

Development of Fluid Flow Control Technology Using Thermoresponsive Gel

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ABSTRACT

In geothermal development, fluid flow localization within reservoirs leads to heterogeneous temperature distributions and uncurtains extraction of geothermal resources. This reduces overall heat extraction efficiency and hinders stable steam production. To address issue of fluid flow localization, we propose a novel fluid flow control approach using a thermoresponsive fluid whose properties change with temperature. This functional fluid responds to local temperature of reservoir, promoting uniform flow distribution, homogenizing the temperature field, and enabling stable steam production. A thermoresponsive gel that shows a remarkable increase in hardness upon heating has recently been developed. Its Young's modulus rises to 1,800-fold before and after the transition. At the injection of this functional fluid as slurry to reservoir, the gel remains soft near the low-temperature region around the injection well. In contrast, under higher temperature conditions, the gel hardens. This causes flow path plugging through bridging and interlocking of solid particles. Consequently, the flow can be redirected toward low-permeability zones. This redirection leads to a more uniform temperature distribution. Such fluid flow control is expected to improve heat extraction efficiency and stabilize steam production. This study experimentally evaluates the feasibility of this idea. To evaluate the plugging performance under different gel hardness states at room and elevated temperatures, we conducted permeability tests in an artificial fracture under confining pressure with a slurry containing thermoresponsive gel particles, which particle size satisfied bridging conditions. The slurry was injected into flow model while injection pressure and cumulative discharge were measured. At elevated temperature, an early pressure rise was observed, while at room temperature, the pressure increase was slower. These results indicate that the hardened gel plugged flow path more rapidly and resisted fluid pressure better than the soft state. In summary, the thermoresponsive gel shows potential for reservoir fluid flow control. Future work will include permeability tests involving multiple flow paths with different permeabilities to evaluate the feasibility of fluid flow control.

1. INTRODUCTION

In geothermal development, fluid flow localization often occurs due to differences in permeability among flow paths within a geothermal reservoir. Laboratory experiments on single fracture with heterogeneous aperture distribution have demonstrated that channeling flow indicating fluid flow localization can occur (Ishibashi, Watanabe, et al., 2014). At a larger scale, tracer tests conducted in fractured rock masses (Tsang and Neretnieks, 1998) and analyses based on microseismic data obtained from EGS projects (Mukuhira et al., 2017) confirmed the occurrence of fluid flow localization in actual field. Such fluid flow localization can induce a short circuit, in which injected fluid preferentially flows through high-permeability flow path between the injection and production well. This process causes rapid cooling of the high-permeability flow path due to excessive heat extraction from surrounding rock mass of that flow path. As a result, low-temperature fluid is produced in production well.

In the HDR project conducted at Hijiori, Japan, the temperature of the produced fluid decreased from 163 °C to approximately 100 °C within about four months during a circulation test and subsequent numerical analyses suggested that this rapid temperature decline was induced by short circuit (Tenma et al., 2008). Similar behavior has been reported at the Rosemanowes in the UK and the Soultz in France. In these projects, more than half of the injected fluid flowed through specific flow paths (Parker et al., 1999; MIT, 2006). Thus, short circuit reduces the temperature of the produced fluid and hinder stable steam and hot water production. This represents a critical challenge for efficient geothermal development.

Conventional countermeasures against short circuit include temporary termination of water injection and modification of injection patterns. However, long-term maintenance of sufficient steam and hot water production remains difficult. This limitation negatively affects the economic performance of geothermal power generation, and such operation does not fundamentally connect to problem solution.

In this study, a novel fluid flow control approach is proposed to mitigate fluid flow localization at short circuit in geothermal reservoirs. The proposed approach aims to control fluid flow using a functional fluid that changes its properties in response to temperature. By injecting this functional fluid into the reservoir, its properties change in response to the reservoir temperature, thereby dispersing the flow within the reservoir. As a result, the temperature of the high-permeability flow path recovers, and the temperature distribution within the reservoir becomes more homogeneous. Consequently, this leads to recovery of the temperature of the produced fluid.

