

HEAT-ACTIVATED EPOXY FOAM FOR PERMEABILITY ALTERATION IN FRACTURED GEOTHERMAL FIELDS: *PROOF OF CONCEPT*

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ABSTRACT

Geothermal energy plays a growing role in the transition to renewable and carbon free energy sources. A challenge for many geothermal operations is how to enhance water-rock heat exchange, either by creation of new fractures in a tight rock or by blocking short-circuiting large conduits. Here we report a novel approach for blocking large aperture (cm scale) fractures using heat-activated epoxy resin foam. The foam is injected as discrete inert resin droplets that are transported to regions of the geothermal field and activated upon reaching sufficiently high temperatures, where they undergo foaming and curing, thereby locally reducing permeability. In contrast to alternative methods for reducing rock permeability such as silicate gels or heat responsive polymer microbeads that target fractures of small apertures (< 0.1 mm), the epoxy foam can reduce permeability of fractures with large apertures (~ 10 mm) while attaining mechanical strength and thermal stability. Results from laboratory aluminum-glass fracture models provide insights by visualizing the transport phase of resin droplets and their subsequent temperature-induced foaming and curing transformations with associated flow pathway blocking. Modeling results for transport and foaming in a simple fracture considering rheological properties and foaming (volume expansion) behavior are compared with measurements of permeability changes. Challenges associated with upscaling to fracture networks and large transport distances of resin droplets are discussed.

KEYWORDS

Geothermal energy, Epoxy foam, Permeability reduction



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1. INTRODUCTION

Geothermal resources offer clean, steady and renewable sources of energy for electricity production and heating. In addition to geographical challenges and considerable capital investment into a poorly constrained subsurface, many geothermal fields require fluids (water or brine) to extract heat from the subsurface and sufficient permeability to support high flows required for commercial heat extraction (12, 15). Among the wide range of heat extraction methods from geothermal fields, we focus here on challenges of conventional geothermal extraction that require drilling to extract natural liquid flows (15, 31), and enhanced geothermal systems (EGS) in which wells are drilled into dry hot rock requiring injection and extraction of heated liquid (12). Regardless of specific conditions, the lifetime and performance of geothermal fields are defined by the effective fracture area and stimulated rock volume that the circulating fluids can access (24, 26). However, while a larger accessible fracture area generally enhances geothermal performance, the specific geometry and connectivity of these fractures play a crucial role in determining efficiency (20). In particular, if the fracture network includes large-aperture faults or highly permeable connections between injection and production wells, it may lead to short-circuiting, where fluids bypass much of the reservoir rock. Short-circuiting reduces the residence time of the working fluid within the reservoir, where injected fluids tend to follow the path of least resistance, often flowing rapidly through high-permeability zones without adequately sweeping the reservoir. This uneven flow distribution not only leads to localized cooling and under-utilization of the stimulated rock volume, but can also accelerate thermal drawdown near the production well.

In geothermal fields containing extensive fault zones, or well doublets that are connected by large aperture fractures, heat extraction efficiency may be adversely impacted by such “short circuiting” flow pathways (6, 8). The occurrence of short-circuiting is not solely governed by the initial fracture geometry or permeability contrasts, but can also be exacerbated by reservoir stimulation processes. Induced seismicity during EGS operation can result in ‘hyperpermeable’ pathways, as documented in Rosemanowes Quarry (13, 25) where preferential fluid circulation along these shortcuts results in cooling out and reduces the efficiency of the EGS system. Advances in drilling technology adopted from the petroleum industry are now being incorporated in EGS. For example, closely spaced horizontal well configurations (12) require stimulation of fractures to hydraulically connect injection and extraction well pairs (15), which can increase susceptibility to creation of short-circuiting pathways (12). This study aims to examine and provide solutions for scenarios in which well doublets become connected by large aperture fractures (natural or stimulated), resulting in reduced heat extraction efficiency. We hypothesize that targeted reduction of permeability in flow-dominating fracture zones can potentially restore idle geothermal wells (at relatively small capital expenditure) and improve thermal performance of production wells experiencing rapid or unsustainable temperature decline.

We report a novel approach for blocking high permeability pathways in fractured geothermal reservoirs using heat-activated foaming epoxy resin (29). The basic concept is described in **Figure 1**. Briefly, we seek to inject swarms of resin droplets that are passively carried by the injected liquid and subsequently become thermally activated at target temperatures. A central hypothesis critical for the success of the proposed method is that the injection of uniform (at very low concentration) of resin droplets would be preferentially carried to the highly conductive pathways in proportion to the volumetric flow passing through these conduits. The thermal activation entails release of CO₂ blocked resin curing agent at the prescribed temperature (presently 120 °C) at which CO₂ molecules are released and simultaneously induce foaming and volume expansion, as well as spontaneous epoxy resin cross-linking and rapid hardening (curing) of the foam. The primary advantages of heat-activated foaming epoxy resin over other measures for permeability reduction, such as silicate gels (10) and temperature-responsive polymers (19), is the high degree of control of the injected resin droplets (size, viscosity), the ability to prescribe activation temperature, and, importantly, the capacity to block large fractures (in the range of 10⁻⁴ to 10⁻² m). These characteristics not only enhance placement precision but also allow the injected resin to respond dynamically to evolving subsurface heterogeneity. We anticipate that flow pathways and preferential

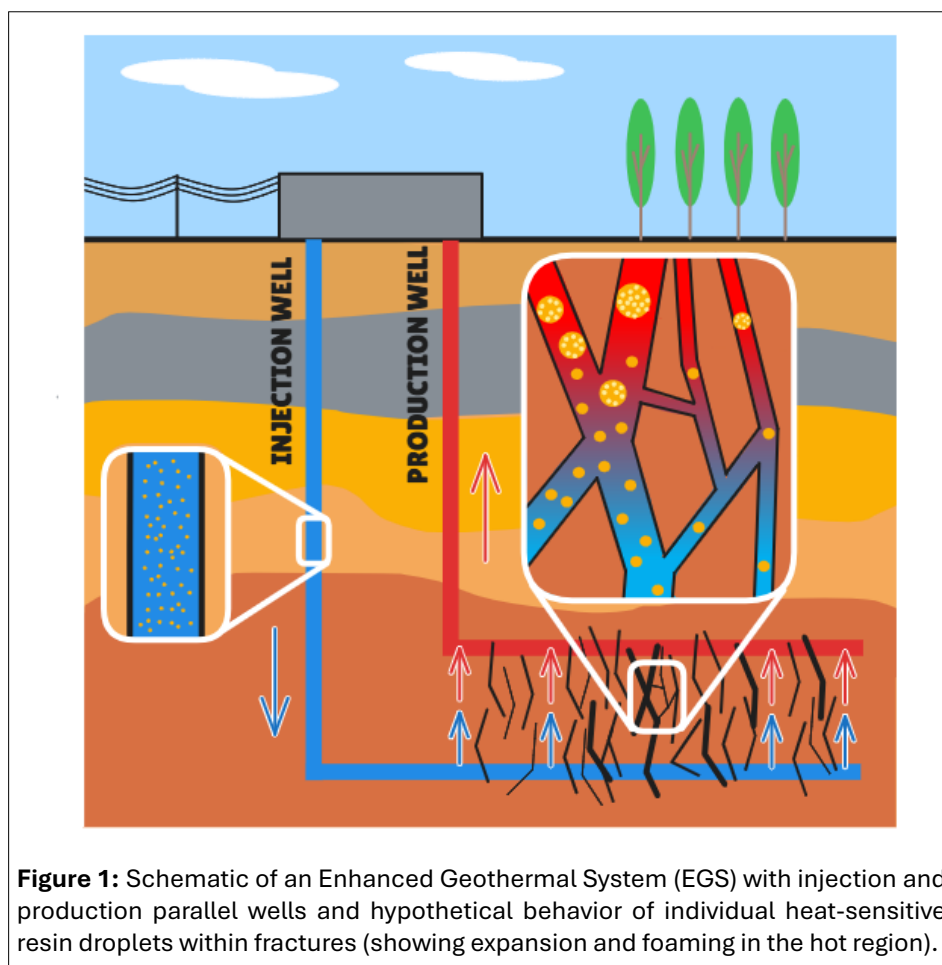
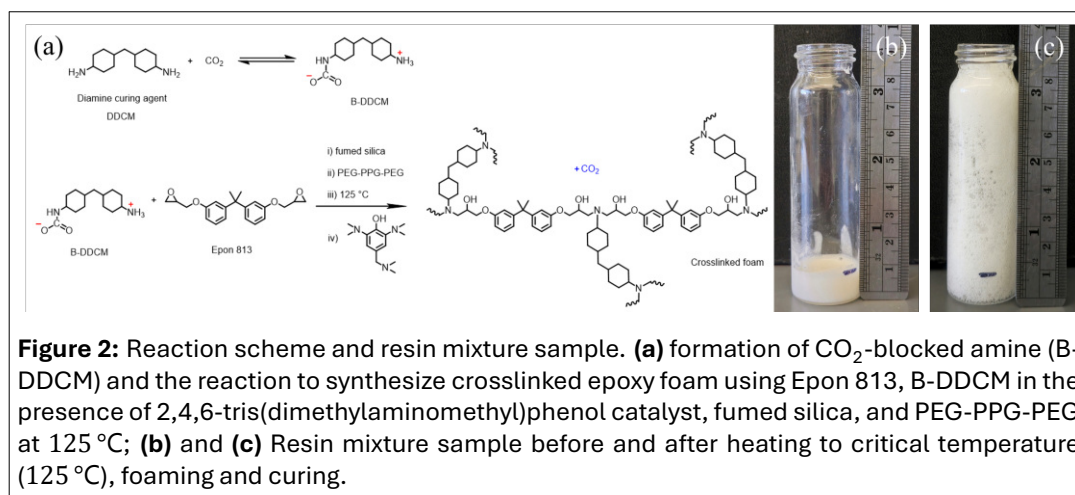


