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Significance and complications of drilling fluid rheology in geothermal drilling: A review

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A R T I C L E I N F O

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A B S T R A C T

The harsh downhole conditions of high pressure and high temperature (HPHT) encountered in geothermal wells make the drilling operation challenging. Drilling in such environments requires a special drilling mud formulation with high thermal stability and good rheological properties to fulfill the drilling fluid functions. Therefore, great efforts should be put into selecting the suitable drilling fluid, optimize and monitor the drilling fluid properties throughout drilling operations, and predicting its performance under downhole conditions. Rheological properties significantly impact many drilling parameters such as hole cleaning, fluid and wellbore stability, wellbore hydraulics, torque and drag, and other drilling issues. This paper discusses water-based drilling fluids' flow behavior under HPHT conditions and highlights the significance of fluid rheology in geothermal drilling. The common challenges and complications related to fluid rheology encountered in geothermal drilling are addressed in this paper, such as hole cleaning, wellbore hydraulics, and drilling fluid stability. This article also reviews the recent advances in drilling mud systems, rheology enhancement, and rheological properties measurements at surface and subsurface conditions. Moreover, the rheology models of drilling fluid at elevated temperatures are reviewed to fully understand their flow behavior and establish a method for drilling engineers to optimize fluid formulations for geothermal drilling.

1. Introduction

Due to the high demand for energy and the growing environmental concerns associated with the oil industry, geothermal reservoirs are considered a great renewable and clean energy source. Thus, the number of geothermal exploration and drilling projects to access the geothermal reservoirs has significantly increased in the last decades (De Angelis et al., 2011; Kiran and Salehi, 2020; Reinsch et al., 2015). The geothermal energy can be generated by drilling wells in geothermal reservoirs and transferring the earth's heat using a circulation fluid produced from the geothermal reservoirs or injected from the surface (Finger and Blankenship, 2010). The drilling operations of geothermal and oil wells are similar (Bavadiya et al., 2019; Capuano, 2016; Teodoriu et al., 2019). Therefore, the advances made in drilling technologies in the oil industry are the key to develop geothermal well drilling techniques (Teodoriu, 2015; Teodoriu et al., 2018). Moreover, the similarity in downhole conditions between geothermal and HPHT oil and gas wells enables engineers to correlate the technical issues and the learned lessons from drilling HPHT oil and gas wells to better understand the complexity of drilling geothermal wells. The main differences between geothermal and HPHT oil and gas wells are the type of fluid produced and the environment in which the produced fluid exists (Capuano, 2016; Vollmar et al., 2013).

Geothermal wells are classified into three categories based on their temperature: low temperature (less than 150℃), medium temperature (between 150 and 200℃), and high temperature (greater than 200℃) (Kruszewski and Wittig, 2018). However, in geothermal wells, the temperature can exceed the water's critical temperature, at which the complexity of drilling and completion operations becomes more challenging (Bland et al., 2006; Kruszewski and Wittig, 2018).

1.1. Main challenges in geothermal drilling

The harsh reservoir environment brought many challenges in the drilling operations of geothermal wells, including issues related to well control, well integrity, and lost circulation (Chemwotei, 2011; Finger and Blankenship, 2010; Kiran and Salehi, 2020; Shadravan and Amani, 2012; Vollmar et al., 2013). In addition to high temperatures, hard formations add more technical limitations on selecting drill bits, casing material, drilling mud, and cement formulations. These conditions create the urge for more technological advancements to cope with the

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Nomenclature

API	American petroleum institute
b, c	model parameters
CTE	cuttings transport efficiency
DRU	density rheology unit
ECD	equivalent circulating density
HPHT	high-pressure high-temperature
K	consistency coefficient
LCM	lost circulation material
LSYP	low shear yield point
MPD	managed pressure drilling
m	exponent
n	flow behavior index
PV, μ_p	plastic viscosity
ROP	rate of penetration
YP	yield point
γ	shear rate
γ_c	shear rate where the stress is equal to twice the yield stress
γ_s	surplus shear rate
τ	shear stress
τ_0	yield point
τ_s	surplus stress$(\tau - \tau_y)$
μ	dynamic viscosity
μ_∞	viscosity at infinite shear rate

HPHT challenges and mitigate the drilling issues (Finger and Blankenship, 2010). The HPHT conditions require special drilling fluid formulations with high thermal stability to withstand high downhole temperatures and avoid any complications resulting from fluid degradation. The harsh conditions may also damage the casing, cement sheaths, and downhole tools. The common types of formation rocks in geothermal reservoirs are volcanic rocks such as granite, quartzite, granodiorite, and greywacke (Vollmar et al., 2013). These types of rocks are well known for their hardness and abrasiveness that increase the wear on the drill bits and shorten their life (Baujard et al., 2017; Finger and Blankenship, 2010; Miyazaki et al., 2019). As indicated by Bavadiya et al. (2017), the hardness of drilled formation increases the drill string vibration, resulting in the failure of downhole tools. It was revealed that variations in high-temperature geothermal wells induce thermal stresses on the casing. When these stresses exceed the yield stress of casing material, the casing fails due to thermally induced stress fatigue (Shadravan and Amani, 2012; Teodoriu, 2015; Wu et al., 2020). Additionally, other casing failure forms result from corrosion, wear, and overloading during drilling and casing operations in geothermal wells (Kruszewski and Wittig, 2018; Teodoriu, 2015; Teodoriu et al., 2018, 2019). These types of damages will inevitably disrupt drilling, well testing, and production operations, and they may lead, in some severe cases, to well abandonment (Kruszewski and Wittig, 2018).

Another challenge in the geothermal industry is the high cost of drilling operations (Bavadiya et al., 2019; Randeberg et al., 2012; Vollmar et al., 2013). Fig. 1 shows the cost allocation of a geothermal plant. Depending on the nature and complexity of geothermal reservoirs, the cost of drilling operations varies between 40–60 % of the total cost of a geothermal project, including confirmation and development drilling. Compared to the oil industry, the high drilling cost and low revenue put more burden on the geothermal industry, and the need for commercial drilling operations still exists (Randeberg et al., 2012). Randeberg et al. (2012) discussed different means for reducing the high cost of drilling operations in geothermal wells, starting by reviewing and understanding the complexity and major expenses of drilling operations and well construction. Transferring the technologies and advancements in oil and gas drilling to the geothermal industry and moving towards automated operations would ensure cost-effective drilling and make geothermal projects more feasible (Falcone and Teodoriu, 2008; Petty et al., 2009). The geothermal industry should also invest in developing advanced tools that are more appropriate to hard and abrasive formations for more efficient and fast drilling (Randeberg et al., 2012).

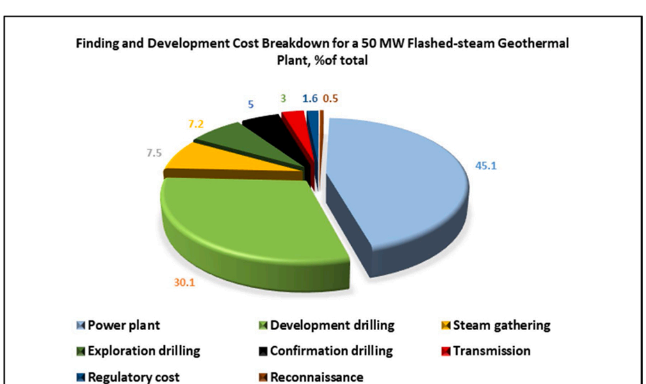

Fig. 1. Cost allocation for a geothermal project (Adapted after Bavadiya et al., 2019).