The concept of the proposed fluid flow control approach is explained. In recent years, the thermoresponsive gel that is soft at low temperatures and hardens at elevated temperatures has been developed (Nonoyama et al., 2020). This gel consists of polyacrylic acid (PAAc) and calcium acetate (CaAc). Its Young’s modulus increases dramatically from 0.07 MPa at 20 °C to 119 MPa at 70 °C, representing an increase of approximately 1,800-fold. When short circuit is suspected, the gel is injected into the reservoir as a slurry (Fig. 1). The gel slurry will preferentially flow into high-permeability flow path with large aperture. Since the injected fluid is cold, the reservoir temperature near the injection well is low. In addition, the high-permeability flow path where short circuit occur are also cooled due to fluid flow concentration. Under these conditions, the injected gel remains soft while flowing through high-permeability flow path. As temperature increases along the high-permeability flow path far from the injection well, the gel hardens. The hardened gel is expected to plug high-permeability flow path by particle-based bridging and interlocking. Bridging refers to the formation of an arch-like particle structure that plugs a flow path. The probability of bridging increases significantly when the particle diameter exceeds one-sixth of the flow path diameter (Hafez et al., 2021). Interlocking occurs when particles with non-spherical or complex shapes mechanically engage with each other. Selective plugging of high-permeability flow path becomes possible through this flow control process. After plugging, the injected fluid is switched to water or another fluid. Flow into the plugged high-permeability flow path is suppressed and fluid flow is redirected toward low-permeability flow path, which is expected to retain higher temperature. The temperature of the previously plugged high-permeability flow path gradually recovers as flow is suppressed and heat can be supplied from surrounding formation by convection. The temperature of the produced fluid therefore increases, and the severity of short circuit is relieved.

Based on this concept, improvement of heat extraction efficiency and stable steam production can be expected by fluid flow control using thermoresponsive gel. The objective of this study is to experimentally evaluate the feasibility of fluid flow control using thermoresponsive gel. As a fundamental step, flow path plugging behavior is evaluated for gel with different hardness under room temperature and elevated temperature condition

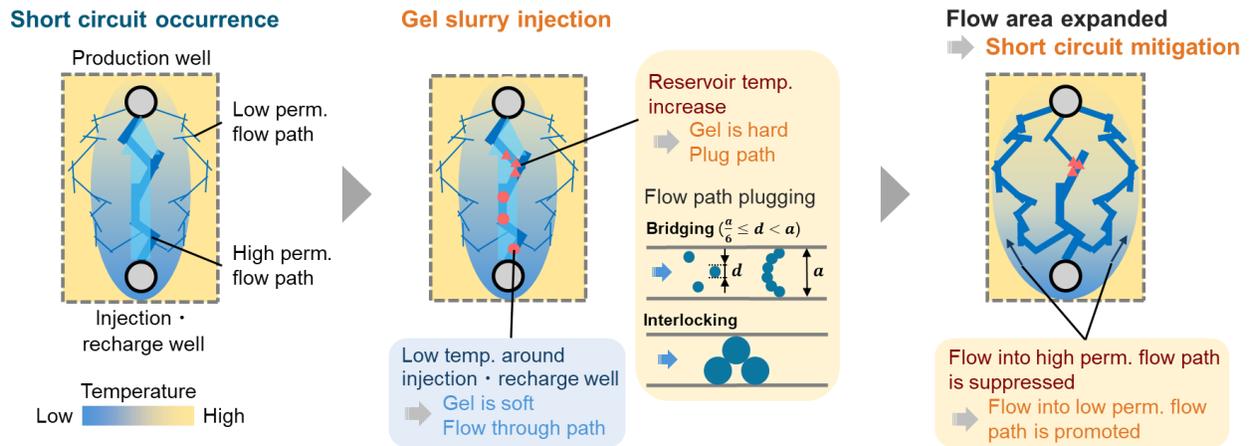


Figure 1: Conceptual illustration of fluid flow control technology using thermoresponsive gel for short circuit mitigation. The schematic represents a horizontal cross section of geothermal reservoir.

