# Experimental Investigation of a Smart LCM Using a High-Temperature Flow Loop for Geothermal Drilling

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**Keywords**

*Lost circulation, Smart LCM, Shape memory polymer, HT Flow loop, Geothermal drilling.*

## ABSTRACT

Lost circulation presents challenging issues in drilling operations, especially in high-temperature and fractured formations. Lost circulation events increase the nonproductive time (NPT) and the total cost of drilling operations. In some severe cases of high or total losses, well control is jeopardized, leading to a loss in lives and resources. Therefore, selecting a suitable lost circulation material (LCM) and an optimized fluid formulation is vital to the success of a lost circulation remedy. This paper introduces and studies a new smart material for dealing with lost circulation in geothermal drilling applications. The proposed material is a thermoset shape memory polymer (SMP) that activates at high temperatures (+150°) and increases its particle size to seal large fractures.

A large-scale high-temperature (HT) flow loop has been built to investigate the impact of SMP particles on the mud rheological behavior at high temperatures. The annular flow of SMP mud was studied to confirm the SMP activation process. The SMP transportation was also compared with other conventional lost circulation materials such as walnut and cedar fiber. Different test parameters were considered in studying the LCM dispersion, such as its concentration, annular velocity, and pipe rotation.

The results show that the smart lost circulation material can be activated at high temperatures (above 150°) to seal complex fractures efficiently. The activation process was confirmed by the 80-100 % increase observed in the LCM particle size. The mud sample containing the smart LCM is a non-Newtonian fluid with a strong shear-thinning behavior that is favorable in drilling operations as it makes the wellbore frictional pressure drops less sensitive to the increase in flow rate (shear rate). The pipe rotation and annular velocity were found very effective in dispersing the LCM particles into the mud stream to improve the sealing efficiency and avoid any complications that may arise from the deposited particles. The smart LCM outperformed cedar fiber and walnut in terms of suspension behavior, making it a suitable candidate for treating lost circulation in geothermal wells.

## 1. Introduction

The high cost of drilling operations in geothermal wells greatly impacts the geothermal development feasibility. According to Bavadiya et al., 40 to 60% of the geothermal projects' cost is spent on exploration and development drilling applications (Bavadiya et al., 2019). The high drilling cost is because of the extended drilling time, harsh downhole conditions, depth, and geothermal formation nature (Chemwotei, 2011; Kruszewski and Wittig, 2018; Olasolo et al., 2016). The high-temperature conditions encountered in geothermal formations cause many drilling issues such as casing and cement failure, drilling fluid degradation, and downhole equipment failure (Baujard et al., 2017; Bavadiya et al., 2017; Finger and Blankenship, 2010; Miyazaki et al., 2019; Shadravan and Amani, 2012; Wu et al., 2020). Moreover, most geothermal formations are weak and naturally fractured formations with large and complex fracture networks, presenting significant challenges to geothermal drilling such as lost circulation, well control, and well integrity issues (Kiran and Salehi, 2020; Mohamed et al., 2021a; Vivas et al., 2020; Vollmar et al., 2013).

Lost circulation is a phenomenon encountered while drilling operations, where the drilling fluid is partially or completely lost into the drilled formation. It is a challenging issue in drilling applications because of the great efforts and resources spent solving it. For instance, between 1993 and 2003, lost circulation events are responsible for more than 10% of the nonproductive time in the Gulf of Mexico. Additionally, 10 to 20% of the geothermal cost is consumed on treating lost circulation events in the U.S. (Lavrov, 2016). Many factors cause the lost circulation in geothermal formations, such as low fracture gradient, large and complex fracture networks, and unoptimized drilling fluid properties (Lavrov, 2016; Magzoub et al., 2020; Ravi et al., 2006; Tare et al., 2001). In addition to LCM pills and cement squeeze, using lost circulation materials is the most common method to treat the losses (Wagle et al., 2018).

Depending on the downhole conditions and loss severity, several materials were introduced and tested to treat the lost circulation issue (Akhtarmanesh et al., 2016; Alsaba et al., 2014; C. P. Ezeakacha et al., 2017; Javeri et al., 2011; Lee and Taleghani, 2020; Loeppke et al., 1990; Magzoub et al., 2021; Mansure, 2002). However, sealing complex fractures, clogging downhole equipment, and formation damage are considered the main drawbacks of using conventional LCMs (Magzoub et al., 2021). Therefore, the technological developments in the industry are focused on introducing more advanced materials to cure the losses, such as LCM blends, nanoparticles, encapsulated pills, and shape memory polymer (SMP).

