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Rheological Properties of Drilling Fluids Containing Special Additives for Geothermal Drilling Applications

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ABSTRACT

The high pressure and high temperature (HPHT) encountered in geothermal wells make the drilling operation challenging. Drilling in such environments requires special drilling fluid formulations with high thermal stability and suitable rheological properties to function as drilling fluid. Rheological properties impact many drilling parameters such as hole cleaning, fluid and wellbore stability, wellbore hydraulics, torque and drag, and other performance indicators. Therefore, great efforts should be put into selecting suitable additives to maintain drilling fluid performance throughout the operation.

In this study, the effectiveness of different additives was evaluated in maintaining drilling fluid rheology at HPHT conditions. The additives considered in this investigation are bentonite, xanthan gum (XC), low-viscosity and regular polyanionic cellulose (PAC-L and PAC-R), hydroxyethyl cellulose (HEC), other synthetic polymers and clay such as THERMA-VIS. Fluid samples were prepared in various concentrations and left to hydrate for 20-24 hrs. The rheological analysis was performed under HPHT conditions using a rheometer. Different parameters were considered in the screening, such as temperature, concentration, shear rate, and aging time.

The results of this study showed that temperature has a significant impact on the stability and rheological properties of the fluids. The rheological behaviors of tested additive-containing fluids vary substantially with temperature, and THERMA-VIS was superior to the other additives in terms of viscosity and thermal stability. The viscosity of THERMA-VIS-based fluid was low at room temperature and increased with temperature up to 375°F (maximum testing temperature). During the test, the fluid became viscous enough to suspend rock cuttings and other heavy solids. The optimum concentration of THERMA-VIS was found to be 3.0 lb/bbl. Exceeding this concentration resulted in a highly viscous fluid and mud gelation at high temperatures.

1. INTRODUCTION

Geothermal wells are the key to unlock and utilize the earth's heat to generate clean and renewable energy. The high demand for energy and the growing concerns about the environment has increased geothermal exploration and drilling activities in the last decades (Ahmed et al., 2020a; De Angelis et al., 2011; Kiran and Salehi, 2020; Reinsch et al., 2015). However, the harsh downhole conditions present significant challenges for drilling operations (Vivas et al., 2020). These challenges are associated with drilling fluid, drill bit, casing, cement, and downhole equipment. Such high-temperature conditions push the geothermal industry to its limit in selecting the materials and increase the need for more advanced tools and technologies (Finger and Blankenship, 2010). Consequently, drilling geothermal wells becomes more costly than drilling oil and gas wells (Bavadiya et al., 2019; Randeberg et al., 2012; Vollmar et al., 2013).

Drilling fluid is considered a major factor in the cost and success of geothermal drilling operations (Chemwotei, 2011; Vivas et al., 2020). It is introduced to the wellbore mainly to control the well, carry and transport drilled cuttings to the surface, lubricate and cool the drill bit, and maintain the wellbore stability (Bourgoyne et al. 1984; Caenn et al., 2011; Hossain and Al-Majed, 2015; Mohamed et al., 2020a). Great attention should be given to select appropriate drilling fluid additives for optimizing drilling fluid properties to ensure successful and efficient drilling operations (Ahmed et al., 2020b; Mohamed et al., 2017; 2020b). Thermal stability and rheological behavior are essential parameters to be considered while selecting drilling fluid additives, especially under high-temperature conditions. Rheological properties significantly impact drilling parameters such as wellbore hydraulics, hole cleaning, fluid stability, filter cake formation, rate of penetration, and lost circulation (Basfar et al., 2020; Da Silva and Naccache, 2016; Gamwo and Kabir, 2015; Kulkarni et al., 2013; Pakdaman et al., 2019; Pandya et al., 2019a, 2019b; Zamora and Roy, 2000).

Thermal stability is a vital property for mud additives in geothermal drilling applications. The high temperature encountered in geothermal wells promotes the thermal degradation of polymeric additives used with drilling fluid. The degradation can diminish the performance of drilling fluid, which, in turn, decreases the drilling efficiency and increases the drilling time and cost (Amani and Al-Jubouri, 2012; Avci and Mert, 2019). Bentonite mud is commonly used to drill geothermal wells. However, it causes an undesirable change in mud viscosity at high temperatures due to clay flocculation (Zilch et al., 1991). Therefore, more stable viscosifying additives should be used to drill geothermal wells to improve the drilling efficiency and prevent any complications.

This study evaluates the thermal stability and rheological behavior of different polymeric and clay additives used with drilling fluid for geothermal drilling applications. The additives are divided into two groups: viscosity control additives and filtration control additives. The additives are mainly selected based on the thermal resistance (above 300 °F). The screening is performed at different conditions by changing temperature and concentration. Further analysis is performed using the best additive by varying the shear rate and aging time to ensure stable performance. First, the material and experimental conditions of rheology experiments are described. Then, the obtained results are discussed and summarized, and at the end, some conclusions are drawn.