2. METHODOLOGY

To evaluate flow path plugging behavior associated with differences in gel hardness under room temperature and elevated temperature condition, we conducted laboratory permeability tests with constant flow rate in a fracture under confining pressure. A slurry containing gel was used as the injection fluid. Plugging behavior was evaluated based on temporal changes in injection pressure and cumulative discharge.

The experimental system consisted of the flow path model, a syringe pump for slurry injection, a syringe pump for applying confining pressure to the flow path model, a pressure vessel housing the flow path model, a blender, a mantle heater, a thermocouples, a temperature controller, a strain-gauge-type pressure sensor for measuring injection pressure, a scale for measuring discharged slurry (Fig. 2). The flow path model is a metal parallel plate to simulate a subsurface fracture. It consists of two halved aluminum cylinders with a stainless-steel foil inserted between them. This model forms a parallel plate flow path through which slurry flows. The fracture aperture is controlled by changing the thickness of the stainless-steel foil. After experiment, the flow path model can be disassembled to observe particle deposition

within the flow path. The blender discharges slurry by advancing a piston through hydraulic pressure supplied by a syringe pump. Continuous mixing maintains a uniform particle distribution in the slurry during injection. The gel particle diameter was set to 20 μm to satisfy the bridging condition during gel hardening (Fig. 3). A 20wt% calcium acetate aqueous solution was used as the dispersion medium to ensure sufficient gel dispersibility and flexibility. The mantle heater temperature was set to 75 $^{\circ}\text{C}$ based on preliminary permeability test. This setting ensured that the slurry temperature exceeded the gel hardening temperature of 70 $^{\circ}\text{C}$ at the inlet of the flow path model.

A slurry containing 1 vol% gel was injected at a constant flow rate of 10 mL/min. The fracture aperture was 0.1 mm, the fracture width was 5 mm, and the fracture length was 25 mm. Previous studies have reported that, in fractured systems, fracture permeability differences exceeding two orders of magnitude are commonly observed between high- and low-permeability flow paths (Bauer et al., 2019). To identify significant plugging, fracture permeability needed to decrease by at least two orders of magnitude. Here, the fracture permeability k is expressed as follow (Witherspoon et al., 1980):

$$k = \frac{a^2}{12} \quad (1)$$

where a is fracture aperture, which can be calculated from the following equation, known as the cubic law.

$$a = \left(\frac{12QL\mu}{w\Delta P} \right)^{\frac{1}{3}} \quad (2)$$

where Q , w , L , μ , ΔP are flow rate, fracture width, fracture length, fluid viscosity and differential pressure over the fracture length L , respectively. Based on the cubic law, slurry injection was continued until injection pressure reached 3 MPa, corresponding to an approximately two-order-of-magnitude reduction in fracture permeability relative to the initial fracture permeability (from $8.3 \times 10^{-10} \text{ m}^2$ to $1.9 \times 10^{-11} \text{ m}^2$).

