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Evaluation of Ultra-high Temperature Swelling-Delayed Preformed Particle Gel for the Preferential Fluid Flow Control in Geothermal Reservoirs

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ABSTRACT

Enhanced geothermal systems (EGS) are emerging as a promising carbon-neutral energy source. However, the short-circulation in some geothermal reservoirs diminishes heat extraction efficiency and production lifespan. Natural and hydraulic fractures introduce significant heterogeneity in the reservoir, making injected cold fluid to direct quick flow through super-K channels or fractures, thus limiting heat-extraction efficiency. Therefore, plugging unexpected fractures is vital to mitigate heterogeneity and increase heat recovery. Polymer gel treatment is a common method to be applied in oil and gas reservoirs, which can also reduce undesirable flow in geothermal reservoirs. Current particle gels can remain stable in hydrothermal conditions (greater than 150 °C) for several months but at a rapid swelling rate, confining its transport ability gel. Supported by DOE, we are developing a novel swelling-delayed high-temperature preformed particle gel (HT-PPG) and evaluating the effect of temperature on swelling behavior, mechanical strength, and long-term hydrothermal stability. The dried gel can swell over 60 times its original weight, and the elastic modulus of the fully swelled gel can reach over 4000 Pa at room temperature at a swelling ratio of 22; after 3 months of aging at 150℃, the swelling-delayed HT-PPG(HT-DPPG) still has the gel strength of 340 Pa at a swelling ratio of 60. HT-DPPG offers a promising approach to control swelling rates, enabling it for preferential fluid flow control in geothermal reservoirs.

1. INTRODUCTION

Fossil fuels, including coal, petroleum, and natural gas, have historically been the primary energy sources. Recent data indicates a 1.1% increase in carbon dioxide emissions from the previous year (2023). This trend continues to raise concerns about the environmental consequences of relying on traditional energy sources, emphasizing the importance of transitioning to more sustainable energy alternatives.

Compared to fossil fuels, geothermal energy has many advantages, like renewable energy and cost efficiency. Fractures are the principal conduits facilitating heat transfer between the rock matrix and the recovery fluid, typically water, in geothermal systems (Villaquiran, 2023). However, the nature and hydraulic fractures inevitably lead to heterogeneity, which causes short-circulation problems, decreasing heat-transition efficiency between rock and displacing flooding. Short-circulation has been discussed for many years in the petroleum and natural gas industry; chemical treatment was widely applied in mature and harsh oilfields, which can divert post-flooding to unswept fractures. The low density, cost-effectiveness, and good injectivity make high-temperature resistant foam a feasible way to block the high-permeability zones and divert post-flooding into low-permeability zones in heterogeneous reservoirs with steam. However, the foam treatment has a limited resistance factor of around 200, and the stability is affected by many factors, so it is not easy to apply the far wellbore in long-term production (Li, 2011). The in-situ gel treatment has good injectable capacity (Sydansk, 1988; Hutchins, 1996; Morgan, 1997). However, the inevitable shear degradation and chromatographic fractionation in far wellbore transportation can not be fixed properly in metallic crosslinkers (Cr3+), phenol–formaldehyde, and polyethyleneimine systems, resulting in a limited plugging efficiency. Meanwhile, those methods also have a temperature limitation of 140 °C in oil reservoirs.

The preformed particle gel (PPG), a novel technology for conformance control, has a 3D network and can only absorb brine without dissolving. PPG has been applied to treat excessive water production at high temperatures. However, the conventional PPG can achieve a full swelling ratio quickly, leading to potential dehydration and potentially decreasing the plugging efficiency in far-wellbore opening fractures (Song,2018). In contrast, Swelling-Delayed PPG maintains a small size with a controllable swelling rate during injection, effectively reducing injection pressure and associated costs in the near well-bore transportation process. Subsequently, these gels undergo slight dehydration during placement, a crucial factor in maintaining effective plugging efficiency (Sun and Bai, 2017). Finally, Swelling-Delayed PPG effectively plugs super-high permeability channels and diverts the post-water flow in the unswept channels, enhancing heat-transition efficiency and reducing excessive water production by short-circulation.

Our team has developed a novel, ultra-high temperature-resistant swelling-delayed preformed particle gel. This HT-DPPG with a controllable swelling rate can achieve the full swelling ratio after 31 days at 150 °C and maintains stability for over 3 months, ensuring efficient delivery into a reservoir with a small size in a few days. In this work, we have incorporated a crosslinker that can control the swelling ratio at high temperatures into the previously stable HT-PPG, which can withstand 200 °C for 180 days (Song, 2023). Moreover, we evaluated the swelling-delayed PPG(HT-DPPG) regarding swelling kinetics, thermal stability, gel strength, and plugging efficiency.