Due to the small number of drilled wells compared to the oil and gas industry, the lack and uncertainty in drilling and operational data in geothermal projects present another challenge to the geothermal industry (Kruszewski and Wittig, 2018). For instance, in 2008, less than 100 geothermal wells were drilled in the United States, while thousands of oil and gas wells were drilled in the same country (Bavadiya et al., 2019). This uncertainty endorses the need for technology and experience transfer from the oil industry to fill the gap and improve the efficiency of drilling operations. Fig. 2 summarizes the main challenges encountered while drilling geothermal wells.

1.2. Significance of drilling fluid rheology in drilling operations

Drilling fluids play a significant role in the success and total cost of drilling operations (Chemwotei, 2011). Drilling fluids are used in drilling operations to transport the drilled cuttings to the surface, control the formation pressure, cool and lubricate the drill bit, and improve wellbore stability (Ahmad et al., 2018; Caenn et al., 2011; Hossain and Al-Majed et al., 2015a,b). To fulfill such functions, great efforts should be put into selecting the appropriate drilling fluid formulation and optimizing the drilling fluid properties, particularly under HPHT conditions (Mohamed et al., 2021; 2020a). The rheological properties of drilling fluid have a momentous impact on the drilling fluid performance as they affect many drilling parameters such as rate of penetration, hole cleaning, wellbore hydraulics, filter cake formation, and drilling fluid stability (Da Silva and Naccache, 2016; Gamwo and Kabir, 2015; Monteiro et al., 2005; Pakdaman et al., 2019; Vinod, 1994; Walker and Li, 2000; Zamora and Roy, 2000). It was also confirmed by previous studies that the rheological properties of drilling fluid impact the plugging efficiency and lost circulation significantly (Kulkarni et al., 2013). Sun and Huang (2015) studied the effect of drilling fluid rheology on circulation loss in natural fractures. They concluded that the high shear rate rheology is vital in controlling the mud losses as it affects the losses early. This conclusion also applies to geothermal drilling because geothermal reservoirs are highly fractured by nature (Magzoub et al., 2021; Vollmar et al., 2013).

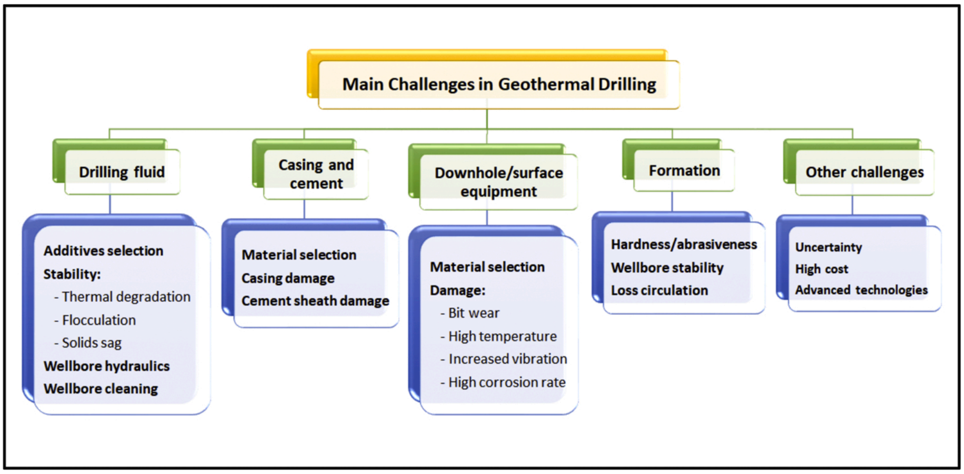

Fig. 2. Main challenges in geothermal drilling.

1.3. Factors affecting the drilling fluid rheology in geothermal drilling

The accurate knowledge of drilling fluid properties under downhole conditions and throughout drilling operations is crucial. Variations in these properties should be mitigated to ensure efficient and cost-effective drilling (Bland et al., 2006). The elevated temperatures encountered in geothermal wells significantly affect the drilling fluid rheology (Ahmad and Federer, 2018; Fridleifsson et al., 2017). Although bentonite mud is commonly used in geothermal drilling, a substantial increase in its yield stress at elevated temperatures has been reported in previous studies. This increase is attributed to clay swelling and flocculation at high temperatures and sodium ions′ substitution (Ahmad et al., 2018; Rossi et al., 1999).

Additionally, high-temperature degrades polymeric additives present in drilling fluid and lower the viscosity of the drilling mud thus, reducing its performance and introducing more formidable challenges to the drilling operations (Amani, 2012; Chemwotei, 2011; Kruszewski and Wittig, 2018; Lee et al., 2012; Sukhoboka, 2017; Tehrani et al., 2007). It was reported that high-pressure increases the viscosity and yield point of oil-based drilling muds by changing the volume of continuous phase due to compression (Amani and Al-Jubouri, 2012a; Rossi et al., 1999). However, the effect of pressure on fluid rheology is less effective than the temperature effect, especially at high-temperature conditions (Amani and Al-Jubouri, 2012b; Bybee, 1999; Davison et al., 1999; Sukhoboka, 2017; Zhao et al., 2008).

Another factor that affects mud rheology during drilling operations is the alteration of its composition due to contamination with drilled cuttings and formation fluids (Bageri et al., 2019a, 2019b; 2020). Bageri et al. (2019b & 2020) studied the effect of drilled cuttings on the mud properties using rock samples from different sandstone formations, particularly calcareous, arenite, ferruginous, and argillaceous. The drilled cuttings were added in 15 and 30 wt.% of total solid weight in the mud system. They concluded that all types of drilled cuttings increased the viscous properties of the drilling fluid. The apparent viscosity, plastic viscosity, yield point, and gel strength (10 min) were increased by 50–139 %, 20–113 %, 50–161 %, and 1–26 %, respectively. At the same time, argillaceous formations had a higher impact on the drilling fluid properties than other formations due to their high clay content (30 wt. %). Therefore, the higher clay content on the drilled formation, the higher the drilling fluid's rheological properties. Ezeakacha et al. (2017) also conducted an experimental study to investigate the impact of formation lithology on drilling mud's filtration and plastering. They tested different core samples at dynamic-radial filtration to simulate the real case in the field. They considered different parameters in the filtration experiments, such as lithology, temperature, differential pressure, pipe eccentricity, and the presence of fractures and lost circulation materials (LCM). The finding of this study highlighted the significance of the lithology on the dynamic filtration performance. Therefore, testing the filtration performance in laboratories yields inaccurate results because the uniform ceramic discs used as a filtration medium fail to represent the filtration behavior in natural formations. However, proper drilling mud design, continuous monitoring of its properties, implementation of sound mitigation strategies, and immediate actions would minimize the drilling fluid rheology complications in geothermal drilling operations.

2. Issues associated with drilling fluid rheology in geothermal drilling

2.1. Drilling fluid stability

Physical and chemical stabilities are crucial characteristics of drilling fluid due to their substantial impact on drilling operations. Chemical stability is the resistance of drilling fluid to chemical interaction that might result from contaminants and drilling fluid components (Bageri et al., 2019a, 2019b; 2020). In contrast, physical stability is the drilling fluid resistance to the physical downhole conditions encountered during drilling and circulation, such as the high temperature, high pressure, and excessive shear (Basfar et al., 2019a,b). In geothermal wells, the presence of high temperature presents a real challenge to drilling fluids. It promotes the thermal degradation of polymeric additives and deteriorates the rheological properties of drilling fluids (Amani and Al-Jubouri, 2012a, 2012b; Avci and Mert, 2019). Another issue associated with drilling fluid stability is bentonite mud flocculation due to high temperature, which causes an undesired change in the rheological properties of bentonite mud. This change is often observed at elevated temperatures above 121 ℃ (250℉) (Zilch et al., 1991).