2. MATERIAL AND EXPERIMENTS

2.1 Material

Several drilling fluid additives were evaluated by measuring the rheology at high-temperature conditions using an HPHT rheometer. These additives are bentonite, low viscosity polyanionic cellulose (PAC-L), regular viscosity polyanionic cellulose (PAC-R), xanthan gum polymer (XC), hydroxyethyl cellulose (HEC), and other synthetic polymers such as THERMA-CHEK, POLYAC PLUS, and THERMA-VIS. These additives were obtained from service companies and selected based on their thermal stability to efficiently drill geothermal wells. Some of these additives are used as a primary viscosifier, while the others are used as filtration control additives and secondary viscosifiers. The targeted thermal stability is above 300 °F. **Table 1** summarizes the properties of the selected additives.

Table 1: Properties of the tested additives

Additive	Appearance	Specific gravity	Thermal stability, °F	Main uses	Recommended concentration, lb/bbl
Bentonite	Variable-colored powder	2.2-2.8	250	Viscosifier and filtration control	20-40
Xanthan gum	Dispersible beige powder	1.5	250	Viscosifier	1.0-2.0
HEC	White to light tan powder	1.38-1.4	205-210	Viscosifier and filtration control	2-7
THERMA-VIS	White powder	1.0	700	Viscosifier	1.0-4.0
PAC-R	White or tan powder	0.8	300	Filtration control and secondary Viscosifier	0.5-2.0
PAC-L	White or tan powder	0.8	300	Filtration control	0.5-3.0
POLYAC PLUS	White granular powder	0.8	400	Filtration control	0.25-1.0 (fresh water) 1.0-3.0 (salt water)
THERMA-CHEK	White or cream powder	1.32	400	Filtration control and secondary viscosifier	1.0-3.0 (fresh water) 4.0-8.0 (salt water)

2.2 Experiments

Different fluid formulations were prepared in the laboratory by adding the additives individually to tap water in various concentrations (1 to 5 lb/bbl). The fluid samples were mixed at room temperature using a variable-speed stirrer mixer and left to hydrate for 20-24 hrs. A 50-mL sample was then taken from each fluid formulation and poured into the sample cup to evaluate the viscosity and thermal stability at different conditions using an HPHT rheometer. A pressure of 400 psi was applied using nitrogen gas to prevent fluid evaporation. The first set of experiments was run at a constant shear rate of 170 1/s, and the temperature was increased gradually starting from room temperature (75°F) up to 375°F. The samples' apparent viscosity was recorded with temperature to evaluate the thermal stability at different concentrations. The experimental conditions are summarized in **Table 2**. Afterward, the thermal stability of the most stable additive was evaluated with time by running the experiments at high temperature for 3-4 hrs to evaluate the stability of the additive with time.

Table 2: The experimental parameters of the rheology tests

Parameter	Description
Base fluid	Freshwater
Temperature	75-375 °F
Pressure	400 psi
Shear rate	170 1/s
Concentration	1-5 lb/bbl

3. RESULTS AND DISCUSSIONS

3.1 Effect of Temperature

The effect of temperature on the performance of drilling fluid additives was studied by measuring the apparent viscosity at a constant shear rate (170 1/s) and different temperatures using an HPHT rheometer. The experiments were started at room temperature; then, the temperature was gradually ramped up to 375°F. **Figure 1** compares the performance of different viscosifiers with temperature. The used viscosifiers are bentonite, xanthan gum (XC), hydroxyethyl cellulose (HEC), and synthetic hectorite (THERMA-VIS). For comparison, all additives, except bentonite, were added with the same concentration of 3 lb/bbl that is within the recommended use in field applications. Bentonite was mixed in a 30 lb/bbl concentration as an average of the recommended concentration as per field practices. Deflocculant and dispersant additives were added to bentonite mud to prevent clay flocculation and improve the rheological performance (Caenn et al., 2011; Hossain and Al-Majed, 2015). As shown in Figure 1, temperature significantly impacted the apparent viscosity of all fluid samples. HEC yielded the highest viscosity of 400 cP at room temperature; then, viscosity dropped sharply with temperature to reach around 1.5

cP at 350°F, indicating poor thermal stability (thermal thinning and/or degradation). XC polymer showed more stable performance with temperature than HEC. XC maintained a viscosity of about 100 cP until 250°F. Beyond that temperature, the viscosity started to decrease dramatically to reach 3.0 cP at 360°F. This performance is attributed to the polymers thermal degradation, mainly through hydrolysis and oxidization mechanisms (Flynn, 2002). This thermal degradation makes these additives unsuitable for high-temperature and geothermal drilling applications. Bentonite mud showed a better performance with an apparent viscosity of 70 cP until 200°F. The apparent viscosity dropped gradually to around 40 cP at 300°F and maintained that viscosity until 375°F. In contrast, THERMA-VIS showed a different viscosity profile. Its viscosity started at approximately 17 cP, then increased gradually and reached a viscosity of around 60 cP at 300°F. The increase in viscosity is attributed to the thermally induced activation of THERMA-VIS. This additive is designed to activate at high temperature to maintain the rheological properties required for drilling operations.

