test was performed in three stages: 1) without insulation, 2) with one insulation layer, and 3) with two insulation layers. Figure 4 compares the heating performance of the flow loop system during the three stages. Without insulation, the system showed a low heating rate of 39.5°F/hr, and due to the high temperature losses and safety concerns, the heating was stopped after the fluid temperature reached around 200°F. Adding one layer of insulation improved the heating rate by 26.8%, with a rate of 50.1°F/hr. The fluid temperature reached 287°F in 4 hrs, and the heating was stopped for safety because the surface temperature of the system was higher than 150°F. Then, another insulation layer was added to the whole system, and the test was repeated. After adding the second layer of insulation, the heating rate was further increased by 26.1%, with a heating rate of 63.2 °F/hr. In around 3 hrs, the fluid temperature reached 300°F, and the test was stopped after reaching 320°F. The surface temperature of the insulation was below 100°F, which makes the system efficient and safe to operate.

After the flow loop was modified for fracture sealing experiments, the setup was heated using a water-based fluid to test the thermal stability of the 3D printed discs. The base fluid was heated to 350°F, the maximum testing temperature. The first design was printed using 25% infill printing density. The infill printing density represents how much material the disc contains, and the remaining percent is pore space. The disc was deformed and failed at 265°F when 25% infill density was used. Then, a slight modification to the design was done by changing the dimensions of the support to strengthen the design. The infill density was also increased to 50%. Consequently, the design was significantly improved, and the fractured disc successfully maintained its stability up to 350°F. Therefore, the new design is used for several experiments without any deformation.

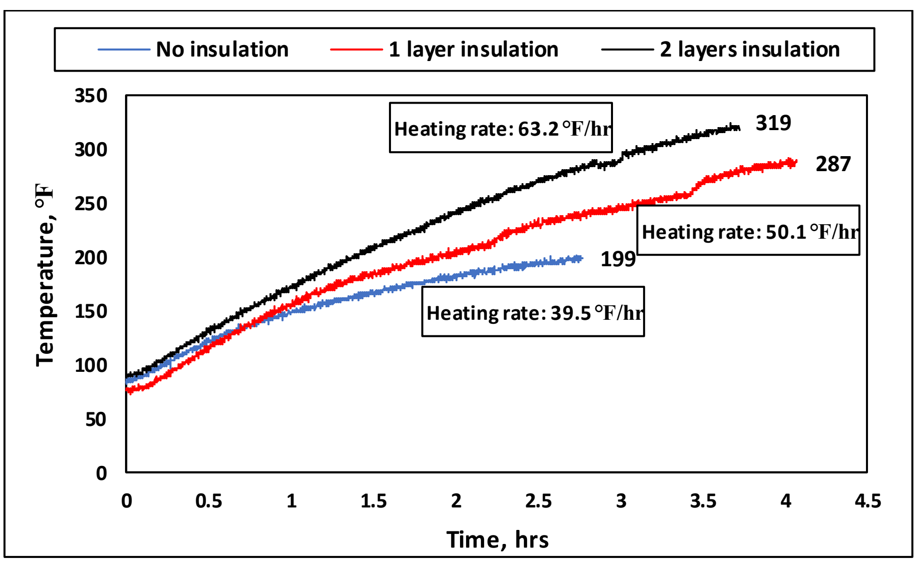

Figure 4: The heating rate during the three stages of insulation.

4.2 Setup Calibration

First, all flow loop instruments were tested by checking the input and output signals to ensure all devices were functional and connected to the data acquisition system. These instruments are flow meters, temperature transmitters, pressure transmitters, and differential pressure transmitters. These instruments' output signals and readings were calibrated to ensure accurate results. Afterward, the pipe viscometer's accuracy was validated by conducting rheology experiments using water-based polyanionic cellulose (PAC-R) solutions at two various concentrations, 0.8 and 1.5 wt.% PAC-R. The rheology measurements were performed at 120 °F and atmospheric pressure. The flow rate was varied from 2 to 36 gpm using the mud pump, and the differential pressure readings were recorded with flow rate. These measurements were converted into shear stress and shear rate, and the flow curve was constructed for each testing fluid. The results were compared with that of rotational viscometer (Fann-35A) for validation.