Fig. 3 shows the impact of temperature on the apparent viscosity of four different commercial polymeric additives used in drilling applications, such as low viscosity polyanionic cellulose (PAC-L), synthetic fluid loss polymers (THERMA−CHEK and POLYAC PLUS), and synthetic hectorite (THERMA-VIS). These additives are commonly used to maintain fluid viscosity and control fluid loss. The additives were tested at their field-recommended concentration, 8.56 kg/m^3 (3.0 lb/bbl), using freshwater as the base fluid. Testing was performed using an HPHT rheometer (Grace model M5600), starting from room temperature. The temperature was ramped up to 190.6 ℃ (375 ℉), while a constant pressure of 2.76 MPa (400 psi) was applied to prevent fluid evaporation. The experiments were conducted at a constant shear rate of 170 1/s. As shown in Fig. 3, PAC-L showed the highest apparent viscosity at room temperature, around 18 mPa.s (18 cP); then, the apparent viscosity dropped dramatically with temperature to reach 4 mPa.s (4 cP) at 107.2 ℃ (225℉). Then, the fluid maintained its viscosity as the temperature

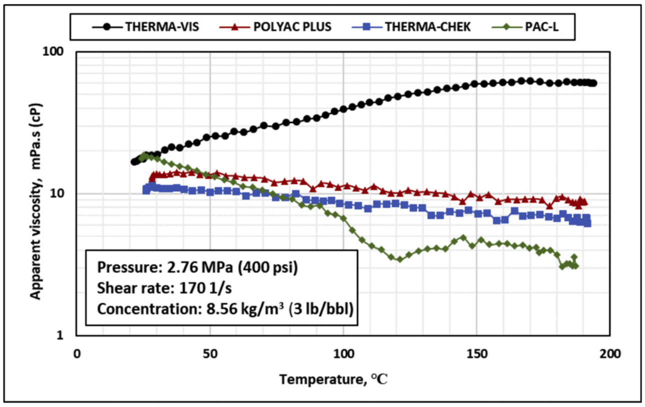

Fig. 3. Effect of temperature on the viscosity of different polymeric additives.

was increased to 190.6 ℃ (375℉). The dramatic decrease in fluid viscosity indicates poor thermal stability of the PAC-L at high temperatures. Comparing other polymers, POLYAC PLUS maintained a higher viscosity than THERMA−CHEK throughout the experiments with a difference of around 3 mPa.s (3 cP). Both polymers showed a slight reduction in the apparent viscosity with temperature, indicating better thermal stability than PAC-L. In contrast, THERMA-VIS showed a different viscosity profile.

The viscosity of THERMA-VIS started at 17 mPa.s (17 cP) and gradually increased to 60 mPa.s (60 cP) and stabilized at 148.9 ℃ (300℉). The increase in viscosity is attributed to the thermally induced hydration of THERMA-VIS as it is designed to activate and build viscosity at high temperature (+130 ℃). After completing the test, the fluid samples were collected to assess the effect of temperature on their physical appearance. As shown in Fig. 4, all the fluid samples were clear and fully transparent (Fig. 4a). The PAC-L color completely changed to dark brown color after the experiment, which confirmed the thermal degradation of PAC-L at elevated temperatures (Fig. 4b). While THERMA–CHEK, POLYAC PLUS, and THERMA–VIS showed a slight change in the color with temperature, THERMA–VIS exhibited the highest viscosity at elevated temperatures. The change in the physical appearance of the fluid also supports the findings of the rheology experiments. This screening study demonstrated the high impact of temperature on the rheology of polymeric fluids. Therefore, at high temperatures, great considerations should be given towards selecting drilling mud additives.

Another form of fluid instability is the separation of weighting agents such as barite from the liquid phase, causing variations in the density fluid column (Fig. 5). This phenomenon is called barite sag, and it is often observed in oil-based muds. It occurs in vertical and inclined wells under static and dynamic conditions (Bern et al., 2010; Nguyen et al., 2011; Omland et al., 2007; Parvizinia et al., 2012). As solid particles are separated from the liquid phase and deposited on the wellbore wall, the fluid column density reduces. Consequently, kick occurs when the mud weight becomes insufficient to control the formation pressure, leading to the loss of well control. The solid particles accumulated in the lower part of the well intermittently slid, causing the mud weight and ECD to fluctuate. This fluctuation may induce fractures in the formation leading to partial or total loss circulation, especially when the mud window is narrow. Moreover, the accumulated solids interfere with drilling and completion operations.

Drilling fluid rheology is considered a good indication of the issues associated with drilling fluid stability, such as flocculation, coagulation, and barite sag (Bern et al., 2000, 2010; Omland et al., 2007). Chilingarian et al. (1986) proposed a tool/method for evaluating the drilling fluid stability based on the measurements of the rheological properties, particularly yield point (YP) and plastic viscosity (PV). The technique of this method is to plot the YP versus PV, and from the slope of these plots, the drilling fluid stability can be evaluated. The degree of stabilization increases with the slope (YP/PV) decrease, while the degree of flocculation and coagulation increases with the slope. This tool detected the degree of stabilization, coagulation, and flocculation of drilling fluid systems. The method has been supported by other studies (Basfar et al., 2018, 2019a, 2020; Elkatatny, 2018, 2019; Mohamed et al., 2021, 2019, 2020a, 2020b) conducted on the sag tendency of drilling fluids under HPHT conditions. Static and dynamic sag factors exceeded the acceptable values (0.53 and 1.0, respectively, as per drilling practices) when YP/PV was less than 1.5. It was revealed that viscous and viscoelastic properties are very effective in controlling and monitoring sag phenomenon and other stability issues encountered in HPHT wells.

2.1.1. Case study 1- Gulf of Mexico

This case history addresses a drilling fluid stability issue encountered while drilling a highly deviated well in the Gulf of Mexico with an inclination of 68°. The sag issue was encountered three times while drilling the well interval from 3183 to 4063 m MD (10,443 to 13,330 ft MD); after tripping at 3,953.3 m (12,970 ft) to test the BOP, while circulating the liner, and after running the production tubing. The interval was drilled with a 1,533.8 kg/m^3 (12.8 ppg) water-based mud (WBM) with a rate of penetration (ROP) ranging between 9.1–12.2 m/hr (30−40 ft/hr). The drilling fluid circulation rate was 56.8 m^3/hr (250 gpm), while the pipe rotation was in the range of 60−70 rpm. The rheological properties of the drilling fluid were yield point (YP) = 71.8–81.4 kPa (15−17 lb/100ft^2), Plastic viscosity (PV) = 18−21 mPa.s (18−21 cP), and low shear yield point (LSYP) = 19.2–28.7 kPa (4−6 lb/100 ft^2). The sag incidents are attributed to be a result of inadequate LSYP, which was below the recommended level, 33.5–71.8 kPa (7−15 lb/100ft^2) due to the difficulty in controlling the rheological parameters of non-inhibited WBM because this mud system required a dilution rate of 8 m^3/m^3 drilled cuttings (8 bbl fluid/ bbl drilled cuttings) for removing the cuttings. Another reason could be the low pipe rotation

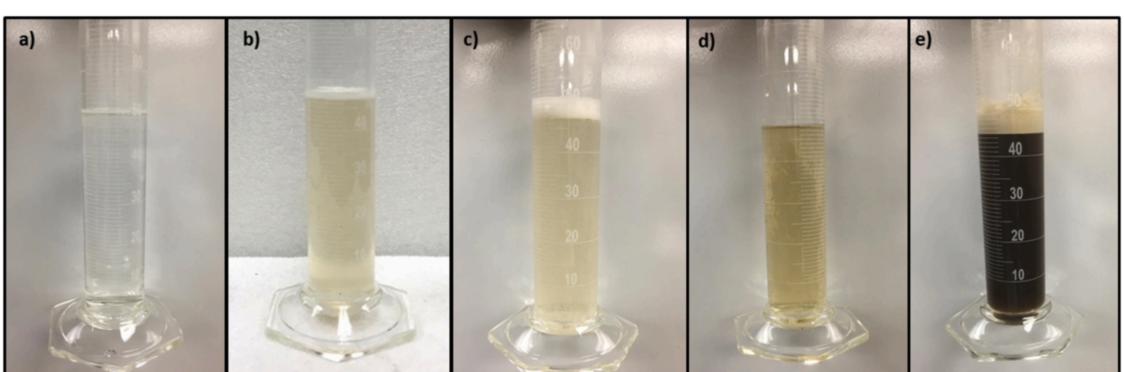

Fig. 4. Fluid sample: a) Before the test, b) THERMA−CHECK after the test, c) THERMA-VIS after the test, d) POLYAC PLUS after the test, and e) PAC-L after the test.