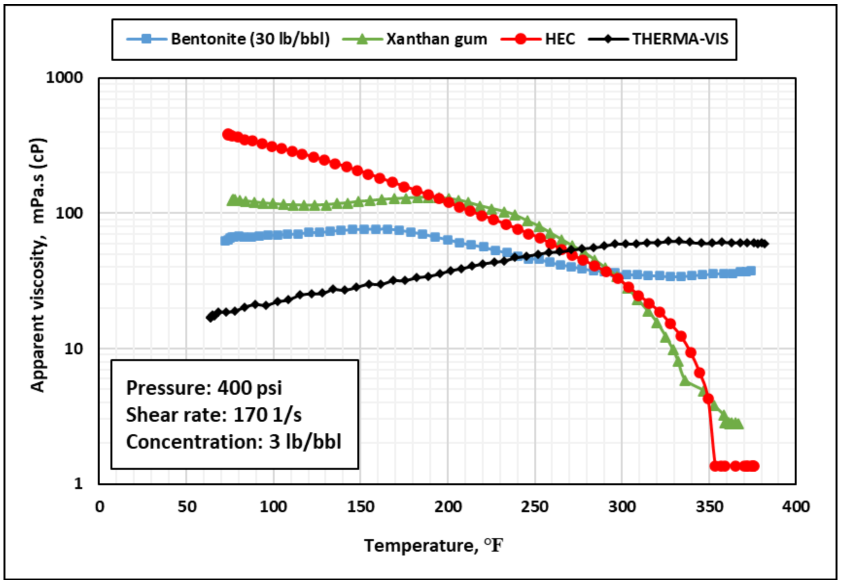

Figure 1: Effect of temperature on the apparent viscosity of different viscosifiers.

Figure 2 shows the temperature effect on the apparent viscosity of fluids containing different filtration control additives. Fluid containing PAC-R showed the highest apparent viscosity at room temperature (around 30 cP); then, the apparent viscosity dropped dramatically with temperature to reach 0.06 cP at 230°F. Similarly. PAC-L-based fluid viscosity started at 18 cP and decreased to 3 cP at 250 °F and maintained that viscosity until 375°F. The dramatic decrease in PAC-L-based fluid viscosity (PAC-L and PAC-R) is due to hydrolysis and oxidization reactions that break the polymer chains, indicating poor thermal stability (Flynn, 2002). Conversely, both THERMA-CHEK and POLYAC PLUS based fluids showed a slight reduction in the apparent viscosity with temperature, indicating better thermal stability than PAC based fluids. POLYAC PLUS showed a slightly higher viscosity than THERMA-CHEK throughout the experiments, with a difference of around 3.0 cP.

After the rheology experiments, all the fluid samples were collected to check the effect of temperature on the appearance of the fluids. All fluid samples were clear before the test (i.e. before the exposure to high temperature). After the exposure, (**Figure 3**), the color of PAC-L-based fluid completely changed to dark brown, which indicates the occurrence of thermal degradation at elevated temperatures. In comparison, fluids containing other additives showed a slight change in the color with temperature. THERMA-VIS solutions exhibited the least change in color among other additives, demonstrating their superior thermal resistance and stability.

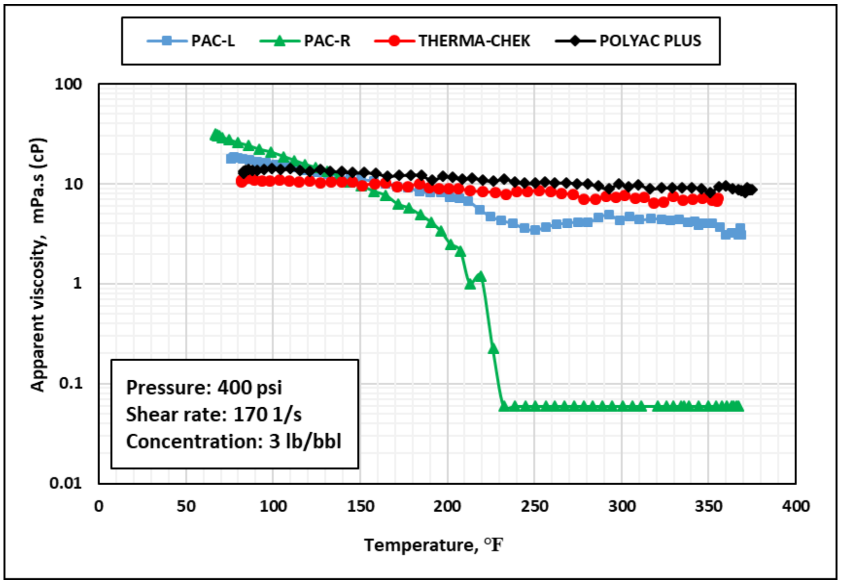

Figure 2: Effect of temperature on the apparent viscosity of different filtration control additives.