2. METHODS

2.1 Synthesis of HT-DPPG

The HT-DPPG was synthesized in our laboratory using free radical polymerization, incorporating two types of crosslinkers: a temperature-labile crosslinker and a thermally stable crosslinker. Detailed synthesis methods are described in our previous publication(Salunkhe et al. 2021).

2.2 Swelling Kinetics

The swelling kinetics was tested to measure the dried HT-DPG volume changed in brine over time. 0.5 g dried HT-DPPG in 1-2 mm was placed in 2 wt.% KCl solution at room temperature. This is followed by the Swelling ratio(SR) multiple measurements at various times. SR was defined by equation(1), where cap V sub t is the volume of the swollen HT-DPPG, and cap W sub i is the initial weight of dried HT-DPPG.

$$SR = \frac{V_t}{W_i} \quad (1)$$

2.3 Rheological behavior

In this study, the Haake MARS III rheometer (Thermo Scientific Inc.) was used to test the rheological properties of HT-DPPG. The spindle was a P35Ti L, with a gap established at 1 mm. The linear strain region was identified via strain-sweep experiments. We determined the elastic modulus of the polymer gels through time-dependent oscillation experiments conducted at a constant frequency of 1 Hz and a controlled strain of 1%. Each sample underwent the gel strength test three times to ensure reliability.

2.4 Hydrothermal Stability Test

Glass sample containers, capable of withstanding high pressure and temperature, were employed, featuring thermally stable O-rings (Ultra-Chemical-Resistant High-Purity Kalrez 6230 O-Ring, McMASTER-CARR, and AA2802 Viton O-Ring - Dash 110, fixsupply) and stainless steel sample cylinders (Swagelok, 304L-HDF2-40). These apparatuses facilitated the assessment of the hydrolytic thermal stability of the polymer gels. Before the aging test, oxygen was meticulously removed.

2.5 Core Flooding Test

A granite sample was utilized in the experiment designed to evaluate the effectiveness of HT-DPPG for plugging fractures. This sample was first dried in an oven to remove any residual water. Following this, it was subjected to a vacuum treatment for 24 hours and then saturated in a 2% KCl solution at ambient temperature.

Figure 1 presents a diagram of the core flooding test setup. It shows the placement of the granite core within a core holder, subjected to a confining pressure of 700 psi. The core was flooded with a 2% KCl solution with different injection flow rates during the test. Throughout this process, stable pressure gradients were monitored, allowing for calculating the granite core permeability under Darcy's law. After completing this phase, the core was carefully removed, split evenly, and fitted with stainless steel strips, each 0.77 mm thick and firmly adhered to its surface. Finally, the core was wrapped in a Teflon sheet for further analysis.

This fractured core was again flooded with 2% KCl at a constant 1.0 cm³/min flow rate until a stable pressure gradient. HT-DPPG, a swelling ratio of 10 in 2% KCl, was injected through the fracture at a rate of 0.5 cm³/min using the syringe pump. After the stabilization of the gel injection pressure gradient, post-water injection at varied flow rates was performed to evaluate the plugging efficacy of HT-DPPG by residual resistance factor (Frr) shown in equation(2), where K_{i} is the initial permeability, K_{a} is the gel-treated permeability.

$$F_{\mathrm{rr}} = \frac{K_{\mathrm{i}}}{K_{\mathrm{a}}} \quad (2)$$

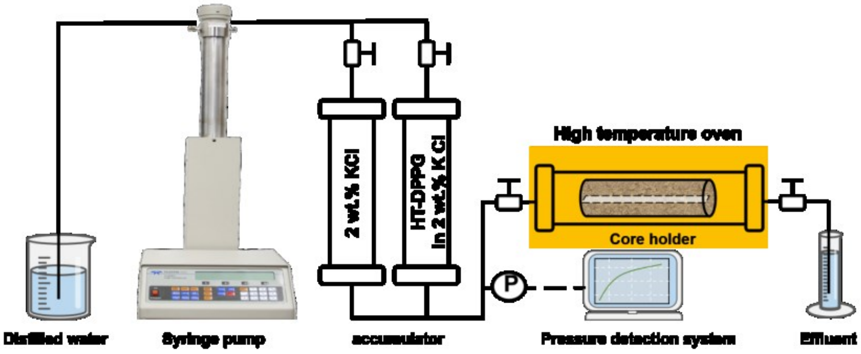

Figure 1. Set up of core flooding experiment.

3. RESULTS AND DISCUSSION

3.1 Swelling Kinetics

Figure 2(a) illustrates the effect of different salt concentrations on the swelling kinetics of HT-DPPG. The figure indicates that HT-DPPG achieves its maximum swelling ratios of 22 in a 2% potassium chloride (KCl) solution, 25 in a 1% sodium chloride (NaCl), and 20 in a 1% calcium chloride ($CaCl_2$) solution. Moreover, the drying particles typically reach these swelling peaks within approximately 120 minutes at room temperature. Initially, the swelling process is rapid but slows down over time as the concentration gradient between the gel matrix and the solvent diminishes(Fariba, 2010). Additionally, Ca2+ has a more substantial effect than K+ and Na+ on restricting the maximum swelling ratio because of counter-ions osmotic pressure (Vervoort,2005).