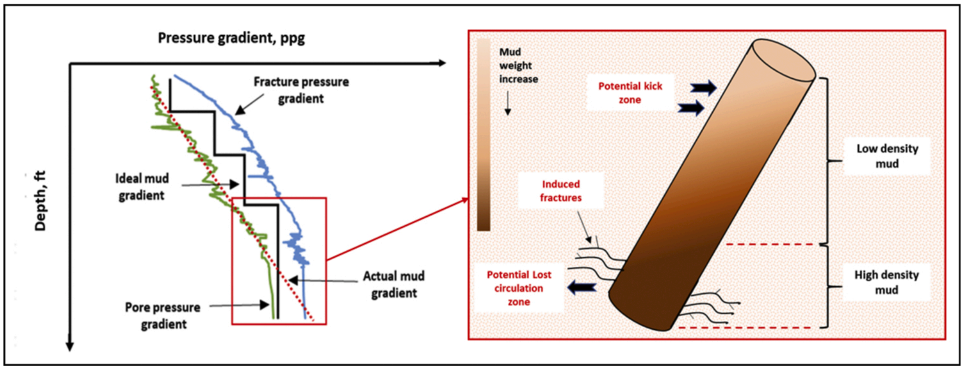

Fig. 5. Occurrence and complications of solids sag phenomenon.

(100 rpm) that was below the minimum recommended value. As a result, the mud system was treated with bentonite and biopolymer after each incident. As a result, it was recommended to use inhibitive WBM or synthetic-based mud (SBM) to drill the subsequent wells (Scott et al., 2004). Thus, selecting the appropriate drilling mud formulation and optimizing its rheological properties plays a major role in mitigating the drilling fluid's stability issues. The applications of using drilling fluid properties in detecting and monitoring the problems associated with drilling fluid stability can be further extended to geothermal drilling applications due to their similarity with HPHT oil and gas drilling applications in downhole conditions.

2.2. Hole cleaning

Cuttings transport is one of the main functions of drilling fluids that significantly affect drilling operations. Cutting beds often form in inclined wells when the inclination angle is greater than 35°. And, its formation is affected by many parameters such as flow rate, inclination angle, pipe eccentricity, rheological properties, and wellbore hydraulics (Werner, 2018). Fig. 6 illustrates the phenomenon of cuttings bed formation. In the case of good hole cleaning (Fig. 6a and 6b), the drilled cuttings are flowing with and transported by the drilling fluid to the surface. In poor hole cleaning, the drilled cuttings tend to settle in the lower part of the well forming a moving bed that can be eroded by the drilling fluid circulation (Fig. 6c). With time, the accumulated cuttings will form both moving and stationary beds (Fig. 6d), reducing the flow area and creating other drilling problems. Inadequate hole cleaning introduces formidable challenges and makes the drilling operation less efficient by decreasing the rate of penetration, causing pipe sticking and difficulties in casing and liner placement, and affecting wellbore stability. Consequently, these issues prolong drilling time and increase the cost (Boyou et al., 2019).

In addition to well inclination and geometry, depth, flow rate, pipe rotation, cuttings size and shape, and mud density, drilling fluid rheology contributes to hole cleaning efficiency (Busahmin et al., 2017; Ramsey, 2019; Vinod, 1994). The yield point of drilling mud shows the fluid's capability to suspend solid particles and drilled cuttings (Caenn et al., 2011; Hossain and Al-Majed, 2015a,b).

Several experimental studies (Boyou et al., 2019; Busahmin et al., 2017; Ford et al., 1990; Kelessidis et al., 2007; Pandya et al., 2019a, 2019b; Saasen and Løklingholm, 2002; Vinod, 1994) were conducted to evaluate the effect of fluid rheology on hole cleaning using flow loop systems and commercial viscometers. Saasen and Løklingholm (2002) stated that the drilling fluid with a low degree of shear-thinning shows a better performance in hole cleaning than that with a high degree of shear-thinning. Ford et al. (1990) reported that the cuttings transport efficiency (CTE) in inclined wells is improved by the high viscosity fluids while, on the other hand, Kelessidis et al. (2007) stated that the low viscosity fluids perform better in horizontal wells, in terms of hole cleaning. Walker and Li (2000) concluded that the flow regime should also be considered in addition to viscosity. Under laminar flow conditions, high viscosity fluids perform better in vertical and inclined wells while low viscosity fluids under turbulent flow conditions are preferable in horizontal wells. Another study conducted by Busahmin et al. (2017), where the hole cleaning phenomenon was modeled analytically and numerically to study the effect of different parameters on the cutting transport efficiency. They concluded that, for vertical wells, yield point, plastic viscosity, and gel strength are considered controlling factors on

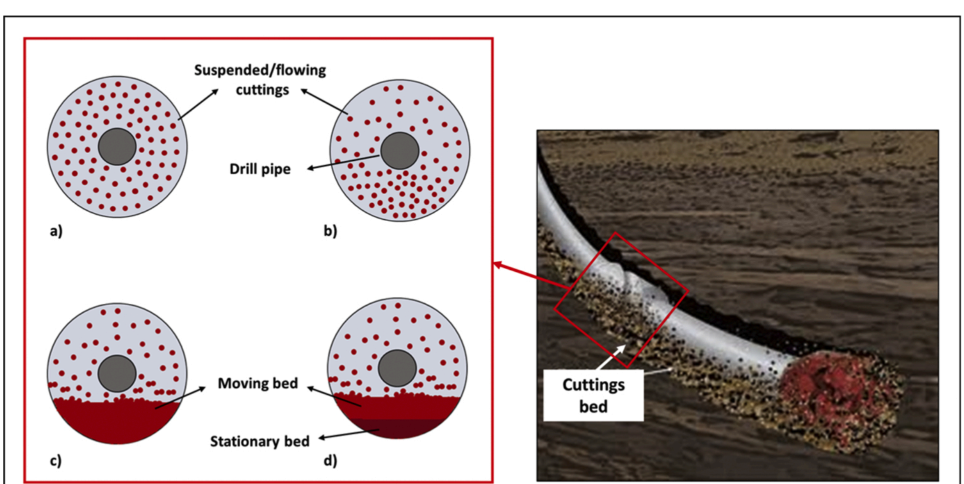

Fig. 6. Formation of cuttings bed (Adapted after Liu et al., 2019; Mahmoud et al., 2020).

the cuttings transport efficiency, in addition to other parameters such as flow rate. Therefore, high temperature encountered in geothermal wells is considered as the main challenge in hole cleaning. It greatly affects the rheological properties of drilling fluid, causing a change in the hole cleaning performance. Unlike HPHT oil and gas wells, the geothermal wells are drilled and completed with a larger hole size to maximize fluid production and extract more energy (Finger and Blankenship, 2010). The well design is another factor that influences hole cleaning in geothermal drilling because the hole size affects the annular fluid velocity, which is the major factor in cuttings transport (Naganawa and Okabe, 2014). To tackle the issues associated with hole cleaning in geothermal drilling, great attention should be paid to the difference in well design between oil/gas wells and geothermal wells and the rheological behavior of the drilling fluid under harsh downhole conditions.