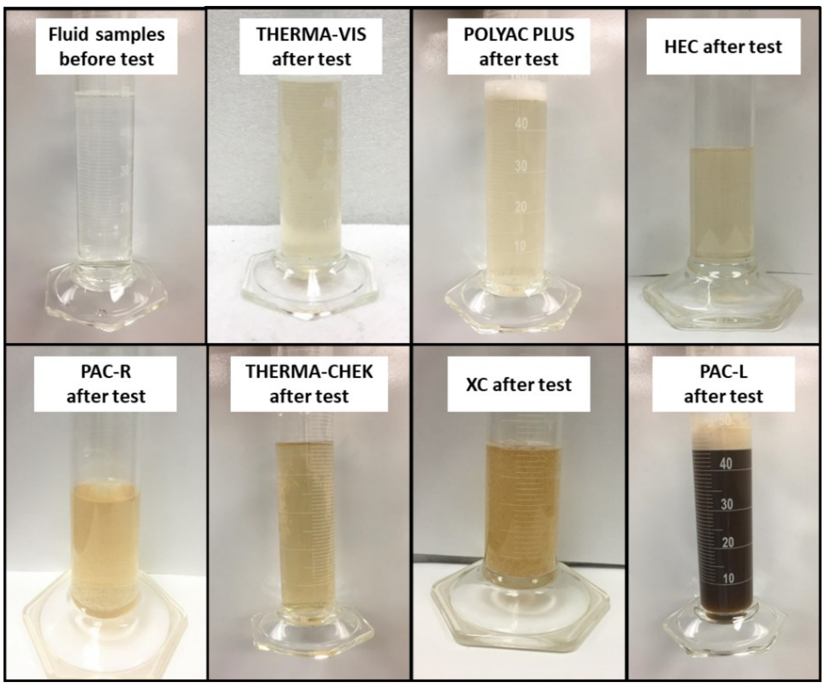

Figure 3: Fluid samples before and after rheology experiments (3.0 lb/bbl).

3.2 Effect of Concentration

Several fluid samples were prepared in the laboratory by varying each additive's concentration from 1 to 5 lb/bbl to study the concentration effect of these additives. On the other hand, bentonite clay was mixed with 10 to 30 lb/bbl as clay requires a higher concentration than polymers to build sufficient viscosity to fulfill drilling fluid functions. **Figure 4** compares the concentration effect on fluid viscosity with temperature for bentonite, XC, HEC, and THERMA-VIS based fluids. For all viscosifiers, the general trend of apparent viscosity with temperature did not change significantly with concentration. As the concentration was increased, higher viscosity was observed with all the viscosifiers. XC and HEC based fluids resulted in the highest viscosity of around 1000 cP at room temperature. For HEC based fluids, the viscosity difference due to concentration decreased at high temperatures (350°F and above). The final viscosity was almost the same for all concentrations. Therefore, when using a viscosifier with low thermal resistance, increasing the concentration would not help maintain the required rheological behavior at high temperatures. Conversely, bentonite samples maintained the same viscosity trend with temperature. The higher the concentration, the higher the viscosity. In contrast, increasing THERMA-VIS concentration from 1 to 3 lb/bbl resulted in a 200% increase in the apparent viscosity throughout the experiment. However, increasing THERMA-VIS concentration to 5 lb/bbl negatively impacted the viscosity profile. Fluid with 5 lb/bbl of THERMA-VIS showed a higher viscosity until 350°F (85 cP); however, the viscosity started to drop gradually and reached 50 cP at the highest temperature. **Figure 5** shows the fluid sample with 5 lb/bbl of THERMA-VIS after the experiments. It can be seen that the fluid formed a gel at high temperature; therefore, the drop in viscosity is due to the slippery effect induced by gelation, and it is not a real viscosity reduction. The gel formation would significantly increase the frictional pressure losses and require very high pressure to circulate the mud, exceeding the equivalent circulating density (bottom hole pressure) limit. Therefore, the optimum concentration for THERMA-VIS is 3 lb/bbl, and exceeding this concentration is not recommended.