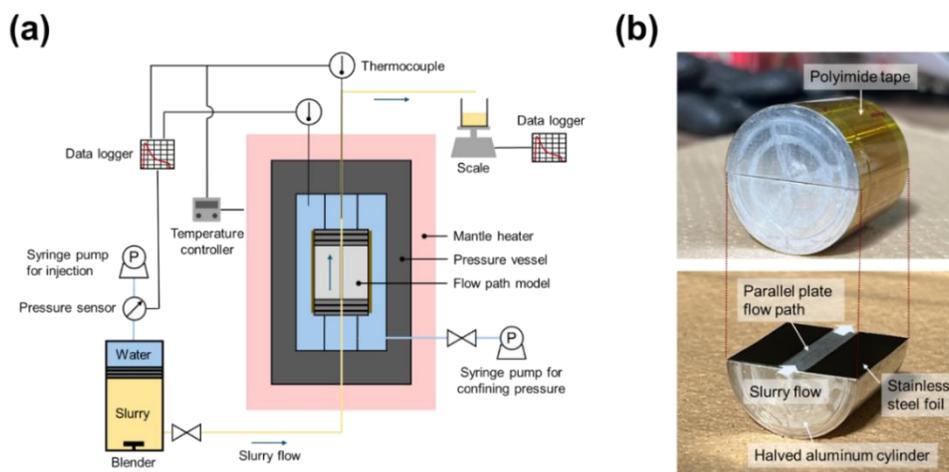


Figure 2: Overview of (a) experimental system and (b) flow path model.

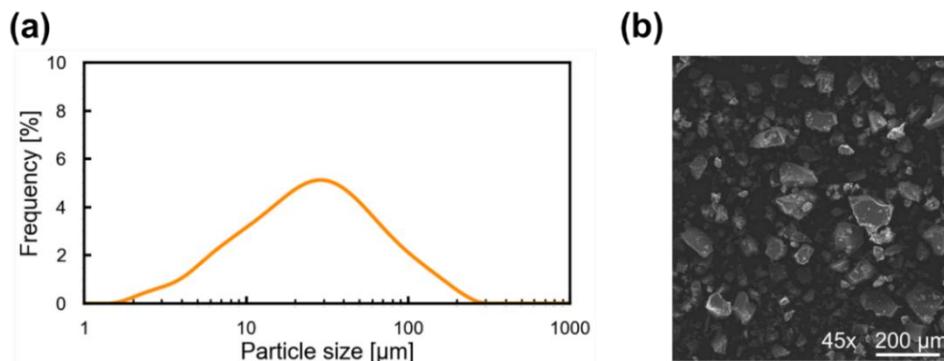


Figure 3: (a) Particle size of thermoresponsive gel in wet condition and (b) SEM image of thermoresponsive gel in dry condition.

3. RESULT AND DISCUSSION

Figure 4 shows temporal changes in injection pressure and cumulative discharge under different temperature conditions of injection fluid. When the temperature of injection fluid was 70 °C, corresponding to the thermally hardened state of the thermoresponsive gel, injection pressure started to increase 2 minutes after the start of measurement. The pressure reached 3 MPa after 4.5 minutes. When the injection temperature was 20 °C (room temperature), corresponding to the soft state of the gel, injection pressure started to increase 8 minutes after the start of measurement. At 9.5 minutes, injection pressure decreased from 1.2 MPa to 0.5 MPa. Injection pressure then increased again and reached 3 MPa at 10.5 minutes. Thus, when the gel was thermally hardened, the start of injection pressure increase occurred earlier. A pressure drop was observed only when the gel remained soft.

In addition, with respect to cumulative discharge, when the temperature of injection fluid was 70 °C, corresponding to the thermally hardened state of the gel, the slope of the cumulative discharge decreased as injection pressure increased. In contrast, when the injection temperature was 20 °C, corresponding to the soft state of the gel, the cumulative discharge became constant as injection pressure increased.

After the experiments, the flow path model was disassembled and observed at room temperature. The temperature of injection fluid was 70 °C, corresponding to the thermally hardened state of the gel, gel particle deposition was observed along the flow path from the inlet to the outlet. The accumulation was particularly concentrated near the outlet. In contrast, when the injection temperature was 20 °C, corresponding to the soft state of the gel, gel particle deposition was observed near both the inlet and the outlet of the flow path. The accumulation was particularly concentrated near the inlet.

We interpreted that the gel caused flow path plugging, which led to an increase in injection pressure. This plugging suppressed fluid discharge from the flow path. Focusing on the differences in injection pressure behavior, these differences were attributed to the stability of the plugging structures. When the gel was thermally hardened, gel deformation was limited and interlocking occurred more readily. The resulting plugging structures were stable and resisted fluid pressure. In contrast, when the gel remained soft, deformation occurred easily and interlocking was less effective. The resulting plugging structures were unstable and easily disrupted by fluid pressure.