For 0.8 wt.% PAC-R sample, the data showed a straight line in log-log scale, which indicates that the Power-law model can represent the fluid. Most of the data fell within the laminar region. Similar behavior was observed when the concentration of PAC-R was increased to 1.5 wt.%, with fewer data points falling in the turbulent flow region due to the increase in fluid viscosity. Afterward, the flow curve was obtained for the PAC-R solutions and compared with that of rotational viscometer (Figure 5). For 0.8 wt. % PAC-R sample, the flow curve obtained from the flow loop matched the rotational viscometer data well until a shear rate of around 700 1/s. Beyond this value, the flow loop data deviated because of the flow turbulence. When the concentration of PAC-R was increased to 1.5 wt.%, a good match between the flow loop and rotational viscometer data was observed. The turbulence was observed at a higher shear rate value, 1300 1/s (Figure 5b). Therefore, the agreement confirmed that the pipe viscometer would yield accurate rheology measurements when the turbulent data is excluded.

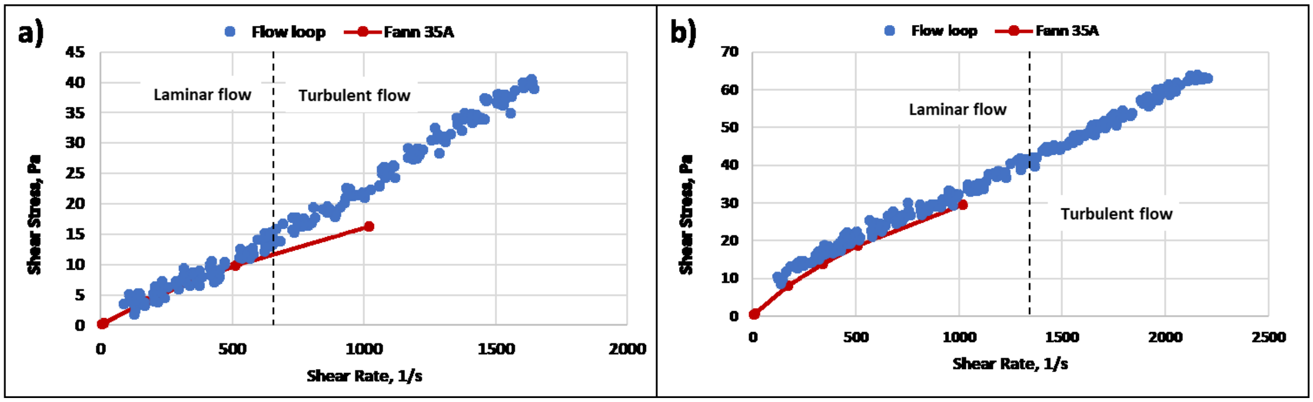

Figure 5: Calibration data for PAC-R solution at 120 °F: a) 0.8 wt.% and b) 1.5 wt.%.

5. SUMMARY AND CONCLUSIONS

This paper introduced a novel flow loop setup to test lost circulation material on a large scale and under high-temperature conditions. Using this setup, we can study mud rheology, mud stability, wellbore hydraulics, LCM transportation and dispersion, and fracture sealing under a broad range of experimental conditions. The fundamental design, features, and components of the experimental setup were explained in Section 2. Detailed testing procedures are well developed and illustrated in Section 3. Based on this work, the following conclusions are drawn:

- The experimental setup was calibrated and tested before running any experiment. All the instruments in the flow loop were successfully installed, checked, and calibrated with the data acquisition system.
- The flow loop successfully passed the pressure testing, and the system is ready to perform the experiments safely at high temperatures up to 350°F.
- The pipe viscometer was calibrated using PAC-R solutions with two different concentrations, 0.8 and 1.5 wt.%. Rheology measurements showed a good match between the flow loop and Fann-35A viscometer; thus, the flow loop system would yield accurate readings.
- Several fractured discs were designed and 3D printed using carbon fiber material to evaluate the fracture sealing efficiency under different fracture sizes and geometries. The design and printing density were optimized to yield a high thermal resistance. The fracture discs were tested in the flow loop, and 50% infill printing density yielded a stable design up to 350°F.
- Although the flow loop experiments are performed under a broad range of parameters on a large laboratory scale, the dimensions are still small compared to field operations. Therefore, a simulation study is required to upscale the results to the field dimensions and generate more data to help optimize the lost circulation treatment in a broader range of operating conditions.

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