Figure 2(b) shows the effect of temperature on swelling kinetics. At room temperature, HT-DPPG reached full swelling ratio in 16 h submerged in a 2% KCl solution. However, as the temperature exceeds 130 °C, the swelling ratio of HT-DPPG accelerates. Furthermore, the higher the temperature, the higher the full swelling ratio.

Moreover, the 31-day swelling-delayed phenomenon observed at 150 ° C facilitates the mobility of HT-DPPG in small-sized, non-sticky particles during flooding, reducing the contact area with fractures to prevent capture and dehydration by the fractures. This is attributed to the characteristics of the two crosslinkers in the recipe. Both exhibit good stability at room temperature, effectively restricting the swelling ratio. However, one of these crosslinkers is temperature-sensitive and is designed to degrade within 31 days, while the other maintains excellent thermal stability over 3 months.

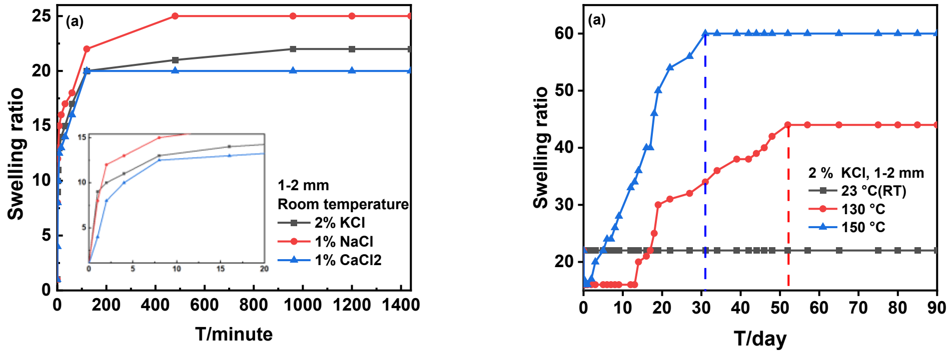

Figure 2. Effect of (a)salinity and (b)temperature on the swelling kinetics of HT-DPG

3.2 Rheological behavior

The gel strength was evaluated by elastic modulus(G') in the linear viscoelastic region. Figure 3 presents the effect of swelling ratio and types of salinity. The elastic modulus decreases with increasing swelling ratio but is slightly affected by the salinity. The G' of HT-DPPG in 2%KCl, 1%Nacl, and 1%CaCl2 were 4220, 3830, and 3940 Pa, respectively. When HT-DPPG reaches the maximum swelling ratio, it can be stable without increasing. After 3 months of aging at 150 °C, it still had an elastic strength of 340 Pa to plug the fractures, as shown in Figure 3. That means two different crosslinkers in the recipe play different roles, both can restrict the initial swelling ratio to present high elastic strength; via aging at 150 °C, the liable crosslinking bond degraded, but the thermal stable crosslinking bond still preformed particle structure.

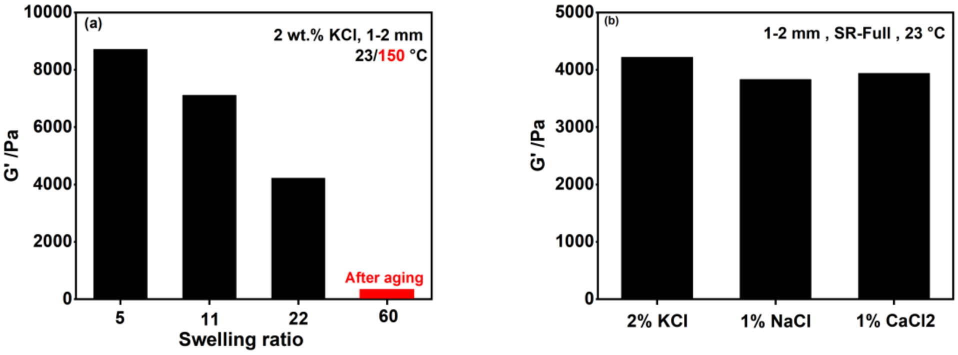

Figure 3. Effect of (a) swelling ratio, (b) salinity on the gel strength on elastic modulus

3.3 Hydrothermal stability

The thermal stability of HT-DPPG affects the gel treatment lifetime and plugging efficiency. So, we evaluated the swelling kinetics and hydrothermal stability at 150 °C, lasting 3 months. As shown in Figure 4, we observed boundaries between particles, staying in a particle structure with clear boundaries. That is because one of the crosslinkers has good hydrothermal stability, which we have already reported(Song, 2023).