Figure 1: Schematic of an Enhanced Geothermal System (EGS) with injection and production parallel wells and hypothetical behavior of individual heat-sensitive resin droplets within fractures (showing expansion and foaming in the hot region).

response to locally high permeability regions (5, 28) will direct a proportional number of resin droplets into highly conductive fractures. Secondary advantages of this approach over other methods include the insensitivity of resin droplets to carrier fluid properties (e.g., pH is known to affect setting of silicate gels) and the high thermal stability of the cured epoxy foam (up to 280 °C). Epoxy resin has been widely employed as a binding material in rock mass consolidation, chemical grouting, and rammed earth engineering. Due to its good resistance to acid, alkali, and salt corrosion, epoxy resin has also been utilized for the stabilization of contaminated soils (18), wastewater treatment applications (22) and coating materials under high salinity environment (4). In the long term, the epoxy resin may go through thermal degradation in a heat-water environment (3), leading to gradual failure or blockage of pathways. A suitable maintenance regime or continuous low-concentration injection should be applied in field applications.

2. SYNTHESIS AND PROPERTIES OF HEAT ACTIVATED FOAMING EPOXY RESIN AND INJECTION SCENARIOS

The basic requirements for the synthesis of thermally activated epoxy resin are stability during injection, transport, and subsequent expansion (foaming), and curing at a prescribed temperature (29, 30, 21). For this proof of concept study, we used commercially available epoxy resin, Epon 813, with a viscosity of 0.8 Pa s. The resin is mixed with CO₂ blocked diamine curing agent. The CO₂ blocking renders the amine non-reactive under ambient temperature conditions. Release of CO₂ above a critical temperature of 125 °C simultaneously increases the volume of the resin (foaming) and activates the amine group that, in turn, initiates the curing process of the epoxy foam via cross-linking of the epoxy base. This foaming and curing process leads to the formation of epoxy foam with substantial volume expansion (tenfold or > 1000% at 125 °C - see Fig. 2). This process is irreversible and lasts only a few minutes (depending on ambient temperature, with higher temperature accelerating reaction rates). The primary reaction of the



resin is neither sensitive nor exposed to the environment (pH, salinity, Eh, EC), it is confined within the resin droplet triggered by external temperature. Other critical processes, such as foaming and curing, are also independent of ambient conditions other than temperature (such resins are used routinely in saline marine systems). The cured resin solidifies forming a cellular structure due to entrapped CO_2 gas bubbles. The exact resin formulation was selected based on target foaming temperature, rapid curing rates, and low resin viscosity to facilitate injection and transport.

2.1. Resin synthesis

The CO_2 -blocked amine curing agent was prepared by dissolving 15 g of 4,4-diaminodicyclohexylmethane (DDCM) in 45 mL dichloromethane (DCM) solvent, followed by bubbling CO_2 gas through the solution for 3 hours. The product, CO_2 -blocked DDCM (B-DDCM), is insoluble in DCM and precipitates out as a white solid. The precipitate was dried in a 50°C oven for 12 hours producing a yield of 98%. The resin mixture involving epoxy resin (Epon 813) (2.970 g, 7.80 mmol), B-DDCM (1.000 g, 3.93 mmol), fumed silica (0.020 g, 0.50 wt.%), poly(ethylene glycol)-block-poly(propylene glycol)-block-poly(ethylene glycol) (PEG-PPG-PEG) (0.058 g, 1.55 wt.%), and 2,4,6-tris(dimethylaminomethyl)phenol (1.00 wt.%) was mixed mechanically until a homogeneous mixture was obtained. A stoichiometric balance between the amine protons and epoxide group at 1:1 molar ratio was maintained. Ammonium carbamates serve as the CO_2 -blocked amine crosslinker. They are stable at room temperature, but decompose at elevated temperatures into CO_2 as the latent foaming agent and amine as the curing agent. Heating to 125°C causes release of CO_2 , activating the crosslinker which then reacts with epoxy group of Epon 813 resin. The 2,4,6-tris(dimethylaminomethyl)phenol is a catalyst that facilitates the curing reaction between the amine curing agent and the epoxy resin. The fumed silica acts as a nucleating agent and PEG-b-PPG-b-PEG as the foam stabilizer. The curing reaction between amine and epoxy resin results in a strongly crosslinked three-dimensional foamed network, as shown in **Figure 2**.

2.2. Thermal decomposition, foaming and curing of epoxy and other properties

The decomposition temperature of B-DDCM at which CO_2 is released was characterized using differential scanning calorimetry (DSC). The DSC analysis revealed that B-DDCM starts to release CO_2 near 80°C , indicating the initial stage of decomposition (and foaming). As ambient temperature increased, the decomposition maximized at 125°C , as indicated by the minimum of the endothermic peak (**Fig. S1** in the **Supplementary Material**, available [here](#)).

The foaming and curing processes of the resin mixture were measured and monitored in-situ using a parallel plate rheometer^a equipped with an Environmental Test Chamber. The resin mixture was tested with an oscillation temperature ramp for which the dynamic moduli, including the storage and loss moduli (G' and G''), were measured as the temperature was increased at a rate of $5\text{ }^{\circ}\text{C min}^{-1}$ from $50\text{ }^{\circ}\text{C}$ to $180\text{ }^{\circ}\text{C}$. The influence of the catalyst was evaluated through comparative experiments conducted in its presence and absence (**Fig. S2 and S3** in the **Supplementary Material**, available [here](#)). The structure of tertiary amine catalysts significantly influences the curing kinetics and reactivity of epoxy/dicyandiamide systems (11), highlighting the importance of catalyst selection in optimizing epoxy resin performance. The catalyst used here was 2,4,6-tris(dimethylaminomethyl)phenol. As shown in **Figure S1** in the **Supplementary Material** (available [here](#)), with the catalyst, G' and G'' started dropping (indicating onset of foaming) at $80\text{ }^{\circ}\text{C}$, followed by large data fluctuation corresponding to release of CO_2 which creates rheological instability within the resin sample. As the temperature continued to increase, G' and G'' started to increase, indicating the progression of the curing reaction. A plateau was reached at $160\text{ }^{\circ}\text{C}$ as curing was completed and a rigid foam was formed. In comparison, without the catalyst, both foaming and curing occurred at temperatures of about $10\text{ }^{\circ}\text{C}$ higher. The catalyst played two roles, decreasing the decomposition temperature of B-DDCM and increasing the curing rate at lower temperatures. The addition of the catalyst also reduced the viscosity of the resin, allowing it to flow more easily during injection and reach target zones before activation. This reduction in viscosity can be seen from the lower G' and G'' with the catalyst in the temperature range of $50\text{ }^{\circ}\text{C}$ to $80\text{ }^{\circ}\text{C}$ before foaming.