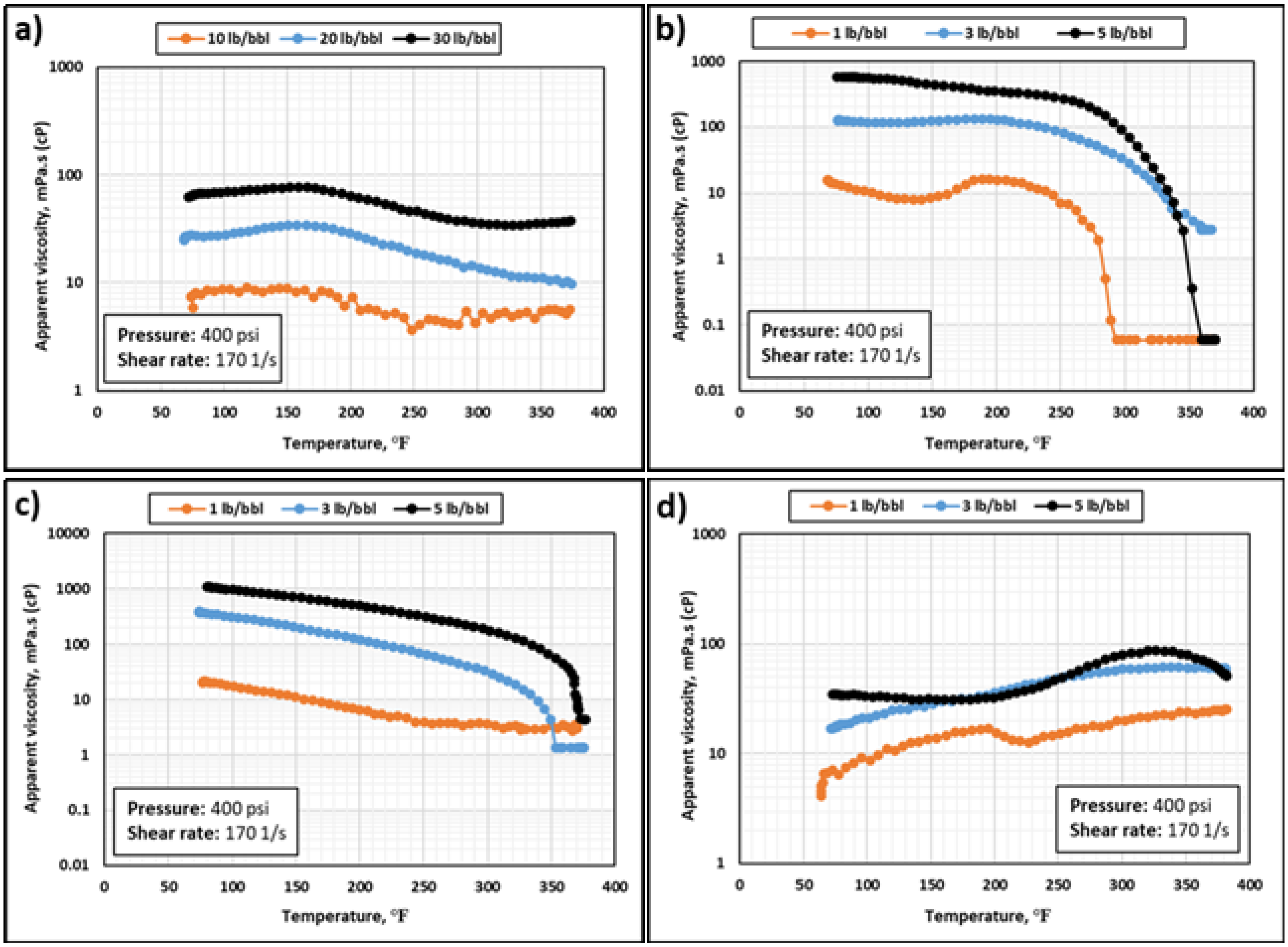

Figure 4: Effect of viscosifier concentration on fluid viscosity with temperature: a) bentonite, b) xanthan, c) HEC, and d) THERMA-VIS.

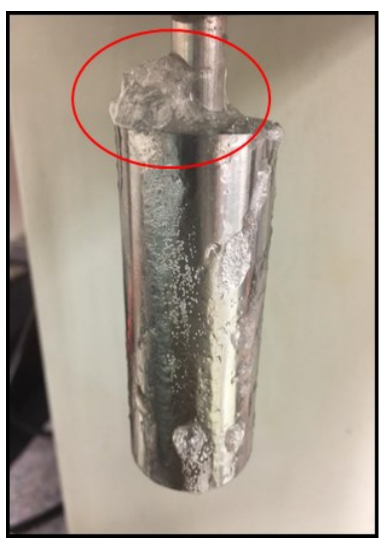

Figure 5: Gelled THERMA-VIS on the rheometer's bob (5.0 lb/bbl).

Figures 6 shows the effect of PAC-L, PAC-R, THERMA-CHEK, and POLYAC PLUS concentrations on the apparent viscosity at different temperature conditions. These additives are mainly introduced to drilling fluids to control fluid loss into the drilled formations. PAC-L, THERMA-CHEK, and POLYAC PLUS additives had minimal effect on fluid viscosity. PAC-L exhibited poor thermal resistance, and the viscosity dropped dramatically with temperature. Increasing the concentration did not have a significant impact on the thermal stability. THERMA-CHEK and POLYAC PLUS based fluids with 1 lb/bbl additives exhibited low viscosity and a considerable drop in the apparent viscosity with temperature. When the concentration was increased to 3 lb/bbl, both additives exhibited a stable fluid formulation with a slight decrease in the apparent viscosity with temperature. Fluid with POLYAC PLUS had a higher viscosity than THERMA-CHECK with a difference of around 3 cP throughout the experiments. Increasing the concentration of both additives to 5 lb/bbl showed an increase of 5 cP in the viscosity at low temperatures; however, increasing the concentration had a detrimental effect on the thermal stability of the fluids. A dramatic decrease in the viscosity with temperature was observed. The apparent viscosity dropped to 1 cP at elevated temperature, and the rheological performance was poor as compared to the 3 lb/bbl fluid. The sharp reduction in the apparent viscosity is due to overtreatment. Therefore, the optimum concentration of these additives is approximately 3 lb/bbl and exceeding this concentration could negatively affect the drilling fluid performance at high temperatures.

Fluid with PAC-R exhibited a high increase in viscosity. Fluid with 1 lb/bbl PAC-R showed an apparent viscosity of 30 cP at room temperature. Increasing the polymer concentrations to 3 and 5 lb/bbl increased the apparent viscosity to 130 cp and 330 cP. However, this additive is not suitable for geothermal drilling due to its low thermal resistance, which was indicated by a sharp reduction in viscosity with temperature. Moreover, excessive mud viscosity is not favorable as it limits the performance of the fluid by increasing the frictional pressure loss in the annulus, drill pipe, and drill bit. Thus, such additives should be used at low concentrations.

