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Active Tracers for Hydraulic Control of Cooled Short Circuits

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ABSTRACT

Commercially-successful geothermal systems require balance between thermal and hydraulic performance. An injector-producer well pair with exceptional hydraulic performance, for instance, may have inadequate thermal performance if the effective heat transfer surface area is insufficient. In such a circumstance the current state-of-the-art is to abandon such well pairs once production well temperatures fall below design/operating criteria. Here, an “active” tracer is introduced as a novel solution that enables cooled “short circuits” to be sealed off and circulating fluids to be redirected to hotter flow paths. This treatment increases the effective heat transfer area and subsequently improves thermal performance by increasing production well temperatures. The basic principle is introduced and the anticipated improvement to thermal performance is determined from a hypothetical case in which inlet-outlet short-circuiting causes rapid thermal breakthrough in a non-uniform, two-dimensional fracture. Finally, progress on the development of the active tracer is given.

1. INTRODUCTION

Frictional pressure loss and production well temperature drop are measurable interwell properties that quantify the thermal-hydraulic performance of a given injector-producer well pair. Ideally, the pressure drop is minimal and production well temperatures remain above engineering/design constraints for the planned commercial lifetime of a geothermal system. Unfortunately, injector-producer well pairs with ideal hydraulic performance may be prone to poor thermal performance in situations where the mean fracture aperture is large but the effective heat transfer surface area is small. The conventional reservoir management approach is to avoid such interwell conditions, which can be expensive and overly cautious. Here, a novel approach is introduced in which these “short circuits” are eliminated and circulating fluids are redirected towards more ideal flow paths.

This novel approach relies on introducing an “active” tracer that performs a prescribed action when triggered by an environmental factor. Specifically, the proposed active tracer introduced here undergoes a volume phase transition in which an engineered colloidal particle expands when exposed to temperatures below the critical threshold temperature. Therefore, introducing this active tracer enables hydraulic control of cooled short circuits by sealing off these cold flow paths and redirecting circulating fluids to hotter flow paths. In this article, the anticipated improvements are determined for a hypothetical scenario in which a planar fracture of non-uniform aperture exhibits channeled-flow behavior between an injector-producer well pair separated by 1000 m. The simulation is performed using a hybrid finite-element-boundary-element treatment of advective heat transfer considering the effects of heterogeneous aperture (Fox et al., 2015). In addition to this numerical simulation of heat transfer, progress towards synthesizing such a particle is discussed.

2. ANTICIPATED IMPROVEMENTS TO THERMAL PERFORMANCE

To determine the improvement to thermal performance, the numerical simulator introduced by Fox et al. (2015) is employed to simulate the combined effects of advection and conduction while circulating cold water through a single, hot fracture. Temperature-dependent viscosity and thermal-mechanical effects are assumed to result in offsetting effects and are therefore neglected here. The non-uniform fracture aperture distribution adopted in this analysis resulted from a machine learning algorithm that used joint pressure-tracer calibration to forecast thermal performance at the meso-scale Altona Field Laboratory in Altona, New York (Hawkins et al., 2020). The resulting aperture distribution from the previous study is then upscaled in space such that the injector-producer well spacing is increased by a factor of 71 which results in a well spacing of 1000 m.