In this study, a new smart LCM is evaluated, which is a thermoset shape memory polymer that can be programmed to store a temporary shape and size. The smart LCM can be activated by formation temperatures above (150°) and regain its original shape (Lakhera et al., 2012; Mather et al., 2009; Yakacki et al., 2007). This new material is cheap, highly elastic, and easy to process, making it an excellent candidate to treat the losses with reduced risk of clogging downhole equipment (Liu et al., 2009; Magzoub et al., 2021; Mansour et al., 2019). Optimizing the LCM mud properties and LCM dispersion plays a vital role in sealing efficiency and lost circulation treatment. Therefore, this study investigates the rheological behavior and dispersion of the smart LCM at high temperatures under different testing parameters using a novel high-temperature flow loop. The performance of this smart LCM was also compared with two of the conventional LCMs, cedar fiber and walnut, in terms of dispersion and settling behavior.

## 2. Materials and Methods

A large-scale flow loop has been designed and developed in the Well Construction Technology Center at the University of Oklahoma to investigate the performance of lost circulation materials at high-temperature conditions (above 150°). The schematic design of the flow loop is shown in **Figure 1**. It consists of five main systems:

1. The mixing and circulation system consists of a mud tank, agitator, and mud pump.
2. The heating system is used to increase the mud temperature to the desired level. It consists of an oil tank, oil pump, heater, and heating coil. The heating oil is circulated through the system in a close loop.
3. The rheology measurement system includes a pipe viscometer, differential pressure sensor, and Coriolis flowmeter to measure flow rate, temperature, and density.
4. The main test section consists of two concentric pipes to simulate the annular flow, a motor to rotate the inner pipe, and two viewports to visualize the fluid flow. The inclination angle of the main test section can be varied from 45˚ to 90˚ from vertical.
5. The data acquisition (DAQ) system is used to acquire and record all the measurements from the flow loop. The DAQ system consists of a computer, a DAQ card, and pressure and temperature sensors.