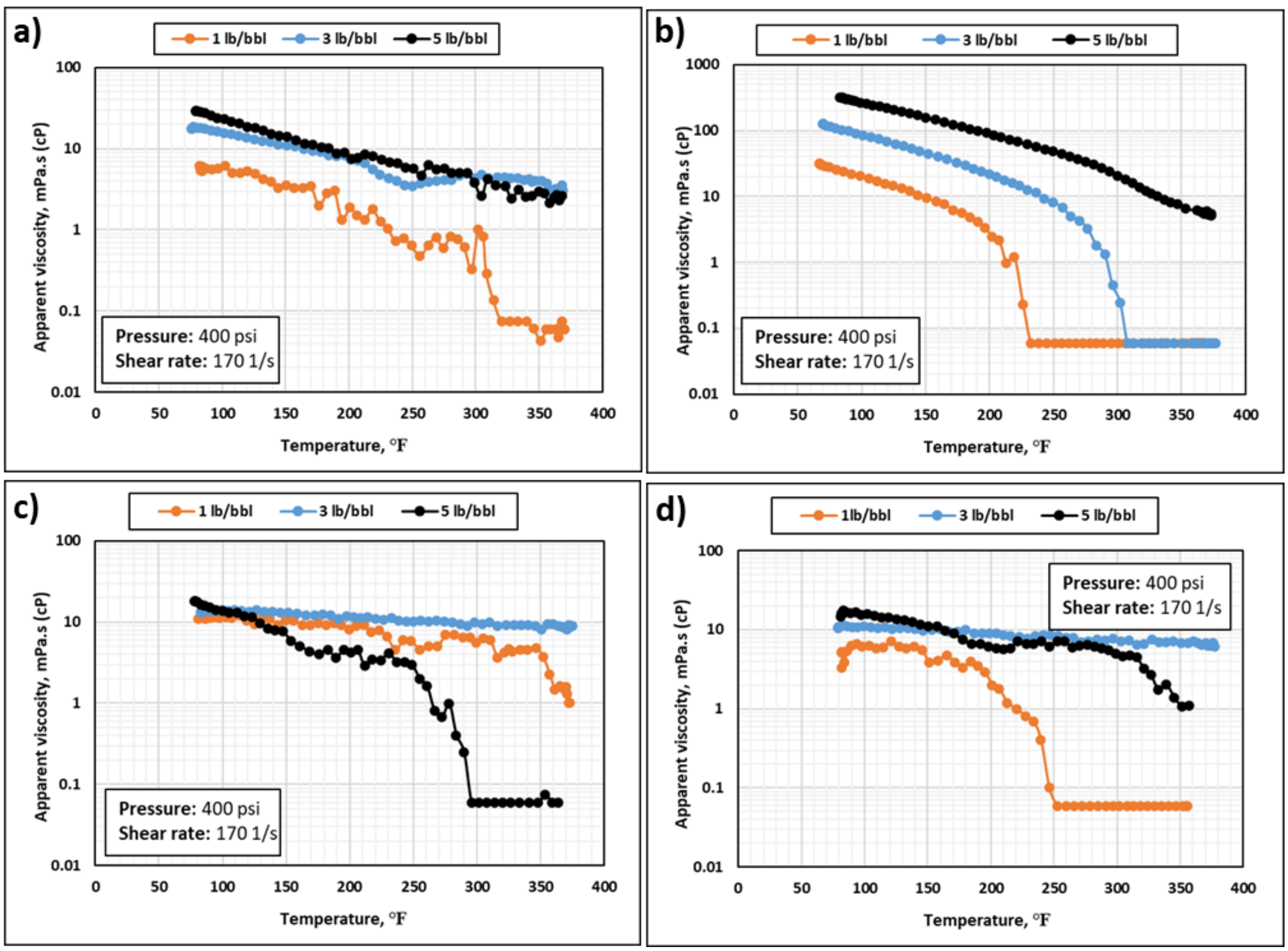

Figure 6: Effect of filtration control additives' concentration on fluid viscosity with temperature: a) PAC-L, b) PAC-R, c) POLYAC PLUS, and d) THERMA-CHEK.

3.3 Effect of Shear Rate

THERMA-VIS was found the best additive to maintain the mud rheological properties at high temperatures due to its high thermal stability; therefore, it was selected for further analysis to study the effect of shear rate on fluid samples. The optimum concentration of THERMA-VIS (3 lb/bbl) was used in this study. The rheological behavior was studied by measuring the shear stress and apparent viscosity at a wide range of shear rate (0.01-510 1/s) and temperature (100-300°F). As shown in **Figure 7a**, fluid samples with THERMA-VIS behaved as non-Newtonian fluids with a high shear-thinning behavior (Skelland, 1967; Mezger, 2006). Their viscosity decreased with the shear rate (**Figure 7b**). The level of shear-thinning can be assessed using the fluid behavior index (n). The flow curves of the fluids are fitted to the Power-law model with a correlation coefficient (R^2) ranging between 0.85-0.93. The fluid behavior index obtained from the curve fitting ranges from 0.1 to 0.2 for all temperatures. The fluid consistency index (K) increased with temperature due to the activation of THERMA-VIS while maintaining the same shear-thinning behavior. This high shear-thinning behavior of drilling fluid is favorable in drilling operations as it would reduce the sensitivity of frictional pressure loss to the change in flow rate.