2.3. Resin injection scenarios

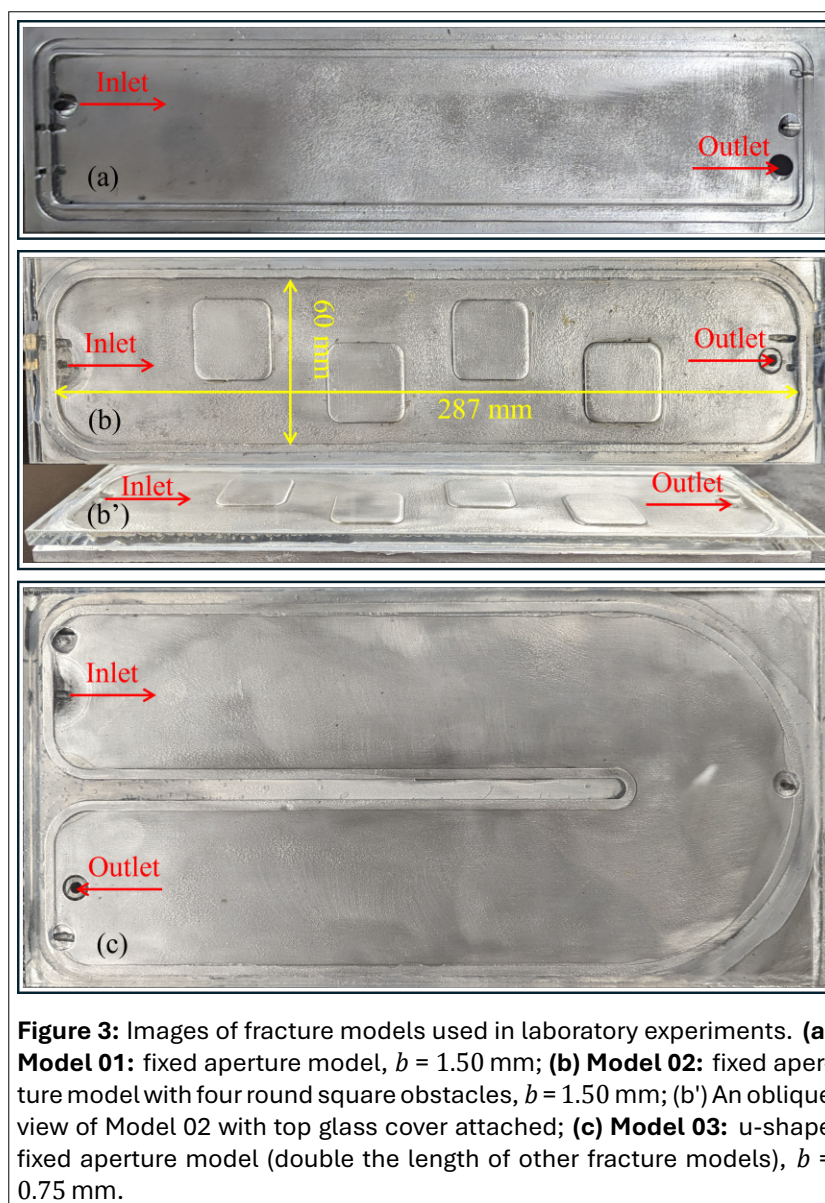
We evaluated two primary modes of resin injection into fractured geothermal fields: **1)** injecting resin fronts designed to be displaced and directed into highly permeable fractures using packers to localize annular injection and promote preferential flow paths; and **2)** injecting small resin droplets, sized to facilitate long-range transport through fracture networks, carried by the injection fluid. Based on preliminary laboratory experiments in simple fracture models, we concluded that the displacement patterns and control of resin fronts is impractical due to the high viscosity ratio between water and the resin (even with silicon oil as carrier due to the high temperatures $> 100\text{ }^{\circ}\text{C}$ in these early experiments). Consequentially, we focused on using resin droplets (generated and injected via special junctions that induce hydrodynamic instabilities and produces similar sized droplets). The injection of swarms of droplets (as experiments and theory show) offered better control over the transport and offered higher likelihood of altering high permeability zones away from an injection well (with less resin volume). This configuration of resin injection as droplets requires special theoretical considerations of transport and activation of discrete sticking events that cumulatively modify the permeability of target (short-circuiting) regions as discussed in the theoretical and experimental sections.

3. LABORATORY EXPERIMENTS

The laboratory experiments focused on injection of epoxy resin droplets into model rock fractures with a portion of the model fracture heated to an activation temperature of $120\text{ }^{\circ}\text{C}$, where resin droplets undergo foaming (expansion) and subsequent curing, thereby reducing local permeability within the model fracture. The laboratory-scale setup represents a single active fracture within fractured rock in an EGS with a constant flow rate of carrier fluid (silicon oil in the experiments report here) and an elevated environmental temperature mimicking a natural geothermal field at moderate temperature to ensure resin activation while maintaining a safer working environment.

We constructed several versions of simple fracture models with fixed apertures (ranging from 0.75 mm to 1.50 mm) using an aluminum plate at the bottom and a cover glass glued with heat-resistant silicon adhesive to withstand temperatures of $230\text{ }^{\circ}\text{C}$. As shown in **Figure 3**, two classes of experimental fracture

^aTA Instruments Discovery HR-2



model designs were considered: **1)** smooth fixed aperture models, and **2)** fixed aperture fracture model with obstacles to mimic heterogeneity in the aperture plane. All models were constructed using machined aluminum plate at the bottom, selected for ease of machining, superior heat conduction, and wettability properties similar to aluminosilicate igneous rock components (e.g. feldspars). Additionally, we constructed a u-shaped aperture model to extend effective length and amplify pressure drop signal. Using numerical simulations, we verified that the measured permeability of the fracture models was comparable to predictions for the same apertures (including obstacles and u-shaped model configurations).

The laboratory experiment setup, shown in **Figure 4**, consists of a flow loop driven by a peristaltic pump for circulating silicone oil (viscosity of $50 \text{ mm}^2 \text{ s}^{-1}$ at 25°C) as the carrier fluid. Given that aqueous fluids are unsuitable at high temperatures under atmospheric conditions, silicone oil was selected for its thermal stability. Also, silicone oil is chemically highly inert and has no reaction with other components due to polarity mismatch. A peristaltic pump established steady state flow of silicon oil into which resin droplets were injected (using t-junction and coaxial injection setting) (9, 27). The model rested on a heated plate^b to control temperature in the fracture and induce foaming of the resin (the plate temperature was set to 160°C during the experiment). The process was monitored from above using both standard video

^bGuardian 5000 heated plate (specifications)

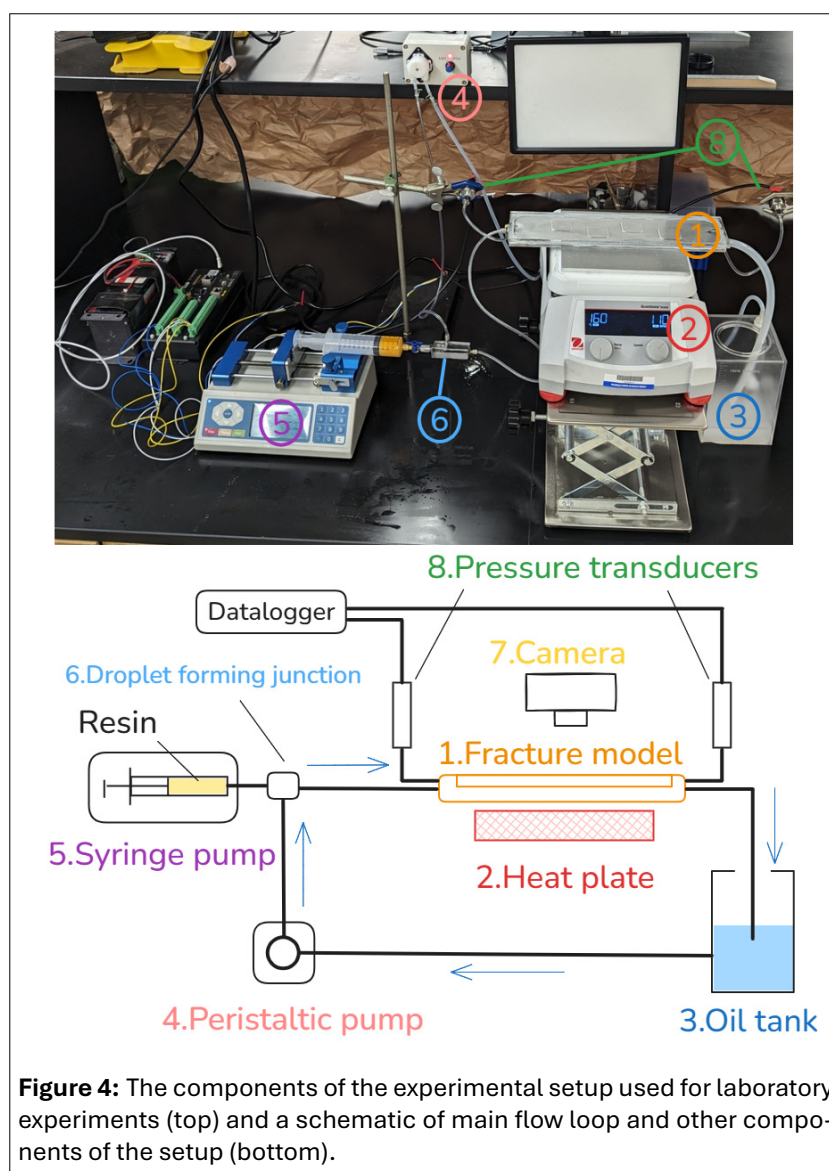


Figure 4: The components of the experimental setup used for laboratory experiments (top) and a schematic of main flow loop and other components of the setup (bottom).