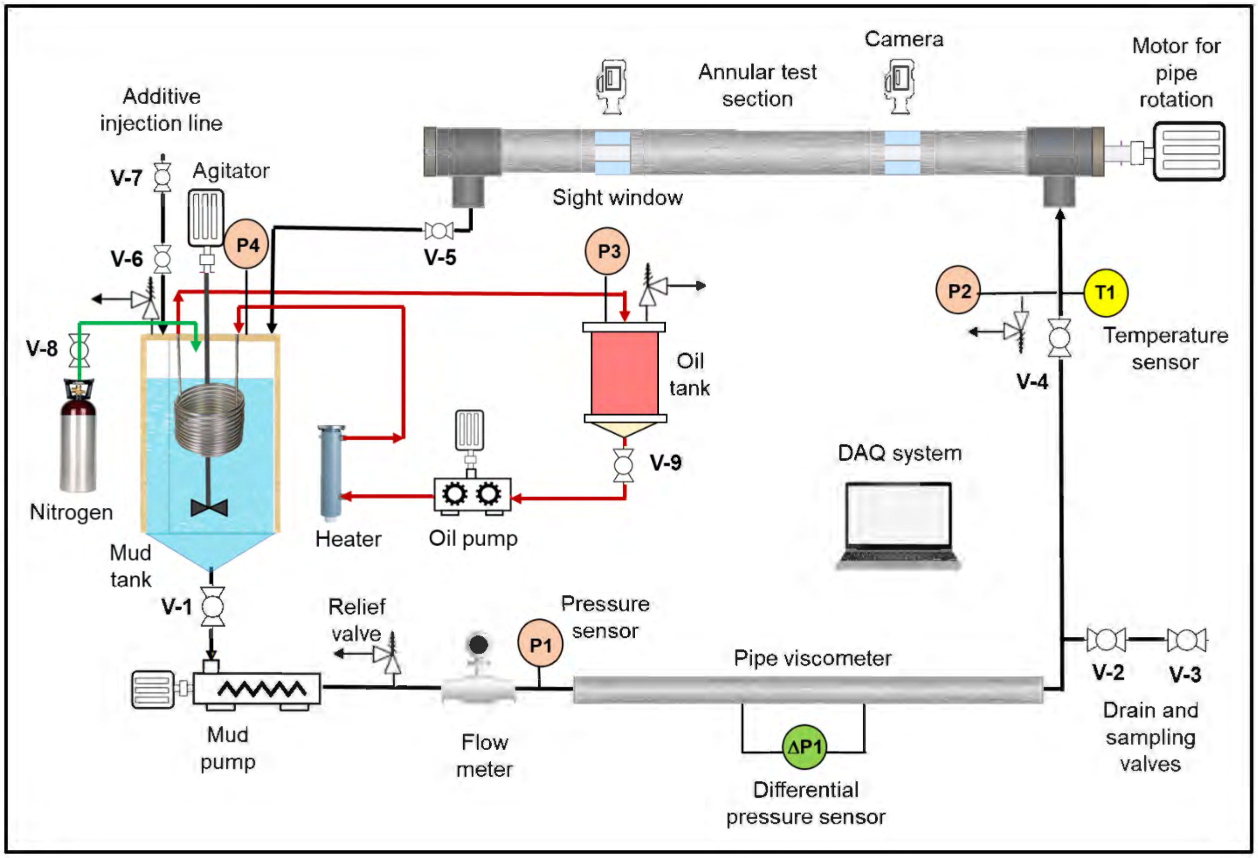


**Figure 1: Schematic of the high-temperature flow loop used in this study.**

Many fluid samples with a volume of 10.5 gallons were prepared and mixed in the mud tank. The fluid samples contain a synthetic hectorite clay (THERMA-VIS) as viscosifier and freshwater as base fluid. The base fluid was left for 16-20 hrs for hydration to maintain a stable performance. The experiment starts with circulating the base fluid while heating to ensure a homogeneous mixture and consistent fluid properties. The LCM was added through the additive injection line in the mud tank after reaching the desired testing temperature (160°). The smart LCM used in this study is a thermoset shape memory polymer (SMP) that is compression programmed and activates at a temperature above 150° (Fan and Li, 2018). Once the SMP activates, its particle size increases to seal large complex fractures. The performance of the smart LCM material was studied and compared with other conventional LCMs such as cedar fiber and walnut. The performance was evaluated in terms of rheology, activation, and settling behavior under different testing parameters. **Table 1** shows the properties of the LCMs used in this investigation. The test parameters of the flow loop study are described in **Table 2**.

**Table 1: Properties of the tested lost circulation materials**

| Property | LCM type | | |
|---|---|---|---|
| | **SMP** | **Cedar Fiber** | **Walnut** |
| Specific gravity | 0.95 | 1.7 | 1.3 |
| Particle size | 840-2360 µm (Average of ~1400 µm) | 53-2360 µm (Average of 550 µm) | 840-2360 µm (Average of ~1400 µm) |
| Appearance |  Granular |  Fibrous |  Granular |

**Table 2: Range of testing parameters for flow loop experiments**

| Parameter | Description |
|---|---|
| LCM concentration | 0, 1.0, and 3.0 wt.% |
| Temperature | 160 ℃ |
| Pressure | 100 psi |
| Inclination angle (from vertical) | 90˚ |
| Flow rate | 1-20 gpm |
| Pipe rotational speed | 0 and 150 RPM |

## 3. Results and Discussions

### *3.1 Rheology Experiments*

The smart LCM material was evaluated in two concentrations, 1.0 and 3.0 wt.%. The differential pressure drops and flow rate data obtained from the pipe viscometer were analyzed to determine the rheological behavior of the mud samples. The rheological analysis of the pipe viscometer data is performed following the procedure presented in the literature (Skelland 1967; Alderman and Pugh, 2004; Ahmed and Miska 2009). Based on the flow curve (shear stress vs. shear rate) obtained from the rheological analysis (**Figure 2a**), the Power-law model can reasonably describe the mud samples with a correlation parameter ranging between 0.93-0.97. The mud samples exhibited a non-Newtonian behavior with a strong shear-thinning that was detected by a very low fluid behavior index (n < 1). The fluid samples showed n values in the range of 0.025-0.101, while fluid with SMP showed slightly lower n values than the base fluid, indicating a higher degree of shear-thinning. The shear-thinning behavior is attributed mainly to the viscosifier used in preparing the base fluid. The viscosifier is a hectorite clay synthesized to build temperature-dependent viscosity with high shear-thinning behavior (Baroid, 2012; Mohamed et al., 2021b). The shear-thinning behavior can also be confirmed from the apparent viscosity plots, in which the viscosity sharply decreased with the shear rate (**Figure 2b)**. This uniquely strong shear-thinning behavior is suitable for managing the bottom hole pressure in drilling operations because it makes the frictional pressure loss less sensitive to the change in flow rate. Proper bottom hole pressure management would help reduce fluid loss and improve the effectiveness of the LCM. Moreover, the high viscosity at low shear rates that usually prevails in the annulus would improve the hole cleaning and help manage equivalent circulating density, ECD (Caenn et al., 2017). Also, the reduced viscosity at high shear rates occurring in the drill pipe would minimize the frictional pressure loss and standpipe pressure.