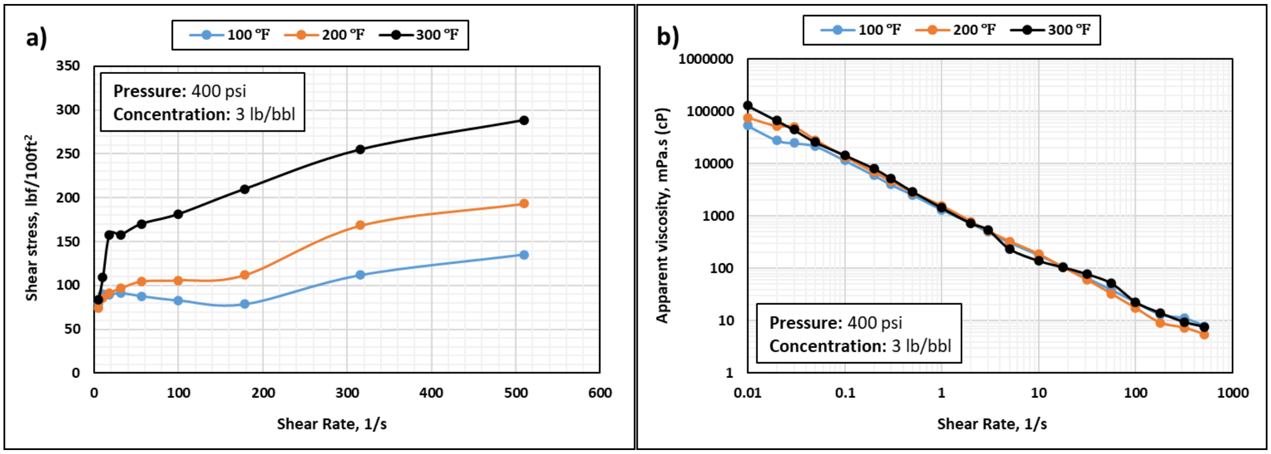

Figure 7: Effect of shear rate on THERMA-VIS viscosity at different temperatures.

3.4 Effect of Time

The thermal stability of THERMA-VIS-based fluid was studied with time to ensure the thermal stability of the fluid throughout drilling operations. The optimum concentration of THERMA-VIS (3 lb/bbl) was used in this experiment. The temperature was increased gradually from room temperature to 350°F and kept constant at 350 °F for more than two hours. As shown in **Figure 8**, the viscosity increased gradually, and THERMA-VIS activated at around 300 °F. Then, the apparent viscosity remained almost constant throughout the experiments. This stable performance with time and temperature makes THERMA-VIS a suitable viscosifier for geothermal drilling applications. It maintains the mud rheological properties and ensures more efficient and successful drilling operations.

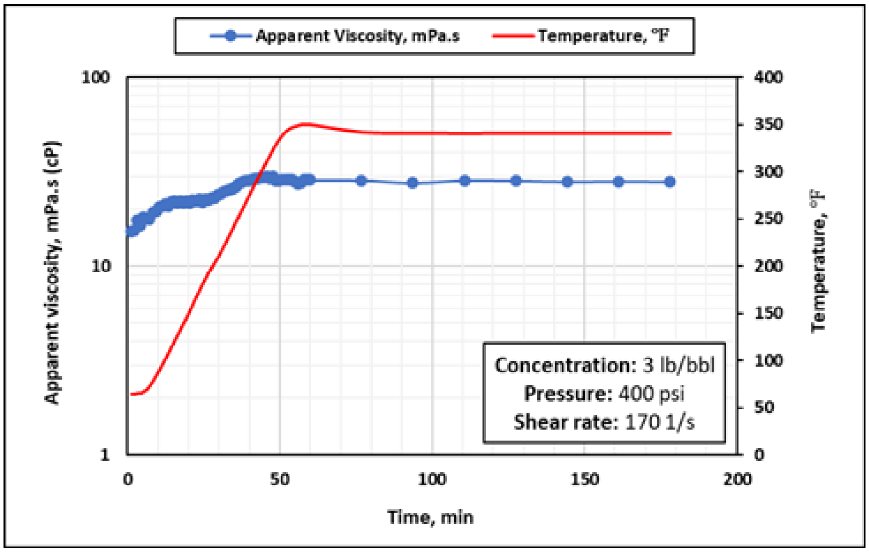

Figure 8: Thermal stability of THERMA-VIS with time.

4. FUTURE WORK

Loss circulation is a challenging phenomenon encountered while drilling geothermal wells because of the high-temperature and highly fractured formations. Selecting the suitable lost circulation material (LCM) and optimizing LCM mud properties is crucial to ensure a successful loss circulation treatment (Magzoub et al., 2020). Therefore, this study is extended to investigate the effect of different LCMs on the mud annular flow using a high-temperature flow loop. This work's main objective is to simulate LCM mud annular flow and study the LCM effect on mud rheological behavior and wellbore hydraulics under different conditions. Many parameters are considered in this study, such as LCM type and concentration, temperature, pressure, flow rate, inclination angle, and pipe rotation. The mud annular flow is also visualized through viewports to investigate the LCM particles distribution and detect any mud stability issues such as flocculation. Moreover, the change in LCM particles is studied to detect the particles' degradation and activation with temperature, particularly for the shape memory polymer (SMP). **Figure 9** shows the schematic and the main components of the high-temperature flow loop used in this study.