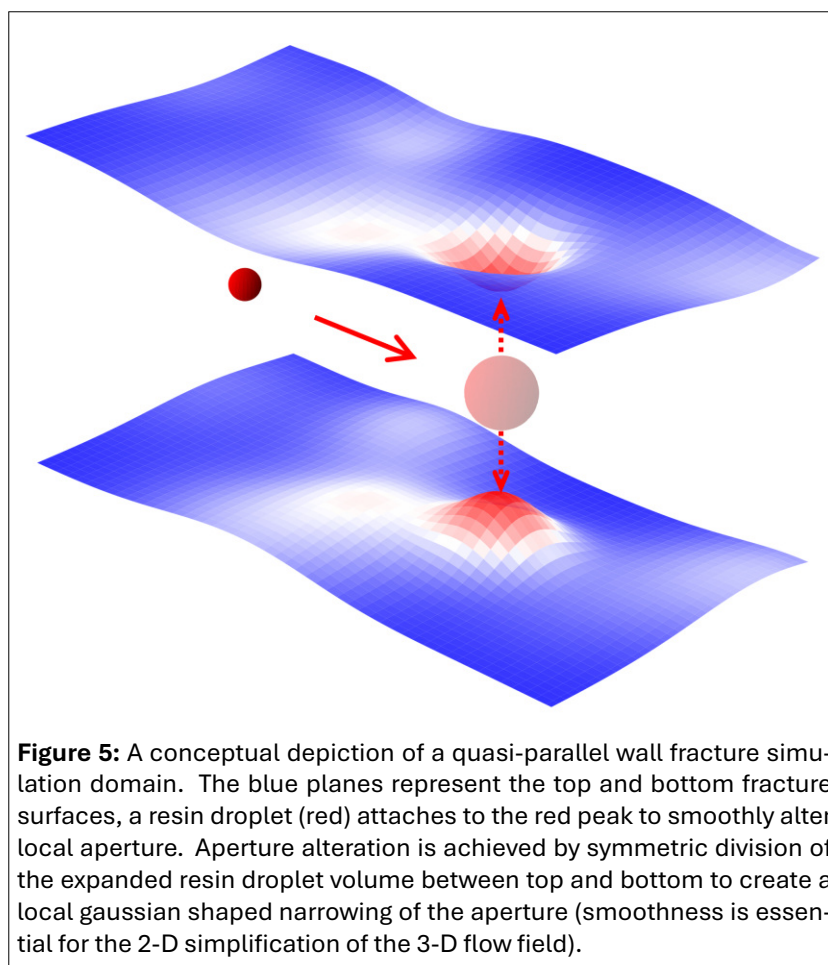
and infrared cameras to capture the behavior of the injected resin droplets, including their displacement, foaming, and curing patterns.

Each experiment was initiated by circulating silicon oil through the liquid loop and measuring pressure drop across the fracture model while the temperature of the heating plate was raised to 160 °C (the temperature was higher than the threshold to account for vertical thermal gradient and heat losses). A constant flow rate of about 40 g min⁻¹ was maintained. Droplets were then injected into the loop from the injection port using a syringe pump^c at a rate of 0.05 g min⁻¹. The droplets size vary with the injection outlet diameter and flow rate of shearing liquid; typical droplet size in the experiments reported here was less than 0.75 mm to ensure passage through all inlets and outlets of the system. This resin injection rate is also low enough to avoid the interaction between droplets, correspond to the low dose of resin injection in the real geothermal field. A sink tank with filter is used for silicon oil cooling and inactivated droplet collection. The flow of the droplets into the model and their transformation and expansion were recorded using high resolution (1920 × 1080 DPI) video camera at rate of 30 Hz. During the transport, sticking, and expansion of the resin, we monitored changes in pressure drop across the fracture model using two high precision pressure transducers^d connected to a datalogger^e. Experiments lasted (typically

^cFusion 200 syringe pump; see [product page](#).

^dOmega PX191-200GV5; see [product page](#).

^eCR1000Xe datalogger; see [product page](#).



2-3 hours) until silicon oil flow was practically blocked or pressure at the inlet reached values that were deemed too risky (> 50 kPa).

4. NUMERICAL MODELING

We developed a two-dimensional Stokes fluid model to simulate the flow field within a single fracture and to represent individual droplet transport, sticking to hot surfaces, and expansion, including the dynamic feedback associated with reducing local aperture and permeability. We focused on the velocity field for the middle plane of fracture apertures, as shown in **Figure 5**. The numerical model implements a modified Stokes equation to describe incompressible flow between two quasi-parallel surfaces (14, 16). The injected resin droplets are passively transported by the background carrier fluid. When the droplets reach a prescribed temperature along their path, they release CO_2 blockers causing foaming and in-situ curing. The model represents this process by making the droplets stick and expand to locally reduce the fracture aperture in proportion to expanded droplet volume as shown in **Figure 5**. We implemented a stochastic sticking process that considers both the fracture geometry and the droplet state. The model predicts adhesion of resin droplets to fracture surfaces based on a stochastic function aware of local aperture, droplet size, and temperature (as discussed below). As droplets adhere and undergo volume expansion, they reduce the local fracture aperture and restrict flow pathways thus decreasing the fracture's overall permeability.

4.1. Depth-integrated flow model

In many practical applications, especially those involving thin geometries or planar domains, fully three-dimensional flow modeling can be computationally intensive and unwarranted. A key aspect of simplifying the Stokes flow equations involves collapsing the three-dimensional flow field into a two-

dimensional form. We assume that fracture aperture varies gradually such that the velocity normal to the fracture walls is approximately zero ($u_n \approx 0$) and viscous forces in the flow field are dominated by shear forces acting normal to the fracture wall ($\nabla^2 u \approx \partial^2 u / \partial n^2$). Incorporating these velocity conditions into the Stokes equation and assuming that the fracture walls are approximately normal to the z-axis yields:

$$0 = \mu \frac{\partial^2 u}{\partial z^2} - \nabla p \quad (1)$$

where $u = (u_x, u_y, 0)$ is a three-dimensional velocity vector with a direction parallel to the x-y plane. Incorporating the no-slip condition ($u = 0$) at the fracture walls, **Equation 1** is integrated across the local aperture (32) yielding:

$$u(x, y, z) = u_m(x, y) \left(1 - \frac{z^2}{(b/2)^2}\right) \quad (2)$$

where u_m is the velocity at the middle plane, and $b = b(x, y)$ is the local aperture. The velocity satisfies a parabolic profile in the z direction, while $u = u_m$ when $z = 0$. The velocity and the velocity goes to zero when $z = \pm b/2$.

For a typical rock fracture, the aperture size (~ 0.1 mm) is much smaller than its length scale in flow direction (> 1 m) (1). In this study, we focus on fluid velocity field for fracture mid-plane, as shown in **Figure 5** for two quasi-parallel plates. Based on these conditions, the integration of 3D Stokes equation over z axis in range $(b, -b)$ becomes:

$$\begin{aligned} \frac{2}{3} \frac{\partial^2 (2bu_{xm})}{\partial x^2} + \frac{2}{3} \frac{\partial^2 (2bu_{ym})}{\partial y^2} - \frac{4}{b} u_{xm} - \frac{\partial(2bp)}{\partial x} &= 0 \\ \frac{2}{3} \frac{\partial^2 (2bu_{xm})}{\partial x^2} + \frac{2}{3} \frac{\partial^2 (2bu_{ym})}{\partial y^2} - \frac{4}{b} u_{ym} - \frac{\partial(2bp)}{\partial y} &= 0 \end{aligned} \quad (3)$$

where the coefficient $2/3$ of the first two terms is due to the volume flux with parabolic velocity profile (it is $2/3$ of the volume flux with uniform profile and mid-plane velocity u_m). The third term acts as a friction term, representing friction forces due to upper and lower fracture walls.

Since we do not invoke any source terms, the continuity equation is unaffected by the velocity profile assumption (parabolic or otherwise). The conserved quantity changes from velocity to the product of velocity and local aperture.

$$\frac{2}{3} \frac{\partial(bu_{xm})}{\partial x} + \frac{2}{3} \frac{\partial(bu_{ym})}{\partial y} = 0 \quad (4)$$

4.2. Transport and adhesion of resin droplets

In previous sections we discussed the preferred configuration for introducing heat-sensitive resin in the form of droplets that are expected to be convected with the carrier fluid. Upon reaching the target thermal conditions within the EGS heat exchange region, the resin droplets are expected to adhere to fracture surfaces, expand as they foam, and subsequently cure to reduce permeability. The droplet adhesion process is influenced by multiple factors, including droplet size, morphology, surface roughness, and temperature, etc. In the present study, the droplet state (specifically before and after foaming) also significantly affects adhesion behavior. In the simulation model, droplet adhesion is treated as a stochastic process. At each time step, a droplet possesses a defined sticking probability. During simulation, a uniformly distributed random number is generated; if this value falls below the sticking probability, the droplet undergoes fixation. When the sticking probability remains constant over time, the spatial distribution of droplet adhesion events follows a geometric distribution.

Once a resin droplet is triggered to stick via the stochastic process, it transforms into a localized bump on the fracture surface. This transformation is shown in **Figure 5**. Between two quasi-parallel fracture surfaces (blue planes), the resin droplet (red sphere) transforms into two symmetric bumps, one on each

surface (top and bottom). The symmetric assumption is incorporated in a depth-integrated flow model. The transformation conserves volume, with the total volume of the original resin droplet equal to the combined volume of the resulting two bumps. Each bump is modeled as a 2D Gaussian shape, with a height equal to the radius of the original droplet. The Gaussian profile is selected for its smoothness which is required for implementation of **Equations 3 and 4**.