2.2.1. Case study 2

Naganawa and Okabe (2014) conducted a case study on hole cleaning and wellbore hydraulics of a geothermal well drilled in Japan with a total depth of 3002 m (9850 ft) and inclination of 70° (long extended-reach geothermal well). The study combined experimental and simulation investigations to optimize drilling parameters and ECD for effective hole cleaning. The numerical simulation for the geothermal well was performed using a two-layer hydraulics simulator, and it was based on the experimental and field data. The experimental data was collected by conducting many cuttings transport experiments using a large-scale flow loop. Tests were performed by varying the inclination from vertical (0°) to horizontal (75°) with an increment of 15°. The setup consists of a casing and an inner pipe that can be set either eccentric or concentric to simulate the drill pipe rotation. Table 1 shows the range of experimental parameters used in this study. Field measured annular pressure data were obtained from a geothermal directional well drilled recently in the area. Analyzing experimental, simulation, and field data, they were able to optimize drilling parameters such as mud type and properties, flow rate, and ECD to ensure effective hole cleaning. The main conclusion of the study is that, for effective drilling operations, hydraulics research should be conducted in the planning phase prior to drilling operations because wellbore hydraulics are a key issue in geothermal drilling.

2.3. Wellbore hydraulics

Wellbore hydraulics deal with the pressure losses associated with the drilling fluid flow in the annulus. The significance of wellbore hydraulics optimization in drilling operations was well addressed in the literature. Many drilling issues are related to wellbore hydraulics such as hole cleaning, pipe sticking, low penetration rates, lost circulation, bit balling, solids sag, and borehole enlargement (Mansure and Glowka, 1995; Ramsey, 2019; Zamora and Roy, 2000). A good understanding of fluid rheology and hydraulics is required to predict the flow regime and pressure losses in the wellbore. Generally, the Bingham plastic model, the Power Law model, and the Herschel-Buckley model are the most common rheology models that describe the drilling fluid rheology. Several formulas and models have been developed to predict frictional pressure losses in pipes and annulus with different fluids. All predictive models are highly dependent on the flow characteristics of drillings fluids and the flow rate and wellbore geometry (Ramsey, 2019).

Equivalent circulation density (ECD) is one of the essential hydraulic parameters that affect drilling operations. ECD is the effective mud density exerted on the formation that accounts for the pressure losses in the annulus (Hossain and Al-Majed, 2015a,b). Depending on the formation pressure, low ECD could cause a kick. On the other hand, when the ECD exceeds the fracture gradient of the drilled formation, excessive pressure creates fractures, leading to partial or total fluid losses, particularly in depleted and weak geothermal formations where the drilling window is narrow (Murray et al., 2013). Therefore, ECD should be optimized, considering well parameters and formation pressure to provide effective hole cleaning and avoid fluid losses in weak formations.

Turbulence is a significant factor that contributes to pressure losses while circulating drilling fluid. These turbulent pressure losses occur in the drill bit nozzles, drill string, and annulus. The pressure drops in the drill bit provide the hydraulic power to the drilling operation, and the equations to calculate the pressure drop is well defined. However, the hydraulic models for the annular pressure losses are based on empirical correlations that are not accurate enough to properly analyze the wellbore hydraulics (Zamora and Roy, 2000). To predict turbulent pressure losses and reduce their effect on the drilling operations, some advancements are still required in geothermal drilling, such as developing new tools and methods that can accurately predict wellbore pressure profile and analyze the wellbore hydraulics.

Additionally, the need for low-cost drilling mud systems that exhibit drag reduction behavior and better thermal stability still exists. Moreover, wellbore hydraulics and pressure loss models are crucial in the recent advances of drilling operations such as managed pressure drilling (MPD). The bottom hole pressure is controlled throughout the drilling operation using real-time data. The efficiency of such applications relies on the accuracy of the hydraulic model. Thus, selecting the rheology model that best describes the drilling fluid and considering the change in rheological properties with downhole conditions, especially in HPHT and geothermal wells, would result in satisfactory outcomes (Dareing and Kelsey, 1981; Da Silva and Naccache, 2016).

2.3.1. Case study 3- the Pierce field

The Pierce field in the UK Central North Sea is a good example of managing the fluid losses by controlling the drilling fluid rheology and wellbore hydraulic parameters, particularly ECD. The Pierce field is located 170 miles east of Aberdeen in a water depth of 275 ft. The field produces oil and gas from sandstone formations with a reservoir temperature ranging between 113–133 °C (236–272 °F). After producing for seven years, oil production was supported by three water injection wells. Severe fluid losses were encountered while drilling one of the wells, and no progress could be made in the drilling operation. The existing fractures that were weakened by depletion and the increase in ECD were the reasons for the losses (Fig. 7). These severe losses forced the operator to rethink how subsequent wells should be drilled. They developed a new procedure to mitigate the fluid losses by using a low ECD mud system and improving the loss treatment strategies. Two options were considered: the first one was to reduce the ECD to its minimum by decreasing the pump flow rate. However, decreasing the pump flow rate negatively impacts the hole cleaning and results in forming a cuttings bed that will increase the ECD and cause losses. The other option was to reduce the ECD by optimizing and reducing the rheological properties without impacting the hole cleaning or causing sag issues. The rheological properties, especially the low-end rheology, were optimized by controlling the organophilic clay content and the oil-water ratio. Implementing the latest procedure in the field resulted in successful drilling

Table 1
Experimental conditions for Naganawa and Okabe study (2014).

Parameters	Range
Hole size (I.D.)	12.7 cm (5″)
Drill pipe (O.D.)	5.25 cm (2.063″)
Drill pipe eccentricity	0.8
Hole inclination	0, 30, 45, 60, 75°
Drilling fluid	Mud 1: Water [PV = 1 mPa.s, YP = 0 kPa, Initial Gel = 0 kPa] Mud 2: water + 5% bentonite + 0.1 % PHPA (PV = 20 mPa.s, YP = 67.03 kPa (14 lb/100ft^2), Initial Gel = 14.36 kPa (3 lb/100ft^2)]
Fluid density	1.0 SG (Mud 1), 1.03 SG (Mud 2)
Temperature	30 °C (86 °F)
Flow rate	30–70 m^3/h (130–310 gpm)
Cuttings diameter	~3.2 mm (1/8″)

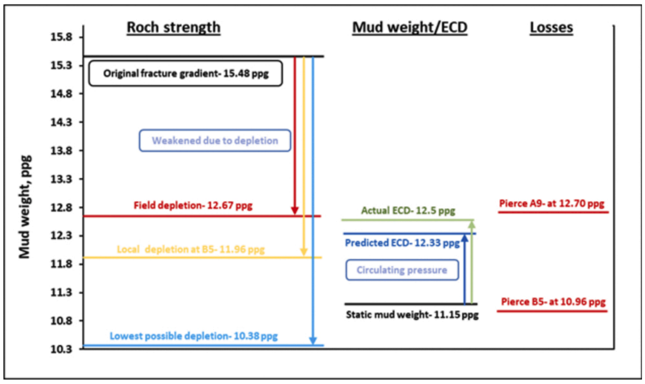

Fig. 7. Drilling window on Pierce B5 (Adapted after Murray et al., 2013).