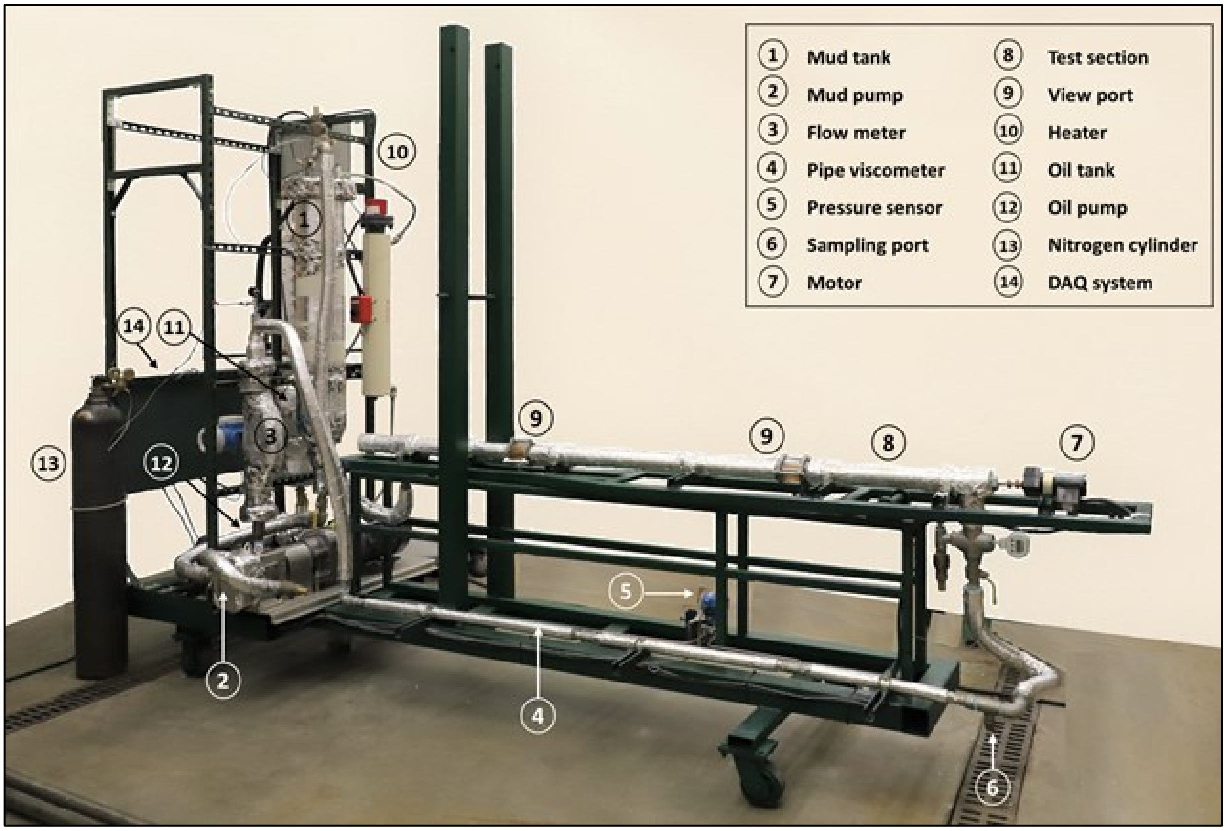

Figure 9: Schematic and main components of the high-temperature flow loop.

5. SUMMARY AND CONCLUSIONS

An experimental study was conducted to evaluate the thermal stability and high-temperature rheology of drilling fluids containing different additives for geothermal drilling applications. The rheology experiments were conducted at different conditions by varying the concentration, temperature, shear rate, and time to determine the best candidates for geothermal drilling. Based on the results, the following conclusions can be drawn:

- The temperature has a significant impact on the stability and rheology of fluids containing the additives. All fluids with additives showed a significant reduction in viscosity with temperature due to thermal degradation and thinning except THERMA-VIS. The reduction varies with additives; some additives showed a slight decrease while others demonstrated a dramatic decline.

- Fluids with bentonite, xanthan gum, and cellulosic additives (HEC, PAC-R, and PAC-L) exhibited a significant decrease in the apparent viscosity with temperature due to low thermal resistance. Therefore, these additives should be limited to normal temperature applications (below 250 °F), and more stable additives such as THERMA-VIS should be used to drill geothermal wells.

- Fluids with THERMA-CHEK and POLYAC PLUS showed good thermal stability with a slight decrease in the apparent viscosity with temperature. The optimum additive concentration was 3 lb/bbl, while POLYAC PLUS showed a higher viscosity than THERMA-CHEK with a difference of approximately 3 cP. Increasing the THERMA-CHEK and POLYAC PLUS concentrations more than the optimum concentration negatively impacted the thermal stability of the fluids. A considerable reduction in apparent viscosity was observed at elevated temperatures.

- THERMA-VIS behaved differently, and the apparent viscosity increased gradually with temperature. This additive is a synthetic hectorite designed to activate at around 300°F. Fluids containing THERMA-VIS maintained a stable rheological behavior with temperature and time. The high shear-thinning behavior exhibited by the THERMA-VIS based fluids is considered a great advantage in managing wellbore pressure to minimize fluid loss and lost circulation.

- Due to the good thermal stability of fluids containing THERMA-VIS, THERMA-CHEK, and POLYAC PLUS, these additives are recommended to maintain the rheological and filtration properties of drilling fluids used in geothermal drilling applications.

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