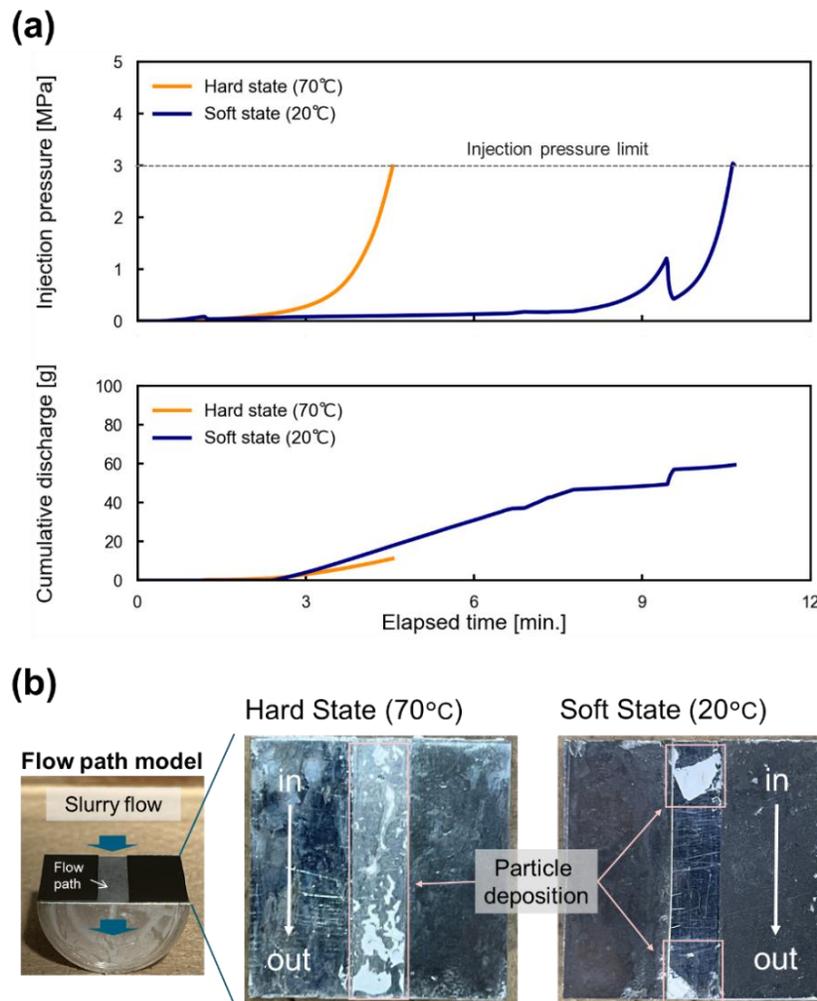


Figure 4: (a) Temporal changes in injection pressure and cumulative discharge under different injection temperature conditions and (b) the condition of the flow path model after permeability test.

4. CONCLUSION

In this study, a novel fluid flow control approach was proposed to mitigate fluid flow localization, which degrades steam and hot water productivity in geothermal reservoir. Laboratory permeability tests were conducted to evaluate flow path plugging behavior associated with differences in gel hardness under room temperature and elevated temperature condition.

The results of experiments showed that flow path can be effectively plugged using thermoresponsive gel in elevated temperature condition and flow path plugging behavior strongly depends on hardness of thermoresponsive gel. Plugging was significantly enhanced under thermally hardened conditions, indicating the formation of stronger and more stable plugging structures. These results suggest that thermoresponsive gel has strong potential as a fluid flow control technology for geothermal reservoir. Future studies will focus on permeability tests involving multiple flow paths with different permeabilities to further evaluate the effectiveness of this flow control approach.

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