Table 2
Main components of mud systems used in early geothermal drilling.

Mud system	Composition	Main technical issues
First-generation	Bentonite Sepiolite NaOH Sodium polyacrylate Modified lignite	- Clay flocculation at high temperatures - Formation damage
Second-generation	Bentonite Sepiolite Lignite Caustisized lignite NaOH Nonionic detergent Bentonite High-temperature deflocculant Modified lignite	- High fluid loss - High viscosity from lignite degradation and contamination
Third-generation	Caustisized lignite High-temperature polymeric fluid loss control additive NaOH Sodium polyacrylate Modified lignite	

operations for the subsequent wells without fluid losses; therefore, optimizing the rheological properties is the key factor in drilling operations (Murray et al., 2013; Wilson, 2014).

3. Advances in controlling drilling fluid rheology for geothermal drilling

3.1. Drilling fluid systems used in geothermal wells

The drilling mud used in the early stages of geothermal drilling mainly consists of water and bentonite clay (Erge et al., 2020). Some polymeric additives are added to maintain and improve the drilling fluid's rheological and filtration properties (Chemwotei, 2011; Finger and Blankenship, 2010). Although oil-based fluids outperform water-based fluids in terms of thermal stability and drilling efficiency, water-based fluids are more common in geothermal drilling because of the high cost of oil-based fluids and the associated environmental concerns (Amani et al., 2012). Brine from geothermal spring was also tested for use as a base fluid to formulate drilling mud for geothermal wells (Avci and Mert, 2019). Clay mud was used to drill the first geothermal well in The Imperial Valley in California. Undesired change in the rheological properties was observed because of clay flocculation at a temperature above 121 ℃ (250 ℉). Later the mud system was treated using lignosulfonate; however, the treatment failed (Zilch et al., 1991). Moreover, drilling with clay fluid is not preferable in drilling the producing formations. It causes formation damage and adversely reduces the reservoir permeability that significantly affects the amount of energy extracted from a geothermal well (Finger and Blankenship, 2010; Kruszewski and Wittig, 2018). Consequently, the industry moved towards other alternatives to replace bentonite fluids. First, sepiolite clay was introduced because it has better thermal stability than bentonite. Nevertheless, sepiolite clay failed to control the filtration properties of the drilling fluid. Some polymers and low bentonite concentrations were added to sepiolite mud to solve the filtration issue (Altun et al., 2010). A series of treatments were done using more lignite and bentonite concentrations to maintain the rheological and filtration properties. This overtreatment led to a high viscosity increase because of lignite degradation caused by high temperature and contamination (Zilch et al., 1991). Furthermore, a new copolymer with low molecular weight was proposed by Perricone and Lucas (1981) to treat bentonite muds. Higher thermal stability was observed, and other polymeric additives were introduced to improve the filtration properties. Table 2 shows the composition of the three mud generations used in the early stages of geothermal drilling.

High-density weighting materials are used with the drilling fluid to increase the mud weight and meet high downhole pressure requirements. Barite ($BaSO_4$) is a common additive used for such purposes; however, the barite sag issue is likely under HPHT conditions (Bern et al., 2010). Many recent studies were conducted to resolve the barite sag issue in HPHT oil and gas wells by improving the drilling fluid rheology, adding anti-sagging agents, using micronized barite, replacing barite with other alternatives, mixing barite with other weighting agents (Abdou et al., 2018; Alabdullatif et al., 2014; Basfar et al., 2018, 2019b, 2020; Elkatatny, 2018, 2019; Fakoya, 2019; Mohamed et al., 2021, 2019, 2020a, 2020b; Nguyen et al., 2011; Parvizinia et al., 2012; Walker, 1983). The promising findings of these studies provide the geothermal industry with more options for drilling fluids to drill geothermal wells. For instance, ilmenite ($FeTiO_3$) was successfully used as a weighting agent in the DESCRAMBLE geothermal project (Venelle-2 well), where sepiolite clay was used to suspend the weighting agent. The small particle size of ilmenite and good thermal stability of the mud system resulted in a successful drilling operation without a sagging issue (Bertani et al., 2018).

Another type of drilling fluid used in geothermal drilling is the polymer mud formulated with water and thermally stable polymeric additives that maintain the rheological and filtration properties. Polymeric muds can be prepared using natural or synthetic polymers. Generally, polymer muds are more expensive and have higher filtration rates than bentonite mud; however, they have better lubricity and can be formulated to have optimum rheology (Chemwotei, 2011). High-viscosity polymer pills are commonly used in geothermal drilling to clean the well and mitigate fluid loss (Thorhallsson, 2011; Tuttle, 2005). A combination of both polymer and bentonite was also introduced as an option for geothermal drilling to reduce the cost of polymer-based muds and improve the performance of bentonite mud (Chemwotei, 2011). Moreover, due to the degradation of conventional viscosifiers, deflocculants, and thinners at high temperatures (above 176.6 ℃/350 ℉), several research works were focused on developing a new generation of more thermally stable rheology control additives to be used in geothermal drilling (Thaemlitz et al., 1999; Tuttle, 2005). Several studies were conducted to enhance the properties of drilling fluids by introducing different nanoparticles to the mud system. The findings of these studies confirmed that nanomaterials could greatly improve the rheological and filtration properties of drilling mud and help mitigate the complications associated with drilling fluid rheology such as hole cleaning, lost circulation, and fluid stability (Boyou et al., 2019; Hajiabadi et al., 2019; Pakdaman et al., 2019). Loss circulation is a challenging issue encountered while drilling geothermal wells as most geothermal formations are fractured by nature. Generally, lost circulation treatments are classified into two main categories; preventive and corrective methods. Preventive methods are defined as the methods used to prevent circulation losses in the first place. In contrast, corrective methods are introduced to stop the losses and mitigate their impact on drilling operations (Magzoub et al., 2020). Usually, lost circulation materials (LCM) are introduced to the drilling fluid formulation to mitigate the fluid losses by forming an efficient seal on the drilled formation that can hold throughout drilling operations.

Several additives were introduced as LCM, such as calcium carbonate, graphite, mica, perlite, cottonseed, and fibers (Abshar et al., 2018; Hettama et al., 2007; Lai et al., 2010; Loeppke et al., 1990; Mansure, 2002). Table 3 shows different LCMs used in drilling oil, gas, and geothermal wells. Selecting the appropriate LCM for geothermal drilling depends on many factors such as thermal resistance, sealing efficiency, mechanical properties, and cost. Some of these additives fail in geothermal drilling because of the high temperature gradient. Implementing such innovations in geothermal drilling would have a high impact on geothermal projects, and more research should be carried out to develop more efficient and cost-effective drilling fluids.

3.2. Rheology measurements in laboratories and oilfields

Since the knowledge of rheological properties is of high importance in drilling operations, the standards and best practices to evaluate and measure drilling fluid rheology were established in the early times (Clark, 1995). However, with the advancements in drilling mud systems, the industry needed modernized standards to cope with the complexity of mud systems and downhole conditions (Bern et al., 2006). To measure and characterize the drilling fluid rheology, the industry relied on a series of measurements using various commercial viscometers standardized by the American Petroleum Institute, API (Andaverde et al., 2019). There are different types of viscometers such as capillary tube, pipe viscometer, concentric rotary cylinder, rotating cylinder in an infinite medium, and cone-and-plate. The capillary tube and pipe viscometers' main principle is the measurement of the frictional pressure drop of a laminar fluid flow at a given flowrate across a cylindrical tube with known dimensions. The rotary viscometers concept is the measurement of the angular speed of the rotating cylinder and the torque applied on the stationary cylinder. The cone-and-plate viscometer measures the torque required to rotate the cone at various speeds with the fluid sample located in the small gap between the cone and the flat horizontal plate (Skelland, 1967). The generated data of shear stress and shear rate can be fitted and used to identify the rheology model and calculate the rheological properties of drilling fluids such as plastic and apparent viscosity, yield point, and gel strength (Santoyo et al., 2001). The complexity of mud systems and the significant change in rheology under downhole conditions in geothermal wells pushed the industry to develop more sophisticated equipment that can measure the rheological properties under ultra-high temperature and pressure conditions because inaccurate predictions of rheological properties may cause formidable complications in drilling operations. Measuring rheological properties with such viscometers is time-consuming and unavailable at the rig site; thus, other alternative methods were introduced. Artificial intelligence and mathematical models can be a good option for predicting rheological data in the field. Elkatatny et al. (2018) proposed a

Table 3
Common LCM's used in drilling operations.