We use a simple scaling law to estimate droplet sticking probability P by assuming that sticking probability is proportional to the droplet collision frequency f with walls. This leads to the sticking probability becoming proportional to the droplet velocity u_d and inversely proportional to the difference between the local aperture and droplet diameter (i.e., small droplets in large fracture aperture have lower sticking probability), as:

$$P(x, y, d) \sim f \sim \frac{u_d}{b(x, y) - d} \quad (5)$$

During the simulation, the droplet diameter followed a normalized distribution $d \sim \mathcal{N}(d_0, d_0/10)$, where d_0 is the mean droplet diameter within experiment. From the experiments, we can also calibrate the mean droplet sticking probability, $P_0 = P(d = d_0)$. The sticking probability for droplets under other injection scenarios can be calculated using **Equation 5**. In a subsequent study, we will report more rigorous testing of the statistical behavior of a swarm of droplets in a fracture network. In this study, we demonstrate the feasibility of this ad-hoc sticking probability relation in the numerical results shown in the next section.

5. RESULTS

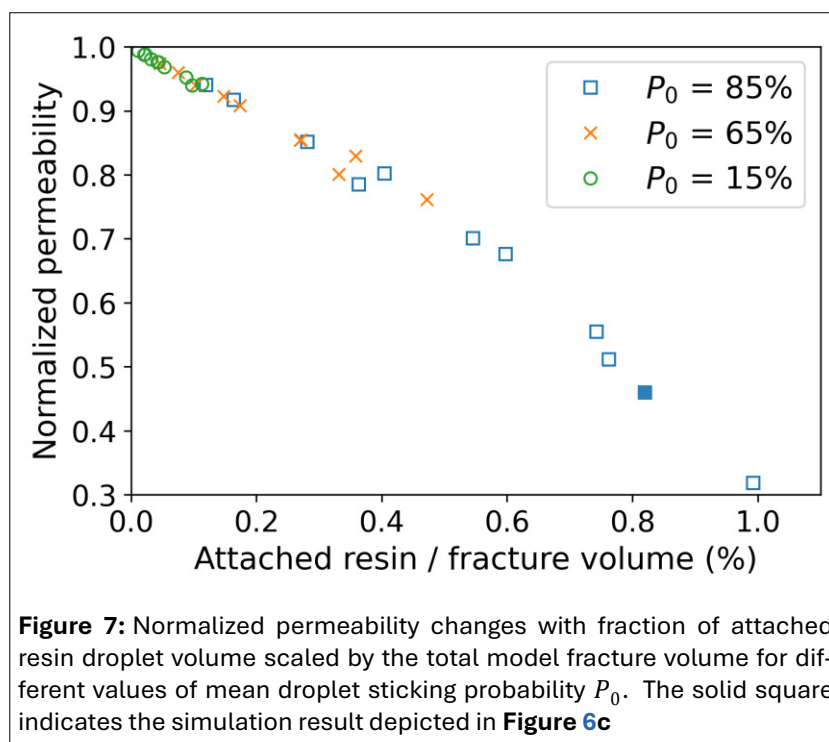
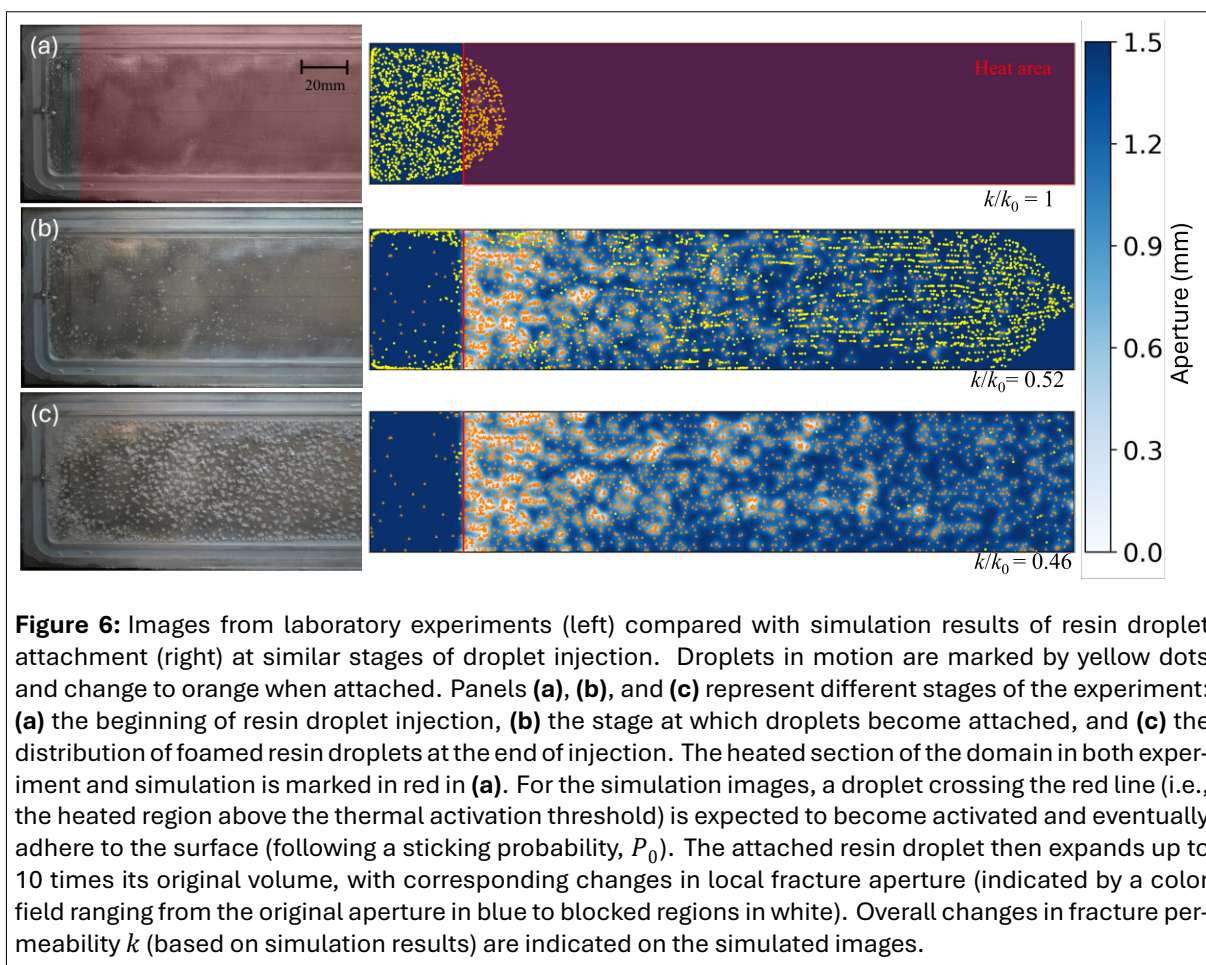
5.1. Numerical Model

For comparison, a simulation was conducted using a domain similar to the experimental setup. A total of 7,000 droplets (diameter $d \sim \mathcal{N}(b/10, b/100)$) were progressively released from a line source at the fracture inlet. The average droplet sticking probability was set to $P_0 = 85\%$, meaning that 85% of the droplets are expected to adhere to the fracture walls within 1 m.

Figure 6 shows a qualitative comparison between laboratory experiments and simulations at similar stages of droplet injection. The right panel shows how the aperture field (initially set to 1.50 mm) changes with the adhesion and expansion of resin droplets, with white regions marking smaller local apertures due to resin droplet attachment and expansion. The resin droplets (yellow dots) are transported by the flow and expand after passing the heated region of the fracture (marked by red line). Each droplet has a defined sticking probability during transport, and once attached, it is marked as an orange dot. These adhered droplets modify local aperture, representing resin droplet sticking behavior observed in laboratory experiments (shown in next section). At the end of simulation, the model permeability k decreased to half of its initial permeability k_0 . In the intermediate stage shown in **Figure 6b** right, downstream alignment of 'droplet lines' is observed. This alignment arises because earlier-attached droplets locally alter the fracture aperture, thereby guiding the paths of following droplets and inducing spatial organization.

By adjusting the total number of droplets (1000 to 20000) and their mean sticking probability, $P_0 = 15\%$, 50%, 85%, **Figure 7** shows that fracture permeability is reduced (nearly linearly) with the fraction of attached droplet volume, irrespective of the details of the attachment dynamics. The results in **Figure 6** also illustrate internal feedback mechanisms, whereby droplet adhesion influences subsequent adhesion behavior.