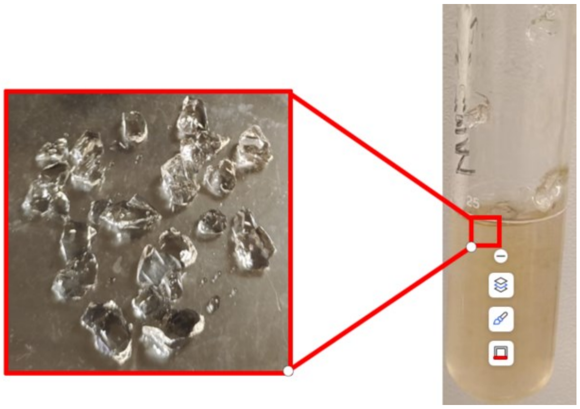

Figure 4. Gel aging appearance after 3 months

3.4 Core Flooding Test

Figure 5 indicates the gel injection pressure gradient and breakthrough pressure. The observed stable injection pressure was 138.56 psi/ft, influenced by the size of dried HT-DPPG and the width of the fracture. Thoroughly degraded, achieving a maximum swelling ratio of 60; the water breakthrough pressure gradient during the post-flooding procedure was 18.62 psi/ft. Subsequently, varying injection rates of 0.1, 0.25, 0.5, and 1 mL/min were used to assess the plugging efficiency of HT-DPPG in fractures, yielding stable pressure gradients of 7.68, 8.12, 10.52, 14.67, and 15.01 psi/ft, respectively. Following the full swelling of HT-DPPG and its placement in the opening fractures, formation permeability was dramatically decreased. Moreover, the residual resistance factor was noticed as a parameter in the post-flooding process(Song,2023), and the plugging efficiency in the post-flooding process was high, exceeding 99.999%, attributed to the significant reduction in permeability, shown in **Error! Reference source not found.**.

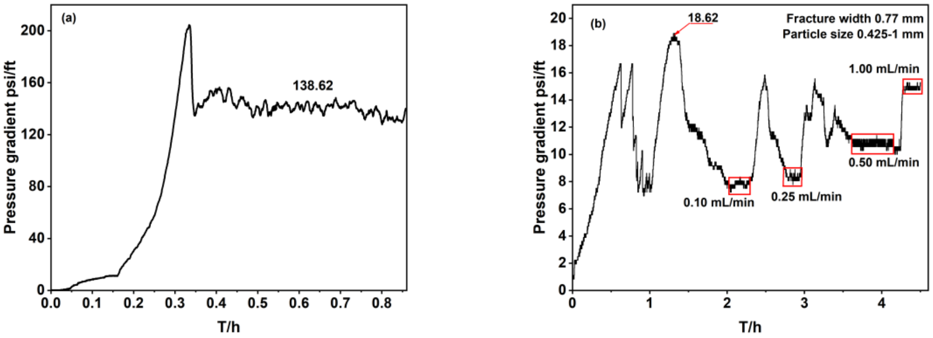

Figure 5. (a) Gel injection, (b) Water breakthrough test

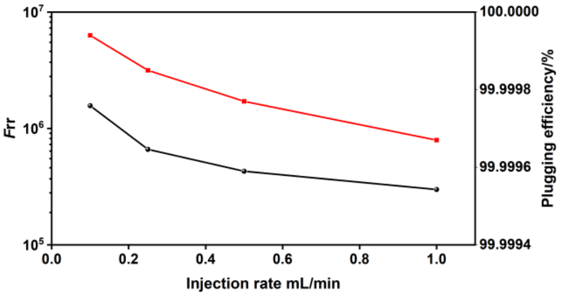

Figure 6. The residual resistance factor and plugging efficiency of HT-DPPG

4. CONCLUSION

This paper investigates the swelling kinetics of the novel HT-DPPG at both room and high temperatures, its rheological behavior, long-term hydrothermal stability, and plugging efficiency. This delayed-swelling particle gel demonstrates a maximum swelling ratio of 22 at room temperature and 60 at 150 °C in 2% KCl solution. It is noted that the fully swollen elastic modulus of both the initial and aged HT-DPPG exceeds 4000 and 300 Pa, respectively, exhibiting a delayed swelling phenomenon of over 30 days. Following a 3 months hydrothermal test, it still forms a 3D network at 150 °C.

Moreover, the core flooding test showed a plugging efficiency of over 99%. Our delayed-swelling HT-PPG offers a promising approach for controlling swelling rates, which is crucial for effectively plugging super-K channels and diverting post-flooding into unswept fractures in geothermal reservoirs.

5. FUTURE WORK

We will test the current HT-DPPG at the current temperature for longer time observation and at a higher temperature (200 °C) to observe swelling kinetics and hydrothermal stability.

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