Material	Category	Specific gravity	Temperature: Maximum tested	Temperature: Successful up to	Observations
Calcium Carbonate (Abshar et al., 2018; Alsaba et al., 2014)	Granular	2.71	149 °C (300 °F)	126 °C (260 °F) alone /149 °C (300 °F) in blends	High Solubility to acid and low pH muds
Cellophane Flakes (Liles et al., 1976; Luzardo et al., 2015; Nayberg and Linafelter, 1984)	Flake	1.42	149 °C (300 °F)	149 °C (300 °F)	Typically used in blends/ Highly damaging to productive formations/ High resistance to shear when wet.
Graphite (Hettama et al., 2007; Alsaba et al., 2014)	Granular	1.9−2.3	149 °C (300 °F)	149 °C (300 °F)	Can reduce seal efficiency at HT due to lubricity effect/ It should not be used in blend at HT conditions/ It is not affected by temperature when used alone
Black Walnut Shells (Loeppke et al., 1990)	Granular	1.1	260 °C (500 °F)	260 °C (500 °F)	They have fiber-like structures on the surface that could prove helpful in sealing fractures
Mica (Akhtarmanesh et al., 2016; Loeppke et al., 1990)	Flake	2.4−3	260 °C (500 °F)	260 °C (500 °F)	Typically used in combinations with other LCM's/ Standard concentration: 28.53 kg/m^3 (10 lb/bbl)/ Should be used with care due to high SG
Perlite (Loeppke et al., 1990; Mohamed et al., 2020c)	Granular	1.1	204 °C (400 °F)	204 °C (400 °F)	Used with cement only in Shallow Depths/ It does not resist pressures higher than 13.8 MPa (2000 psi).
Mixed Nut Shells (Chellappah et al., 2018; Loeppke et al., 1990)	Granular	1.2	149 °C (300 °F)	149 °C (300 °F)	More Effective at higher temperatures (swelling)/ More effective on their own than in blends/ Good from a solid degradation point of view
Thermoset Rubber (Loeppke et al., 1990)	Granular	1.48	149 °C (300 °F)	149 °C (300 °F)	LCM capabilities rapidly degrade with temperature/ Higher concentrations than 71.33 kg/m^3 (25 lb/bbl) can be detrimental
Cellulosic fibers (Alsaba et al., 2014)	Fiber	1.2−1.5	100 °C (212 °F)	100 °C (212 °F)	–
Cotton Seed Hulls (Cromling, 1973)	Mixed/ Mostly flakes	0.32	121 °C (250 °F)	93 °C (200 °F)	–
Plastic Foil (Liles et al., 1976)	Flake	1.4	260 °C (500 °F)	–	Although the normal degradation temperature of PVC is low, plastic foil is still listed as a geothermal LCM, which implies that other materials might be used in the plastic foil composition
Alder Wood (Loeppke et al., 1990)	Granular	0.37	204 °C (400 °F)	Completely degraded at 204 °C (400 °F)	Not Suitable for geothermal applications due to low thermal resistance
Coal (Lee and Taleghani, 2020; Loeppke et al., 1990)	Granular	2.3	204 °C (400 °F)	156.6 °C (330 °F)	%30 loss of seal strength up to 156.6 °C (330 °F)/ Poor Mechanical Properties
Foam Wedge (Alsaba et al., 2014)	Flake/Fiber	Variable	82 °C (180 °F)	82 °C (180 °F)	Requires time to strengthen the seal
Expanded Aggregate (Loeppke et al., 1990)	Granular	2.6	204 °C (400 °F)	204 °C (400 °F)	Poor Mechanical Properties/ High Density/ Very abrasive/ Seals created were very unreliable
Gilsonite (Loeppke et al., 1990)	Granular	1.06	121 °C (250 °F)	More than 110 °C (230 °F)	Typically Used in cement Slurries/ Low S/E ratio suggest poor to medium plugging capabilities/ Poor Mechanical Properties
Marble (Loeppke et al., 1990; Savari et al., 2012)	Granular	2.7	187 °C (370 °F)	187 °C (370 °F)	–
Tires (AlAwad et al., 2018)	Granular	~1.15	90 °C (194 °F)	90 °C (194 °F)	Very low price and high availability

new tool to predict the yield point, plastic viscosity, apparent viscosity, and flow behavior index for water-based drilling fluids using real measurement data of Marsh funnel viscosity, density, and solid percent. This data is frequently measured and available at any rig site. The new tool was based on an artificial neural network method (ANN) and yielded high accuracy prediction with an average error of less than 6%. A similar study was conducted by Alsabaa et al. (2020) to predict these properties for invert emulsion muds and yielded satisfactory results with an error of less than 5.7 %. These studies can be further extended by collecting more data on the mud systems used in geothermal drilling and developing more accurate models to predict the rheological behavior under the surface and downhole conditions. Moreover, such tools can easily be integrated with automated drilling operations that could help take timely actions.

One of the main advances in rheology measurement is developing automated monitoring systems that provide a continuous measurement of mud density and viscosity in laboratories and fields (Vajargah et al., 2016). These systems reduce human interaction and provide accurate data. Dotson et al. (2017) introduced an automated system to frequently measure and monitor the rheology and density of drilling fluid at the rig site. The unit is called the Density Rheology Unit (DRU). It consists mainly of densitometer and concentric viscometer. The fluid patch enters the densitometer and viscometer after a specific period, depending on the user-defined test temperature and initial fluid temperature. The rheology measurements are conducted at the API recommended speeds of 600, 300, 200, 100, 6, and 3 RPM. The fluid sample is pressurized to collapse large air bubbles and ensure accurate measurements. The system has been validated and tested on onshore and offshore rigs. Vajargah and Van Oort (2015) proposed a new method to predict the rheological behavior of drilling fluid under downhole conditions using pressure sensor data. The new method considers the wellbore as a large pipe viscometer. The proposed method was validated with field data obtained from downhole pressure sensors connected to a wired drill pipe. Implementing such methods in geothermal drilling would provide more accurate predictions for drilling fluid properties. However, the real challenge is the design and development of downhole tools that can work safely and efficiently under the harsh conditions of geothermal wells.