The key metric to evaluate this improvement is the increase in thermal breakthrough times for the “post-treatment” case compared to the “pre-treatment” case. The value of this metric is determined through a series of steps, including: 1. Forward model of heat transfer after 90 days; 2. Reduction of fracture aperture by a factor of 40 for finite element nodes corresponding to a hypothetical lower critical solution temperature of 190 °C; 3. Rerun the forward model simulation with the updated fracture aperture distribution; and 4. Compute the difference in thermal breakthrough times for the pre-treatment and post-treatment cases. Three thermal breakthrough times are considered, which are the circulation times, t, corresponding to 1. a 90% reduction in ΔT; 2. A 75% reduction in ΔT; and 3. A 50% reduction in ΔT. The value of ΔT is calculated as $\Delta T(t) = \Phi\left(T_{prod}(t) - T_{inj}\right)$, where Φ is the percent reduction, T_{inj} is the temperature of cold injection fluids, and $T_{prod}(t)$ is the temperature of fluids entering the production well as a function of circulation time. We assume that the initial fracture temperature is uniformly 200 °C and the reinjection temperature is 50 °C, which implies a maximum ΔT of 150 °C. These two assumptions are adopted for both the “pre-treatment” case and the “post-treatment” case. In addition to these temperature boundary/initial conditions, this analysis also assumes that the mass flow rate, rock thermal conductivity, and the density of fluids/rocks are 20 kg/s, 2.5 W/m-K, and 1000/2500 kg/m^3, respectively.

After 90 days of continuous circulation, 2034 of the 7196 finite element nodes drop from an initial temperature of 200 °C to a temperature equal to or below 190 °C. With the modified fracture aperture distribution determined (Figure 1), the forward model of heat transfer (Figure 2) was rerun and the three thermal breakthrough times corresponding to 90%, 75%, and 50% were found to be 14.5 years, >30 years, and >30 years, respectively (Figure 3). For comparison, the pretreatment times were 1.1 years, 3.4 years, and 28.6 years, respectively. At the end of the 30-year simulation period, production well temperatures for the pre-treatment and post-treatment cases were 124 °C and 177 °C, respectively. To summarize, the anticipated thermal lifetime for a system designed to tolerate a 90% drop in ΔT is improved by more than a factor of 13 and a system that tolerates a 75% drop in ΔT will remain above the temperature threshold for at least 30 years.

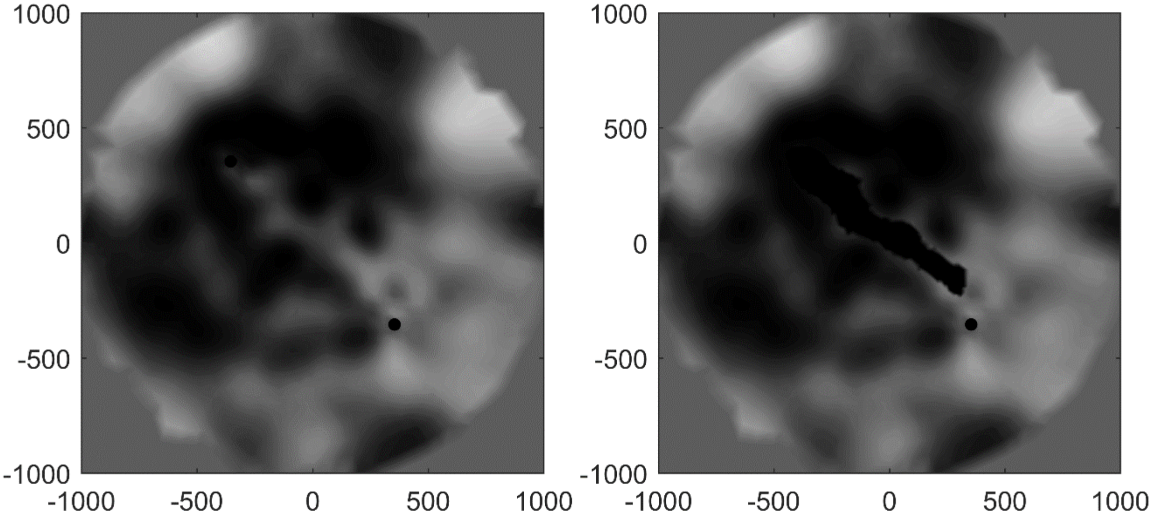

Figure 1: Fracture aperture distribution for the pre-treatment case (left) and the post-treatment case (right). Spatial coordinates are in meters and fracture aperture ranges from a minimum of 0.1 mm (dark colors) to 10 mm (light colors). Original fracture aperture map from Hawkins et al. (2020).