Importantly, the simulation results highlight the potential efficacy of the proposed method for altering fracture permeability with relatively small volumes of injected resin. Based on numerical results for a single fracture, relatively small volumes of attached resin droplets (0.2% of the fracture volume) may result in more than a 10% decrease in fracture permeability. Experimental evidence suggests (see Experimental



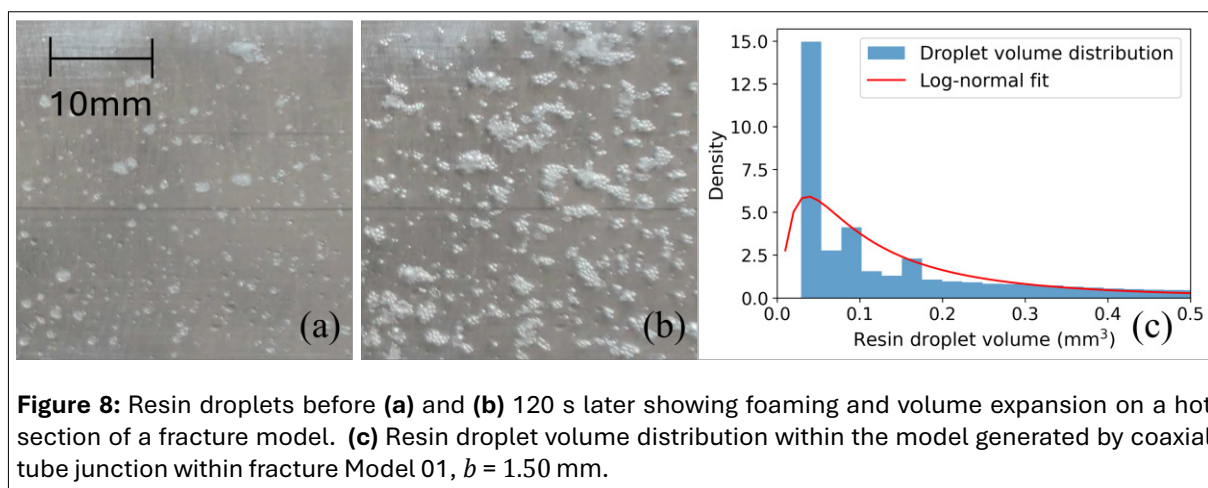


Figure 8: Resin droplets before (a) and (b) 120 s later showing foaming and volume expansion on a hot section of a fracture model. (c) Resin droplet volume distribution within the model generated by coaxial tube junction within fracture Model 01, $b = 1.50$ mm.

section) that an order-of-magnitude reduction in fracture permeability is possible with approximately 1% volume, due to the distributed nature of attached resin droplets.

Moreover, the process is not sensitive to the specific value of the droplet sticking probability, but rather to the cumulative volume of attached resin droplets, implying that prolonged resin injection campaigns using a low density of droplets can achieve the desired permeability alterations. Following additional calibration of the numerical model, we will use the model to explore resin droplet dynamics within large-scale fracture networks and emerging behaviors that are currently challenging to investigate experimentally.

5.2. Laboratory experiments

An illustrative example of the transformation associated with resin activation and foaming of mm-scale resin droplets on the hot section of a fracture model (surface temperature 160°C) is depicted in **Figure 8**. Within two minutes, the resin droplets carried by silicon oil exhibit noticeable volume expansion and evidence of foaming due to CO₂ bubbles entrapped in the epoxy resin (and subsequent curing and hardening). In laboratory experiments, a fraction of the resin droplets undergoing foaming may be carried by the flow out of the fracture model before adhering to the surface. Through image analyses, continuous frame images are thresholded to binary masks, from which the centroid and shape information of resin droplets can be extracted. The identified resin droplets are tracked using a particle tracking algorithm (2) to avoid repeat counting. We summarize the droplet volume distribution in **Figure 8c** for experiments within Model 01 ($b = 1.50$ mm). Droplet volume is estimated from its projected area. Droplets are counted only when their projected area exceeds 4 pixel² (≈ 0.1 mm²) and their diameter is smaller than 1.00 mm (inlet tube diameter).

For the experiments reported in this study, resin droplets were generated using a coaxial tubing junction (7, 27). Based on the viscosity ratio between the dispersed phase (resin mixture) and the continuous phase (silicone oil), the droplet size and generation frequency can be controlled by adjusting the flow rate ratio and channel diameter ratio. In the experiments, the coaxial tubing junction consists of a 14G blunt-tip needle (outer diameter 2.10 mm) as the inner channel and a 2.74 mm drilled well in a plastic block as the outer channel. Most generated droplets had a volume of approximately 0.05 mm³ ($d \approx 0.5$ mm).

The core experimental results are shown in **Figure 9**, which illustrates dynamic changes in liquid pressure drop in the fracture model, along with slight variations in silicone oil injection rates during the experiment. The preheating process begins with silicone oil circulating in the system. The increase in temperature of the circulating silicone oil reduces its viscosity, leading to a decrease in pressure drop and an increase in flow rate. After approximately 40 minutes, the silicone oil flow rate reaches a steady state of about 40 mL min⁻¹ and the measured pressure drop across the model stabilizes at around 3 kPa as for Model 03. At this point, epoxy resin injection is initiated. The initiation of resin droplet injection is marked as time 0. During the resin injection phase, the pressure drop increases exponentially from 3 kPa to 30 kPa

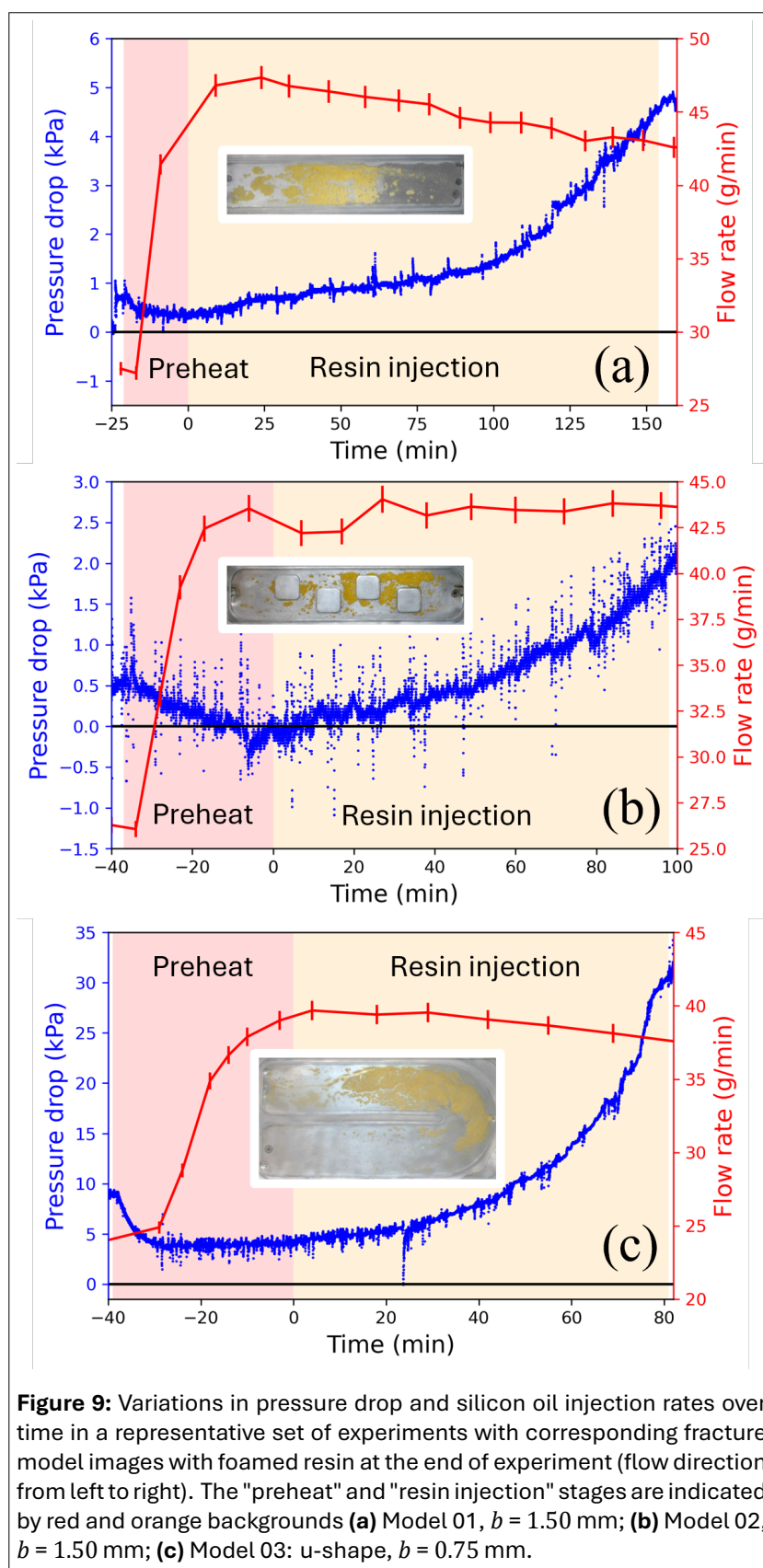
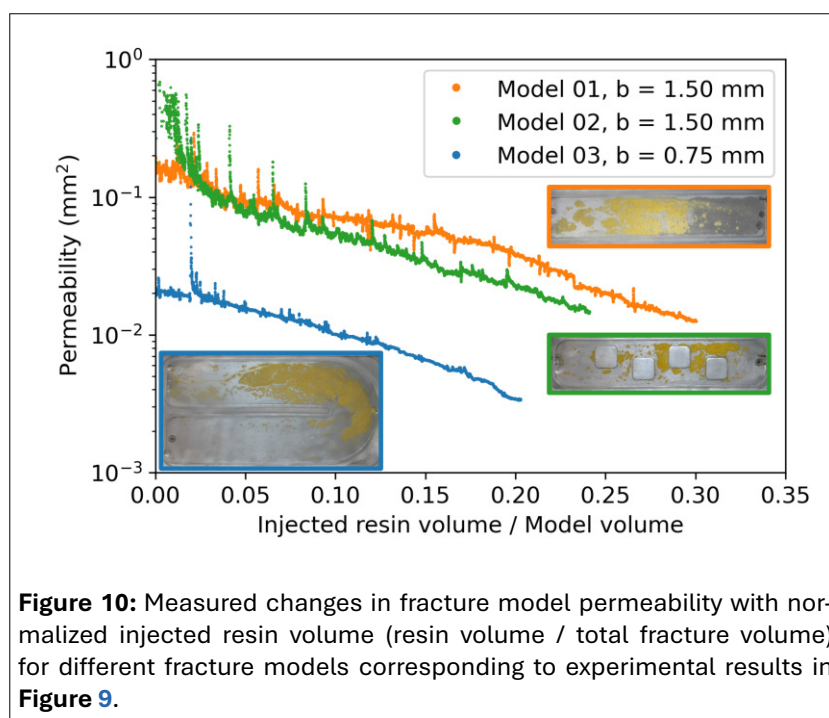