3.3. Rheology models

Rheology models describe the flow behavior of drilling fluids governed by the relationship between shear stress and shear rate. Based on their rheology, fluids are classified into two main categories, Newtonian and non-Newtonian fluids. Drilling fluids are considered non-Newtonian fluids when the relationship between shear stress and shear rate is nonlinear at a given pressure and temperature (Skelland, 1967). Several models are developed to describe the flow characteristics of non-Newtonian fluids. The most popular rheology models used for drilling fluids are the Bingham plastic model, Power Law model, and Herschel-Bulkley model (Clark, 1995; Hajiabadi et al., 2019; Okafor and Evers, 1992; Skelland, 1967). Selecting the best model that provides accurate predictions of frictional pressure losses is necessary to improve wellbore pressure management and well design. Hajiabadi et al. (2019) studied the rheological behavior of oil-based mud treated with carbon-based nanomaterials using the conventional rheology models. They found that the Carreau model outperformed the other traditional models in terms of accuracy in describing the fluids. Nasiri and Ashrafizadeh (2010) proposed a new correlation to predict the rheological parameters of drilling fluid by introducing an additional logarithmic term. The new model was compared with the common rheology models used for drilling fluids. Another mathematical model was developed by Andaverde et al. (2019) to analyze the drilling fluid rheology used in petroleum and geothermal industries based on a nonlinear fit of the measured data of shear stress and shear rate. The new model was tested on 87 sets of experimental data, and a good match with 81 % of the data was observed. Table 4 summarizes the common rheology models that can be used with drilling fluids. The recent advances in drilling fluid and the critical downhole conditions of geothermal wells increase the complexity of rheological behavior and the urge for more studies to better characterize and understand the rheological behavior of such complex mud systems (Adewale et al., 2017).

4. Summary

The hard fractured-formations and high temperatures encountered while drilling in geothermal reservoirs always present many challenges for drilling engineers and drilling companies. These challenges are associated with drilling fluid, casing, cement, formation, and downhole hole equipment, which pushed the geothermal industry towards inventing more sound technologies to meet such requirements. These challenges were addressed in section 1.1.

The drilling fluid rheology is an essential factor in the success of drilling operations. As well addressed in the literature and from the experimental results presented in this paper, drilling fluid properties are significantly impacted by temperature. Therefore, great efforts should be put into optimizing and monitoring the drilling fluid rheological properties under that critical downhole conditions to ensure safe and successful operations. The importance of rheological properties is evident from their impact on many drilling parameters such as fluid stability, hole cleaning, wellbore hydraulics, rate of penetration, and lost circulation. The mechanisms and effects of fluid rheology on these parameters were discussed in section 2, along with some research and field studies.

In the early stages of the geothermal industry, drilling operations were performed using simple drilling fluid systems that consist of water and bentonite clay. Polymeric additives and other clay types such as sepiolite were introduced to the drilling fluid systems to mitigate the issues encountered with simple drilling fluid systems, such as high fluid losses and flocculation. To access more and deep geothermal resources, researchers and engineers put great efforts into developing more practical and efficient drilling fluid systems by introducing new additives to the drilling fluid formulation. However, these advancements increased the complexity of the fluid mixture, which made it more challenging to characterize, predict, and understand the rheological behavior of such fluid systems using the classic old viscometers and rheology models at high-temperature conditions. The recent advancements in drilling fluid systems, rheology measurements, and rheology models were discussed in section 3.

5. Conclusions

Based on this review, the following conclusions can be drawn:

- The harsh environment encountered in geothermal wells makes the drilling operations a challenging task. These critical conditions pushed the industry to its limit in selecting the material for drilling fluid, casing, cement, and downhole equipment to withstand the high temperature and pressure.
- The resemblance in drilling operations between the oil and geothermal industries and the lack of technology development in the geothermal industry encouraged the knowledge and technology transfer from the oil industry. This transfer would effectively mitigate the challenges and minimize the high cost of geothermal drilling in order to increase the feasibility of geothermal projects.
- Drilling fluid rheology plays a vital role in geothermal drilling and impacts many drilling parameters such as hole cleaning, wellbore hydraulics, penetration rate, and drilling fluid stability; however, little attention is given to the drilling fluid rheology. Therefore, researchers should pay more attention to fully understand the rheological behavior, especially under the critical downhole conditions of geothermal wells, and how improving and monitoring the

Table 4
Common rheology models.

Model	Equation	Remarks
Bingham plastic	$\tau = \tau_0 + \mu_p \gamma$	- Simple model - Cannot describe complex mud system, especially highly pseudoplastic suspension, where the relationship between shear stress and shear rate is nonlinear.
Modified Bingham plastic	$\tau = \tau_0 + \mu_p \gamma + c\,\gamma^2$	- Describes the nonlinear behavior better than the Bingham model - Cannot describe highly shear-thickening fluid (n>2)
Power law	$\tau = K\,\gamma^n$	- Easy to use - Ideal for shear-thinning fluids
Herschel-Bulkley	$\tau = \tau_0 + K\,\gamma^n$	- Describe the nonlinear relationship between shear stress and shear rate - The consistency parameter cannot be determined directly from the fluid measurements - Curve fitting may yield different sets of K and n for the same data - Underestimate yield stress values of shear-thinning fluids - Overestimate yield stress values for shear-thickening fluids.
Modified Herschel-Bulkley by Nelson and Ewoldt	$\tau = \tau_y \left[1 + \left(\frac{\gamma}{\gamma_c}\right)^n\right]$	- Adequate accuracy for 3D printing materials - Not accurate for low yield stress fluids - It is difficult or sometimes impossible to present the shear rate where the shear stress is twice the yield stress - Requires more measurements than other models to estimate the parameters, which makes it impractical when using field viscometers.
Modified Herschel-Bulkley by Saasen and Ytrehus	$\tau = \tau_y + \tau_s \left(\frac{\gamma}{\gamma_s}\right)^n$	- Uses a dimensionless form of shear rate - Solves the problem of estimating Herschel-Bulkley parameters (K and n).
Robertson-Stiff	$\tau = K(\gamma + b)^n$	- Fit drilling fluid data better than Bingham plastic and Power-law models - Good for cement slurries and more accurate than Herschel-Bulkley - The wall shear rate and pressure-drop/flowrate relationship are valid only for fluids with zero yield stress.
Casson	$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\mu_p \gamma}$	- Used to describe the flow of viscoelastic fluids - Has a more gradual transition from Newtonian to the Yield region - Fit drilling fluid data better than Bingham plastic, Power-law, and Herschel-Bulkley models.
Sisko	$\tau = \mu_\infty \gamma + K\,\gamma^n$	- Three-parameter model - Useful in describing flow in the Power law and upper Newtonian regions - Less accurate than Casson model.
Nasiri-Ashrafizadeh	$\tau = \tau_0 + b\,\gamma + K\,\gamma^{(n-m)}\ln\boxed{f_0}(1+\gamma)$ Where, $0 \le m \le 1;\ 0 \le n \le 1$ $\tau_0 \ge 0; b \ge 0$	- A hybrid model of Bingham plastic, Power-law, and Herschel-Bulkley models with a logarithmic correction factor - Can describe the rheological data of drilling fluids adequately - Overcomes the problem of infinite viscosity at zero shear rates.

rheological properties would impact the efficiency and total cost of drilling operations.

- Great efforts should also be put into selecting the best model that describes the rheological behavior of drilling mud to accurately predict the pressure losses and wellbore hydraulic parameters that significantly impact hole cleaning, fluid stability, and loss circulation events.
- A research study should be conducted by integrating experimental and simulation work to determine the optimum drilling parameters before commencing the drilling operations to minimize complications and ensure satisfactory results in real-field applications.
- Drilling engineers should consider all the drilling aspects when trying to solve drilling-related issues, especially when the solution includes altering the rheological properties or introducing a new additive/mud system to the geothermal well, because variations in rheological properties may trigger other issues and in turn delays and increases the drilling cost.
- Despite the increasing number of geothermal projects worldwide, more research is needed to develop and implement sound strategies for drilling operations to tackle the associated challenges. More technological advancements in drilling fluid systems, data analysis, continuous monitoring for rheological properties, analytical and numerical rheology models, and automated operations are still required for geothermal drilling.

Declaration of Competing Interest

The authors declare no conflict of interest.

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