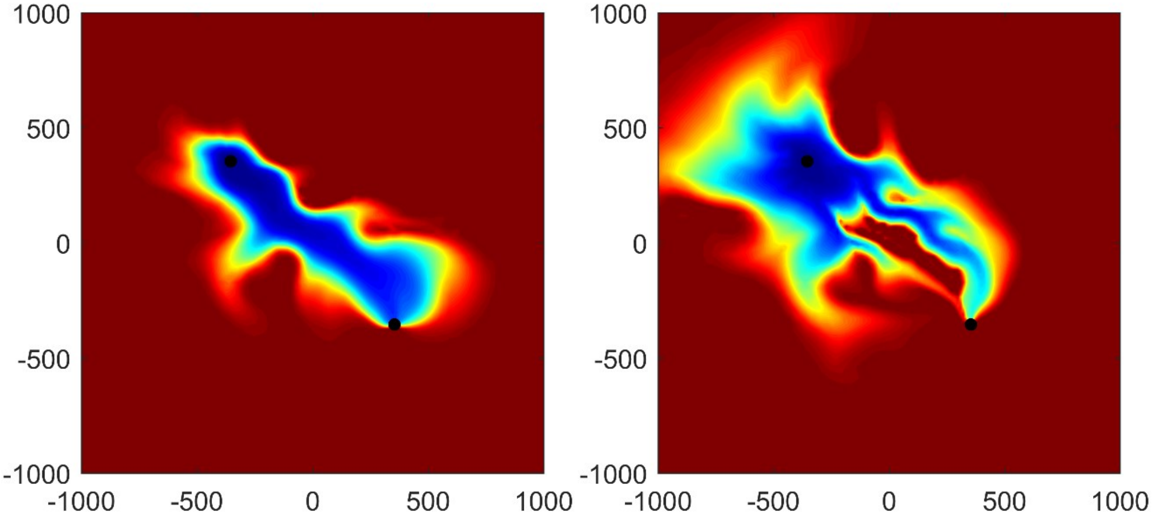

Figure 2: Fracture fluid temperature after 30 years of continuous circulation for the pre-treatment case (left) and the post-treatment case (right). Spatial coordinates are in meters and temperature ranges from a minimum of 50 °C (blue) to a maximum of 200 °C (red). The locations of the injection well (upper left) and production well (lower right) are displayed as black circles.