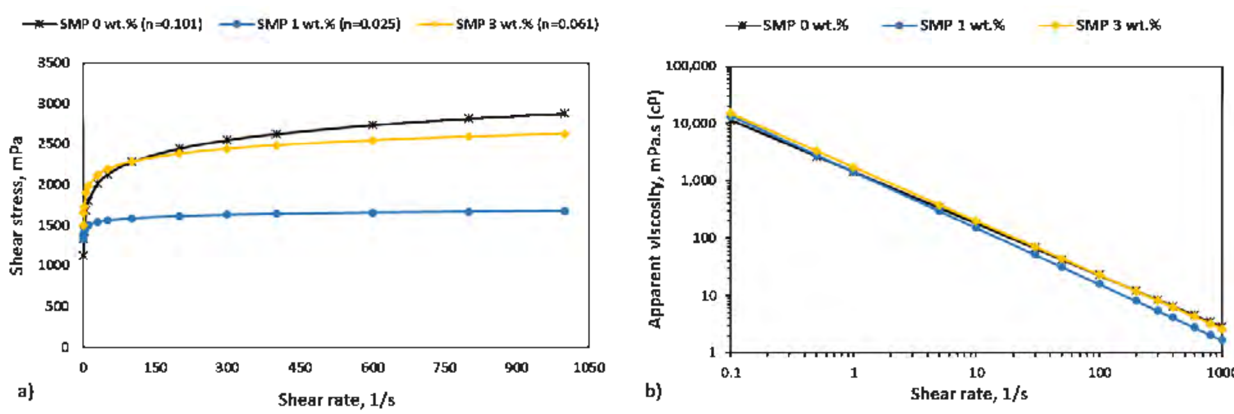


**Figure 2: Effect of SMP concentration on a) shear stress and b) apparent viscosity (160°).**

### *3.2 SMP Activation Process*

In this section, the smart LCM (SMP) activation process was studied using the videos acquired through the viewports with the aid of a high-speed camera. SMP was added at a low concentration (1.0 wt.%) to ease the video processing and detect the change in particle size with temperature. Two experiments were conducted at room temperature (21°) and a high temperature (160°). Then, the recorded videos are analyzed to detect the activation process of the shape memory polymer. **Figure 3** shows the SMP particles at a temperature of 21° and 160°. At 21°, the SMP particle size ranged from 1 to 2 mm (**Figure 3a**), while the SMP particle size increased significantly at high temperature (160°), reaching up to 4 mm (**Figure 3b)**. The increase in particle size confirmed the thermally induced activation of the shape memory polymer. Therefore, the polymer can serve as a smart LCM with a controlled thermal activation to seal complex fractures with minimal risk of clogging downhole tools. Moreover, the size variation of SMP particles is considered an advantage in the sealing mechanism (Ezeakacha et al., 2017;

Magzoub et al., 2020; Whitfill, 2008). Large particles will form the bridge on the fracture, while small particles will create the seal matrix to plug the space between large particles and the fracture wall (Magzoub et al., 2021).