Figure 9: Variations in pressure drop and silicon oil injection rates over time in a representative set of experiments with corresponding fracture model images with foamed resin at the end of experiment (flow direction from left to right). The "preheat" and "resin injection" stages are indicated by red and orange backgrounds **(a)** Model 01, $b = 1.50$ mm; **(b)** Model 02, $b = 1.50$ mm; **(c)** Model 03: u-shape, $b = 0.75$ mm.



due to adhesion of droplets within the model fracture aperture and their subsequent foaming. Even after the resin injection ceases, the pressure drop continues to increase as the epoxy resin foams and expands within the model, eventually stabilizing at approximately 40 kPa.

Figure 10 depicts the commensurate changes in the permeability of the three different fracture models as a function of resin injection. The permeability decreases exponentially by an order of magnitude as the resin foam blocks flow pathways, with no more than 8 mL of resin mixture injected (the total volume within the model is 15 mL to 25 mL). During the initial stage of resin injection, the majority of resin droplets that entered the fracture model were swept away by the flow, with only a small fraction adhering to the fracture surfaces. As droplet adhesion occurs, the flow pathway becomes increasingly complex, promoting further droplet adhesion. The two fracture models with 1.50 mm apertures exhibited similar initial permeability, but the model with square obstructions experienced a faster permeability decline. In contrast, the model with a 0.75 mm aperture shows a comparable rate of permeability reduction to the 1.50 mm square-aperture model. This similarity likely arises from their identical cross-sectional area in the direction of flow, as the square obstructions have half the width of the main channel (see **Fig. 3**).

6. LIMITATIONS AND CHALLENGES

While our laboratory-scale experiments provide important insights into resin droplet transport, deposition, and blockage mechanisms under controlled conditions, real-world geothermal reservoirs present additional layers of complexity. The controlled geometry and flow conditions in single-fracture models allow for systematic observations that support the development of a mechanistic understanding; however, natural fracture networks are inherently more heterogeneous and dynamically coupled. Consequently, translating the findings of these idealized experiments to field-scale applications is not straightforward. The upscaling of laboratory observations of droplet behavior from a single fracture to natural fracture networks is challenging, in part due to topological complexity and the potential for droplet screening and entrapment in natural fractured media. The natural tendency of resin droplets to coalesce is likely to be influenced by interactions with upstream neighboring and already entrapped resin droplets. Likewise, heterogeneous flow fields that naturally arise in fracture networks can produce velocity variations of several orders of magnitude, even when apertures are uniform, due to complex internal geometry and fracture intersections that are likely to influence droplet migration, breakup, and

expansion, thus posing a challenge for the prediction of travel distances and clogging behavior at larger scales. The nonlinearities of droplet transport distances and sticking probabilities as a function of fracture aperture and flow rates are difficult to capture with simple upscaling or averaging techniques at the network scale. Blockages in an individual fracture or at certain critical junctions may have a disproportionate effect on the global permeability of the geothermal field, depending on the redundancy and connectivity structure of the network. Since scaling laws derived from single-fracture models may not directly apply to complex fracture networks, ensemble simulation approaches may be oversimplified, thereby masking the mechanistic insights gained from idealized single-fracture studies. Scale-aware multiscale modeling approaches may become essential to properly incorporate network topology, heterogeneous flow, and nonlinear transport behavior to bridge the gap in droplet transport between single-fracture models and large-scale network behaviors.

Further, the experiments under atmospheric pressure conditions are of limited value when considering the transport and volume changes of the resin under high fluid pressures expected at depths of natural EGS settings (2 to 3 km). High liquid pressures may affect the kinetics and extent of droplet expansion and curing, and the use of water as a carrier liquid has not been tested (due to the high temperatures) and thus the hydrodynamic behavior of the resin under these conditions is largely unknown. We have established activation temperatures, as well as rheological and mechanical behavior of the resin under atmospheric conditions; however, we should expect different foam morphology and potentially different mechanical properties under high pressures. In summary, the evaluation of the concept under atmospheric conditions in a simple fracture model is encouraging, however, this represents no more than a preliminary proof of concept, and more rigorous testing is needed before field-scale testing can be conducted.

7. SUMMARY AND OUTLOOK

The design and operation of modern geothermal fields borrow heavily from advances in petroleum engineering, such as the use of horizontal parallel wells in the Fervo project in North-Central Nevada (23, 17). These modern drilling and field operations can suffer from flow concentration during fracking and also due to induced seismicity (17). The concept of using heat-activated resin droplets that can expand at target locations (based on prescribed activation temperature) and adhere to surfaces offers a novel solution to addressing such unintended concentrated flows that might affect EGS performance and economic viability. In this study, we describe the synthesis and properties of the heat-activated epoxy resin and preliminary tests of its properties and chemical “levers” for attaining different viscosity and activation temperatures.

The preliminary laboratory tests demonstrated the viability of the approach for simple fracture models, showing an order of magnitude reduction in permeability for reasonable injection scenarios. We emphasize that these tests were performed under atmospheric pressure and not the high-pressure conditions expected in standard EGS applications (2 to 3 km), nor were they subjected to the complex flow topology of natural fractured rock. Additional complications may arise due to the behavior of natural carrier liquid (water); however, since the resin is immiscible in aqueous solution (as in the experimental silicon oil), these difference may not be critical for field applications.

Fracture network aspects are being investigated numerically and experimentally and will be reported in a future study. The new method offers promise in addressing cm-scale fractures not easily addressed with present permeability alteration methods (10, 19). Droplet formation for field injection protocols needs to be refined to ensure sufficient travel distances without premature screening of the droplets. The numerical results offer insights into the robustness of the injection strategy in which the alterations are cumulative and can be induced over long resin injection campaigns at low resin volumes (or droplet density in the carrier liquid).

STATEMENTS AND DECLARATIONS

Supplementary Material

Further details on the “Heat activated epoxy resin foam” as well as the “Fracture model permeability measurements” are available in the Supplementary Material, which can be found here: <https://doi.org/10.69631/3mjx5y19>

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Author Contributions

D. Or conceptualized the research framework and supervised the overall project. **Y. Cui** developed the numerical model and established the laboratory experiment. **D. Or** and **Y. Cui** jointly interpreted the results and co-wrote the manuscript. **Y. Yang** and **M. Bishwokarma** contributed to the heat-activated foam experiments and drafted the corresponding section. **R. Parashar** and **S. Karra** provided supervision and technical guidance on the fracture simulation. All authors reviewed and approved the final version of the manuscript.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data, Code & Protocol Availability

Data can be made available upon reasonable request to the corresponding author.

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REFERENCES

1. K. Bisdorn, G. Bertotti, and H. M. Nick. The impact of in-situ stress and outcrop-based fracture geometry on hydraulic aperture and upscaled permeability in fractured reservoirs. *Tectonophysics*, 690:63–75, 2016. [doi:10.1016/j.tecto.2016.04.006](https://doi.org/10.1016/j.tecto.2016.04.006).
2. Y. Cui, Y. Zhang, P. Jia, Y. Wang, J. Huang, J. Cui, and W. T. Lai. Three-dimensional particle tracking velocimetry algorithm based on tetrahedron vote. *Experiments in Fluids*, 59(2):31, 2018. [doi:10.1007/s00348-017-2485-9](https://doi.org/10.1007/s00348-017-2485-9).