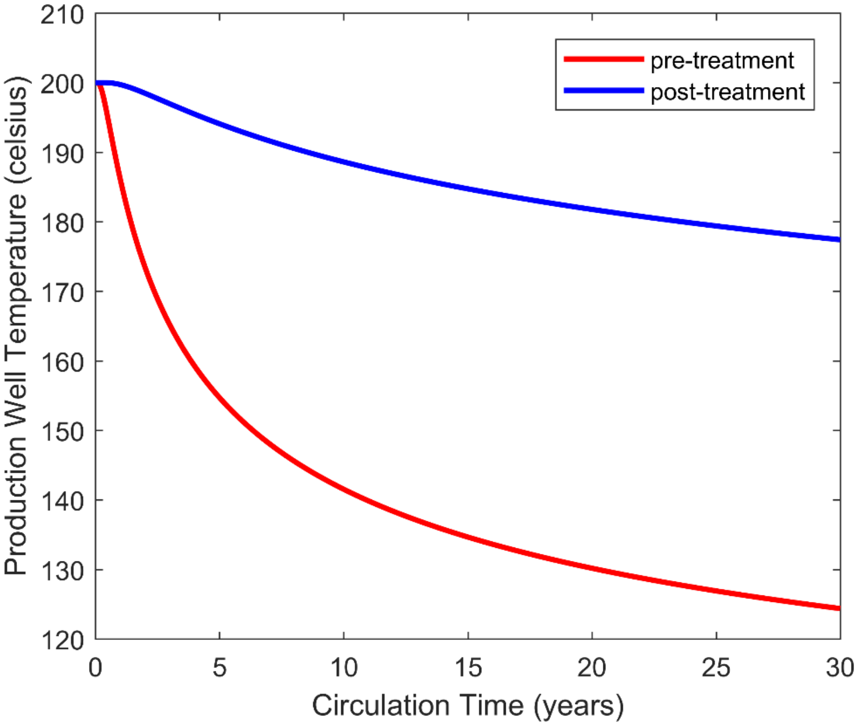

Figure 3: Production well fluid temperature as a function of circulation time for the pre-treatment case (red) and the post-treatment case (blue). At the maximum ΔT, the corresponding thermal power is roughly three $MW_{thermal}$.

3. PROGRESS TOWARDS MATERIAL SYNTHESIS

The use of volume phase transitions in materials science and engineering was pioneered in the 1970's and 1980's by Tanaka (e.g., Tanaka, 1978; Tanaka et al., 1980; Yeghiazarian et al., 2005). The fundamental mechanism of interest to developing an active tracer for hydraulic control is polymer network collapse in polyacrylamide gels. This entropy-driven phase transition exhibits a counter-intuitive behavior in which the material expands when exposed to temperatures below the "lower critical solution temperature." Therefore, circulating such a material through a cooled region of the subsurface will result in swelling of the particle and, as a result, a reduction in the local permeability of the target fracture.

In this section, we describe our progress towards developing such a material, including synthesis methods that introduce tunable properties. These tunable properties are investigated in the context of engineering a specific active tracer that is appropriate for either direct-use geothermal applications (temperatures less than ~100 °C) and/or for electric-power-generating systems (temperatures less than about 300 °C). Therefore, these engineered particles should behave in an inert fashion whenever local temperatures are above the lower critical solution temperature enable to direct the swelling particles to interwell regions of the reservoir. When local temperatures are below the threshold temperature, the particles should swell and form an effective "plug" such that fluid circulation through the channel is redirected towards hotter flow paths.

Tunable properties relevant to the design constraints described above include: 1. Lower critical solution temperatures; 2. Volumetric swelling ratios; 3. Particle sizes; and 4. Particle-particle "stickiness." These properties are tuned using copolymerization approaches with different co-monomers in order to restrict the volume phase transition to the desired temperature window. The foundation of these engineered particles is a N-isopropylacrylamide monomer and desirable properties are tuned by introducing several co-monomers, including: 1. Ionic species (e.g., sodium acrylate); 2. Organic crosslinkers (e.g., N, N'-Methylenebisacrylamide); and 3. Nanocomposite crosslinkers (e.g., laponite clay nanoparticles). Varying the abundance of the ionic species results in tunable threshold temperatures and swelling ratios while varying the relative abundances of the organic and inorganic crosslinkers enables tunable particle-particle stickiness.

Two end-member "recipes" have been identified so far, with a mean spherical diameter of 193 microns and a standard deviation of 600 microns. Using the poly(N-isopropylacrylamide) monomer (PNIPAM) as the volume phase change material, the three representative recipes include: 1. a chemically-cross-linked PNIPAM microgel; 2. A PNIPAM gel-based composite using clay nanoparticles; and 3. A hybrid PNIPAM gel-based composite with both inorganic (i.e., clay nanoparticles) and organic crosslinkers. The first recipe results in a mechanically-weak material which lacks particle-particle interactions while the second recipe results in a mechanically-strong material with high yield strength. The third recipe allows for careful tuning between the two end-members, which is particularly useful for finding a particle that will behave in an inert fashion when above the threshold temperature, but will stick together and form a mechanically-strong gel when local temperatures are below the threshold temperature.