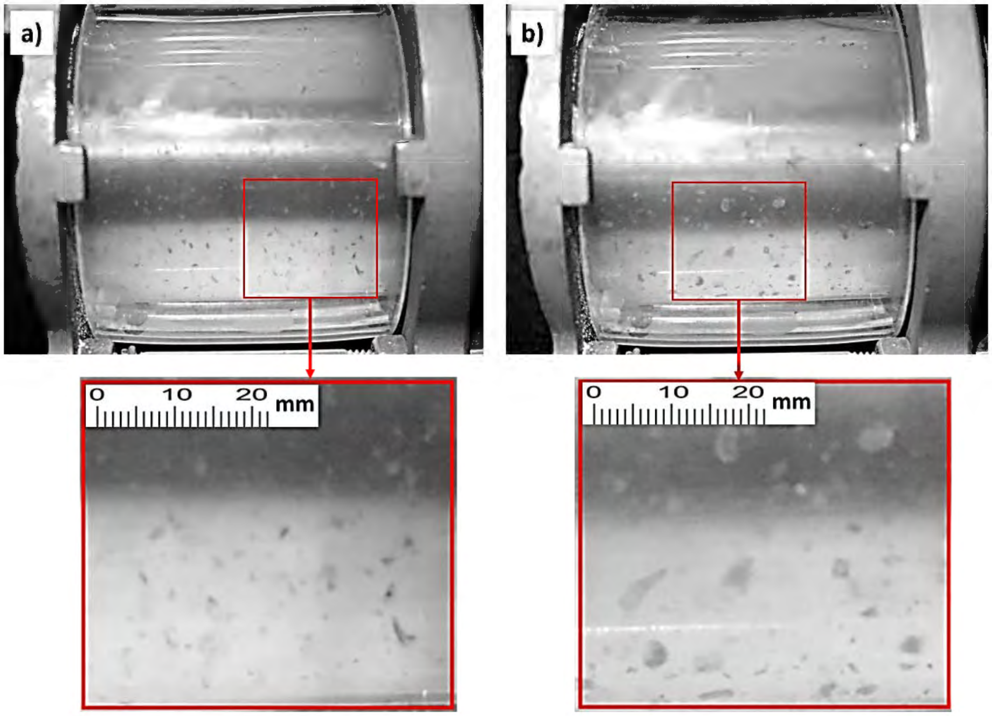


**Figure 3: Effect of temperature on SMP particles: a) 21°, and b) 160°.**

### *3.3 Effect of Test Parameters on LCM Dispersion*

Several experiments were performed to study the dispersive nature of the smart LCM and compare its performance with two conventional LCMs (cedar fiber and walnut). The experiments were conducted at 160° by varying concentration, annular velocity, and pipe rotational speed. The test section was fixed at a horizontal angle to simulate the worst-case scenario for particle dispersion. The level of dispersion was evaluated by measuring the bed height formed due to the deposition of the particles. **Figure 4** compares the bed height formed with LCMs under various annular velocities without pipe rotation. The results showed that the average annular velocity significantly improved the particle dispersion of all LCMs. Increasing the annular velocity helped erode the formed bed, and the bed height decreased significantly. It was also observed that the smart LCM outperformed the other LCMs with a better suspension capability, while walnut exhibited the highest bed height. Although increasing the annular velocity improved the mud carrying capacity, cedar fiber and walnut required high fluid velocity to remove the bed, which is sometimes very difficult to attain in the annulus due to ECD limitations. Increasing the annular velocity would also increase the frictional pressure losses and ECD that may exacerbate lost circulation and even induce more fractures in the formation, complicating the lost circulation events (Mohamed et al., 2021a; Murray et al., 2013). LCM particles deposited in the low-side of the wellbore could reduce the sealing efficiency because of non-uniform particle distribution and LCM placement. The disposition could also cause other operational complications such as pipe sticking and difficulty in placing a casing liner (Boyou et al., 2019).

The pipe rotation (150 RPM) was very effective in dispersing the LCM particles, and significantly low bed heights were observed with all LCMs (**Figure 5**). SMP and cedar fiber particles were uniformly distributed across the annular space, and no bed was formed at all annular velocities. On the other hand, the impact of pipe rotation on dispersing walnut particles was limited; as a result, a thick walnut bed was formed, covering almost 40-50% of the annular space, and removing the bed was challenging.

All LCMs are expected to show better performance at inclined and vertical wells because the vertical component of fluid velocity acting on the particles is zero in horizontal wells, making the solid settlement easier and quicker (Czuprat et al., 2020; Mahmoud et al., 2020). As a result, LCM transportation in horizontal wells is more challenging than inclined and vertical wells.