3. V. D'Eusano, A. G. Rombolà, I. Coralli, D. Fabbri, L. Tassi, and A. Marchetti. Thermal degradation pathways in multi-component epoxy composites. *Journal of Analytical and Applied Pyrolysis*, 189:107107, 2025. doi:10.1016/j.jaap.2025.107107.
4. C. M. Fame, T. Ueda, M. A. N. Minkeng, and C. Wu. Durability of epoxy and vinyl ester polymers in wet, seawater, and seawater sea sand concrete environments: Molecular dynamics simulations. *Construction and Building Materials*, 451:138645, 2024. doi:10.1016/j.conbuildmat.2024.138645.
5. P. Fu, Y. Hao, S. D.C. Walsh, and C. R. Carrigan. Thermal drawdown-induced flow channeling in fractured geothermal reservoirs. *Rock Mechanics and Rock Engineering*, 49(3):1001–1024, 2016. doi:10.1007/s00603-015-0776-0.
6. B. Gee, R. Gracie, and M. B. Dusseault. Multiscale short-circuiting mechanisms in multiple fracture enhanced geothermal systems. *Geothermics*, 94:102094, 2021. doi:10.1016/j.geothermics.2021.102094.
7. Y. Gu, H. Kojima, and N. Miki. Theoretical analysis of 3D emulsion droplet generation by a device using coaxial glass tubes. *Sensors and Actuators A: Physical*, 169(2):326–332, 2011. doi:10.1016/j.sna.2011.02.043.
8. B. Guo, P. Fu, Y. Hao, C. A. Peters, and C. R. Carrigan. Thermal drawdown-induced flow channeling in a single fracture in EGS. *Geothermics*, 61:46–62, 2016. doi:10.1016/j.geothermics.2016.01.004.
9. A. Gupta, S.M. Murshed, and R. Kumar. Droplet formation and stability of flows in a microfluidic T-junction. *Applied Physics Letters*, 94(16), 2009. doi:10.1063/1.3116089.
10. I. Gussenov, N. Nuraje, and S. Kudaibergenov. Bulk gels for permeability reduction in fractured and matrix reservoirs. *Energy Reports*, 5:733–746, 2019. doi:10.1016/j.egy.2019.06.012.
11. M. Hesabi, A. Salimi, and M. H. Beheshty. Effect of tertiary amine accelerators with different substituents on curing kinetics and reactivity of epoxy/dicyandiamide system. *Polymer Testing*, 59:344–354, 2017. doi:10.1016/j.polymertesting.2017.02.023.
12. R. Horne, A. Genter, M. McClure, W. Ellsworth, J. Norbeck, and E. Schill. Enhanced geothermal systems for clean firm energy generation. *Nature Reviews Clean Technology*, 1(2):148–160, 2025. doi:10.1038/s44359-024-00019-9.
13. E. Huenges. Enhanced geothermal systems: Review and status of research and development. pages 451–473. Elsevier, 2025. doi:10.1016/B978-0-443-24750-7.00012-9.
14. R. G. Hughes and M. J. Blunt. Network modeling of multiphase flow in fractures. *Advances in Water Resources*, 24(3-4):409–421, 2001. doi:10.1016/S0309-1708(00)00064-6.
15. M. Khodayar and S. Björnsson. Conventional geothermal systems and unconventional geothermal developments: An overview. *Open Journal of Geology*, 14(2):196–246, 2024. doi:10.4236/ojg.2024.142012.
16. R. Krishna, Y. Méheust, and I. Neuweiler. A two-dimensional depth-integrated model for immiscible two-phase flow in open rough fractures. *Journal of Fluid Mechanics*, 1011:A43, 2025. doi:10.1017/jfm.2025.404.
17. G. Leveille. Hydraulically fractured horizontal wells: A technology poised to deliver another energy-related breakthrough of enormous scale. *Journal of Petroleum Technology*, 76(02):12–15, 2024. doi:10.2118/0224-0012-JPT.
18. Q. Ma, J. Lei, J. He, Z. Chen, and W. Li. Epoxy resin for solidification/stabilization of soil contaminated with copper (II): Leaching, mechanical, and microstructural characterization. *Environmental Research*, 240:117512, 2024. doi:10.1016/j.envres.2023.117512.
19. G. Maddinelli, M. Bartosek, S. Carminati, L. Moghadasi, N. Manfredini, and D. Moscatelli. Design of thermoresponsive polymers to selective permeability reduction in porous media. In *SPE Abu Dhabi International Petroleum Exhibition and Conference*, page D011S016R001. Society of Petroleum Engineers, 2020. doi:10.2118/203492-MS.
20. M. L. McLean and D. N. Espinoza. Thermal destressing: Implications for short-circuiting in enhanced geothermal systems. *Renewable Energy*, 202:736–755, 2023. doi:10.1016/j.renene.2022.11.102.
21. D. S. Mebane, J. D. Kress, C. B. Storlie, D. J. Fauth, M. L. Gray, and K. Li. Transport, zwitterions, and the role of water for CO₂ adsorption in mesoporous silica-supported amine sorbents. *The Journal of Physical Chemistry C*, 117(50):26617–26627, 2013. doi:10.1021/jp4076417.
22. A. B. Nastasović, B. M. Ekmešćić, Z. P. Sandić, D. V. Ranđelović, M. Mozetić, A. Vesel, and A. E. Onjia. Mechanism of Cu (II), Cd (II) and Pb (II) ions sorption from aqueous solutions by macroporous poly (glycidyl methacrylate-co-ethylene glycol dimethacrylate). *Applied Surface Science*, 385:605–615, 2016. doi:10.1016/j.apsusc.2016.05.165.
23. J. H. Norbeck and T. Latimer. Commercial-scale demonstration of a first-of-a-kind enhanced geothermal system. 2023. doi:10.31223/X52X0B.
24. S.N. Pandey, V. Vishal, and A. Chaudhuri. Geothermal reservoir modeling in a coupled thermo-hydro-mechanical-chemical approach: A review. *Earth-Science Reviews*, 185:1157–1169, 2018. doi:10.1016/j.earscirev.2018.09.004.

25. R. Parker. The rosemanowes HDR project 1983–1991. *Geothermics*, 28(4-5):603–615, 1999. [doi:10.1016/S0375-6505\(99\)00031-0](https://doi.org/10.1016/S0375-6505(99)00031-0).
26. A. Pollack and T. Mukerji. Accounting for subsurface uncertainty in enhanced geothermal systems to make more robust techno-economic decisions. *Applied energy*, 254:113666, 2019. [doi:10.1016/j.apenergy.2019.113666](https://doi.org/10.1016/j.apenergy.2019.113666).
27. M. Rahimi, A. S. Khorrami, and P. Rezai. Effect of device geometry on droplet size in co-axial flow-focusing microfluidic droplet generation devices. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 570:510–517, 2019. [doi:10.1016/j.colsurfa.2019.03.067](https://doi.org/10.1016/j.colsurfa.2019.03.067).
28. N. Rangel-Jurado, A. J. Hawkins, and P. M. Fulton. Influence of extreme fracture flow channels on the thermal performance of open-loop geothermal systems at commercial scale. *Geothermal Energy*, 11(1):19, 2023. [doi:10.1186/s40517-023-00261-7](https://doi.org/10.1186/s40517-023-00261-7).
29. Q. Ren, H. Xu, Q. Yu, and S. Zhu. Development of epoxy foaming with CO₂ as latent blowing agent and principle in selection of amine curing agent. *Industrial & Engineering Chemistry Research*, 54(44):11056–11064, 2015. [doi:10.1021/acs.iecr.5b03069](https://doi.org/10.1021/acs.iecr.5b03069).
30. R. B. Said, J. M. Kolle, K. Essalah, B. Tangour, and A. Sayari. A unified approach to CO₂–amine reaction mechanisms. *ACS Omega*, 5(40):26125–26133, 2020. [doi:10.1021/acsomega.0c03727](https://doi.org/10.1021/acsomega.0c03727).
31. T. Sharmin, N. R. Khan, Md S. Akram, and M. M. Ehsan. A state-of-the-art review on geothermal energy extraction, utilization, and improvement strategies: conventional, hybridized, and enhanced geothermal systems. *International Journal of Thermofluids*, 18:100323, 2023. [doi:10.1016/j.ijft.2023.100323](https://doi.org/10.1016/j.ijft.2023.100323).
32. R. W. Zimmerman and G. S. Bodvarsson. Hydraulic conductivity of rock fractures. *Transport in Porous Media*, 23:1–30, 1996. [doi:10.1007/BF00145263](https://doi.org/10.1007/BF00145263).