The swelling ratios and threshold temperatures for Recipe 1 (i.e., the chemically-cross-linked PNIPAM microgel) are shown in Table 1. In the absence of a sodium acetate ionic species, the volumetric swelling ratio and threshold temperature are roughly 12.5 and 36 °C, respectively. Adding sodium acetate increases both the swelling ratio and the threshold temperature and the maximum volumetric swelling ratio and threshold temperature were found to be roughly 51.5 and 60 °C, respectively, which corresponds to a PNIPAM:SA ratio of 82:18.

Table 2: Swelling ratios and lower critical solution temperatures (LCST) corresponding to varying the relative abundance of the poly(N-Isopropylacrylamide) monomer (PNIPAM) sodium acetate (SA) co-monomer.

PNIPAM:SA ratio	Swelling ratio (volume) (n≥3)	LCST (℃)
100:0 (0% SA)	12.5 ± 1.5	36
98:2 (49:1)	25.5 ± 5.5	42
95:5 (19:1)	30 ± 8	48
90:10 (9:1)	36.5 ± 9.5	56
82:18 (4.6:1)	51.5 ± 6.5	60

4. CONCLUSIONS AND FUTURE WORK

This article introduces the concept of an “active tracer” for hydraulic control of cooled short circuits and presents initial progress towards synthesizing such a particle. In addition, a computational study investigated the anticipated benefits of employing this treatment approach in a single fracture of non-uniform aperture with an injector-producer well spacing of 1000 m. In this section, we summarize our findings and discuss future work.

The computational study’s objective was to determine how the improved thermal lifetime compares to the “pre-treatment” scenario. For a geothermal system designed to tolerate a 90% decline in the temperature difference between production temperatures and reinjection temperatures, the study found that one should expect to find thermal breakthrough times corresponding to the pre-treatment and post-treatment cases of roughly 1 year and 15 years, respectively. At the end of a 30-year commercial lifetime, the pre-treatment case results in a production well temperature that has cooled by 76 °C to a temperature of 124 °C. In contrast, the post-treatment case results in a production well temperature that has cooled by 23 °C to a temperature of 177 °C. Therefore, the anticipated benefit of the proposed active tracer treatment is to transform a “short-circuited” scenario where commercial failure occurs in about one year to a favorable scenario with commercially-viable thermal-hydraulic performance for at least 15 years.

Progress towards synthesizing the proposed active tracers indicates that swelling ratios and lower critical solution temperatures can be tuned in the range of 12.5-51.5 and 36-60 °C, respectively, for particles with an average spherical diameter of 193 microns. This tuning is achieved by varying the relative abundances of the volume phase change material (i.e., poly(N-isopropylacrylamide) monomer) and the ionic species (i.e., sodium acetate) in the range of zero to 18 weight percent. In addition, we found that the mechanical properties (tensile and compressive strength) of the swelling particles can be tuned by varying the relative abundance of an organic crosslinker (N,N’-methylenebisacrylamide) and an inorganic crosslinker (laponite clay nanoparticles).

Future work will expand on the laboratory synthesis and computational work presented here. Laboratory synthesis will continue to investigate the tuning behaviors relevant to swelling ratios, particle sizes, threshold temperatures, and mechanical properties. Computational work will incorporate additional transport phenomena, such as temperature-dependent viscosity and thermoelastic effects. The computational work will also investigate more detailed treatments of particle transport and non-linear effects, including non-uniform initial/boundary values (e.g., temperature gradients, buoyancy, etc.).

In addition, future work will investigate the transport properties of these engineered particles under varying thermodynamic/thermophysical conditions across multiple spatial scales. Bench-scale column testing, for instance, will investigate particle transport behaviors such as adsorption, thermal degradation, and temperature-dependent effects in well-controlled column experiments. Meso-scale field testing at the Altona Field Laboratory will investigate the performance of our candidate particles in a single, bedding-plane fracture in crystalline rock.

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