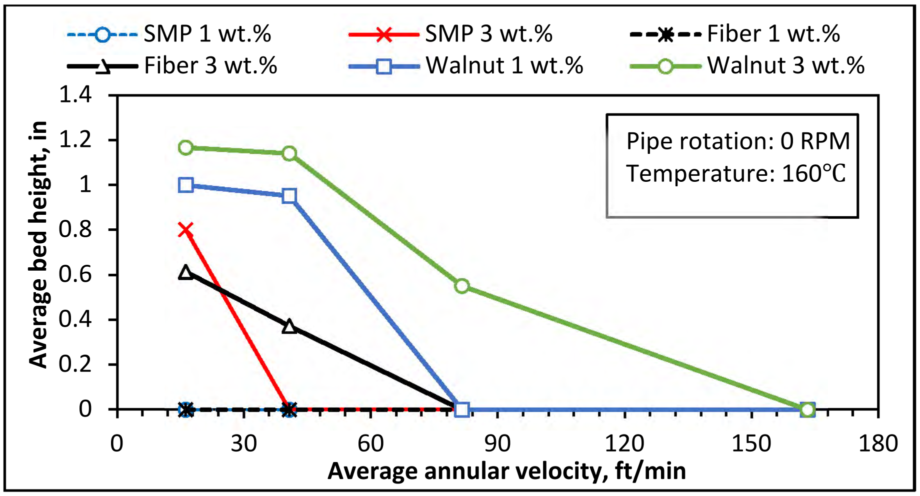


**Figure 4: Effect of annular velocity and concentration on LCM dispersion at a horizontal angle without rotational speed (160°).**

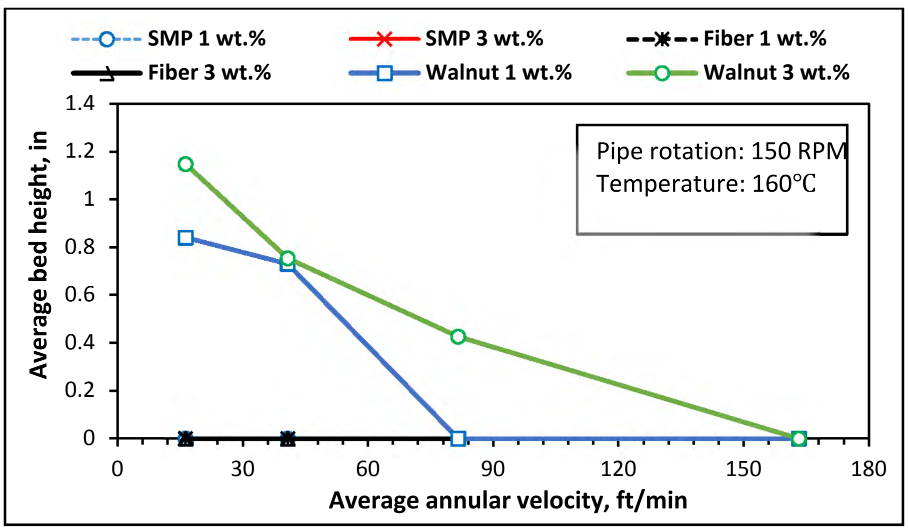


**Figure 5: Effect of annular velocity and concentration on LCM dispersion at a horizontal angle with 150 RPM pipe rotational speed (160°).**

## 4. Conclusions

An experimental study was performed using a novel high-temperature loop to evaluate a smart lost circulation material and compare its performance with conventional LCMs in terms of dispersion and transportation. The rheological behavior, activation process, and settling behavior of the smart LCM were investigated at high temperatures. From the obtained results, the following conclusions can be drawn:

- Similar to the base fluid, the mud samples containing the smart LCM showed a non-Newtonian behavior with a high shear-thinning. The Power law model could describe the rheological behavior of all samples with a correlation parameter of 0.93-0.97. The SMP mud and base fluid showed almost a similar viscosity profile. SMP mud exhibited a slightly higher apparent viscosity due to the SMP presence in the suspension.
- The SMP activation process was captured at a high temperature, and the particle size increased by 2 to 3 fold when the temperature increased from 21° to 160°. This increase in particle size at high temperatures makes the SMP an excellent candidate to effectively seal complex fractures and treat lost circulation in geothermal formations with a reduced risk of clogging downhole equipment.
- Increasing the pipe rotational speed and average annular velocity significantly improved the LCM transportation and eroded the bed formed in the annulus. The SMP particles showed a better dispersion than other conventional LCMs, cedar fiber and walnut. High velocities and pipe rotational speeds were required to remove the formed bed when other LCMs were used.
- The smart LCM showed promising findings in terms of rheological behavior, thermal activation, and dispersion. However, further studies should be performed to investigate the smart LCM sealing efficiency at various testing conditions in fractured media.

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