An Experimental Study of Thermal and Hydraulic Geothermal Reservoir Stimulation of Brittle Impermeable Material

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Keywords: Geothermal, fracture geometry, stimulation, hydraulic, thermal, reservoir.

ABSTRACT
Reservoir stimulation is one of the key technologies necessary for optimization of enhanced geothermal systems. The higher volumetric density of fractures created by stimulation allows for greater access to the rock, which potentially yields higher fluid flow rates and increased injectivity. To study this further a suite of ongoing experiments simulates a brittle, impermeable reservoir subjected to sequential hydraulic and thermal fracturing processes. It is anticipated that cooling and injection protocols could lead to an increase in injectivity that is greater than either of these stimulation processes alone. The combined hydraulic and thermal fracturing process is hypothesized to result in fracture geometries that are significantly different than those produced by either hydraulic or thermal fracturing alone, with potentially higher flow rates. The higher flow rates can directly result in an elevated heat transfer rate in a geothermal system. To assess this potential for increased injectivity and surface area, experiments were conducted in which acrylic specimens were stimulated using methods analogous to those that could be used on a reservoir scale. Fractures that have faces perpendicular to the maximum horizontal principal stress were theorized by Perkins and Gonzolaz (1985) to occur once a hydraulic fissure has been thermally fractured. These fractures were created in blocks of acrylic and validate their findings.

1. INTRODUCTION
Geologic stimulation is a common practice to increase the injectivity/productivity of wells in hydrocarbon and geothermal reservoirs. Generally accomplished by hydraulic fracturing, geothermal stimulation can be achieved in other ways including chemical stimulation, propellant fracturing, and thermal fracturing. While hydraulic fracturing can be effective under most circumstances, understanding the interaction of hydraulic fracturing with thermal fracturing will be relevant to both the geothermal and the petroleum industries. Thermal fracturing has the added benefit of potentially creating fractures parallel to the least horizontal principal stress and perpendicular to hydraulic fractures, which are expected to extend in the direction of greatest principal stress. This allows the artificially created fracture network to grow in a different plane than the hydraulic fracture.

A sensitivity study done by Sanyal and Butler (2005) concluded that the most influential variable for thermal energy extraction from a stimulated geothermal system is the resultant fracture volume. The fracture volume created by a stimulation treatment is related to the fracture geometry, orientation, and in-situ stress conditions of the reservoir. Specifically, the resulting fracture geometry can affect fluid flow, thermal drawdown, short-circuiting, connectivity and injectivity, all of which influence how much thermal energy is extracted. An increase in understanding of and ability to perform stimulation techniques can open up new geographical areas of geothermal production worldwide. Tester et al. (2006) calculated that 2% of the thermal energy contained within the earth between the depths of 3.5 to 7.5 km “is roughly 2,600 times the annual consumption of primary energy in the United States in 2006.” Most of that energy can only be accessed via stimulated Enhanced Geothermal Systems (EGS).

The research performed here experimentally examined how thermal and hydraulic stimulations affect a brittle reservoir. Hydraulic stimulation of reservoirs has been studied for years and is a well-known procedure. Thermal fracturing is the subject of much work done with respect to machine parts and even waterflooding in the oil and gas industry, but those fractures are viewed as side effects of another process (Dulieu-Barton, 1998). In this work, thermal fractures are sought after for their ability for creating unique fracture geometry. The analytical research of Perkins and Gonzalez (1984) indicates that the thermal gradient will travel in an unfractured isotropic reservoir independent of stress orientation, normal to a point or line source. Through conduction of the impermeable reservoir, sub-cooled circular regions within the reservoir will be created. Due to thermal contraction these sub-cooled regions will fracture. If natural fractures or a previously created hydraulic fracture is preferentially oriented towards the maximum horizontal principal stress then an elongated sub-cooled region will occur, which has the potential to form fractures perpendicular to the maximum horizontal principal stress (Perkins and Gonzalez, 1984). This can be seen in Figure 1. The effects of thermal and hydraulic fracturing on preexisting thermal and hydraulic fracture networks will also be studied.

Thermal fractures created along a hydraulic fracture have been analytically and numerically shown to grow normal to the hydraulic fracture plane by Perkins and Gonzalez (1985) and Ghassemi (2007). This concept was validated experimentally. Acrylic blocks were loaded uniaxially normal to the axis of the through hole and subjected to high internal water pressures to cause hydraulic fractures. The same blocks were then thermally fractured with liquid nitrogen while under the same 1,000 psi uniaxial external stress and in the same orientation. The blocks were then evaluated visually to calculate the projected surface area in the direction of maximum principal stress.
2. MATERIALS AND METHODS

Proof of concept experiments were conducted using acrylic specimens, stimulated using methods analogous to those that could be used on a reservoir or wellbore scale. The specimens are made of generic cast acrylic that were cast as one thick sheet then machined to size. Acrylic was chosen because it is isentropic, homogeneous and fractures brittle under the conditions subjected to in this research (McLennan, 1980). Block specimens, 8 by 8 by 12.5 in., were uniaxially compressed in order to simulate a difference in horizontal earth stresses without a polyaxial loading frame. The blocks also have a ¼ in. diameter hole through the center as shown in Figure 2. All tests were conducted with the specimens uniaxially-loaded. An Omni Uniaxial Machine, as seen in Figure 3, applied the load. The force was maintained at 100,000 lbf, which results in an average stress of approximately 1000 psi. The uniaxial stress represents a deviatoric stress (presuming that axis of the hole is in the maximum principal stress direction, the 1000 psi is taken to represent the difference between the maximum and minimum total horizontal principal stresses). This is based on the deviatoric stress of 1100 psi that is estimated at the Raft River, Idaho geothermal site (Tran, 2010). 3 2” thick steel plates were used with a semihemispherical plate (gimble plate) to distribute the load evenly through the specimen. The two sides of the steel plates that contact the specimens were machined to 1/64” smoothness. Kimwipes were used as scratch protectors for the acrylic blocks.

Figure 2: Generic Specimen Shape

Figure 3: Acrylic specimen A4 loaded in the Uniaxial Compression Machine with thermal packers installed

2.1 Hydraulic Fracture Experimental Setup

Hydraulic Packers have been fabricated to seal the hole to the tubes attached by means of compressing rubber O-rings. Figure 4 shows the packers that were designed and built to accomplish this task on such a small scale. The 1/8” Swagelok tubing in the center is secured with a Swagelok fitting at one end and tapped at the other. The other metal parts were made out of turned stainless steel tubing ¼” outer diameter and 1/8” inner diameter. It has been found that the O-rings need to be made out of 90 Durameter rubber in order to maintain their position and the pressure. All moving parts and O-rings, except wedges, are coated in silicon plumbers grease. The grease allows the metal parts to move after loading. The 1/8” tubes bend during the experiment and are only good for at most 2 experiments.
Figure 4: Hydraulic Packer; a. Solid works exploded view b. 4” hydraulic packer made of stainless steel tubing and 90 Durameter O-rings with a ¼” outside diameter, c. Packer installed and wedges tightened with 2” C-clamp.

A pneumatically powered dual piston pump delivers the DI water used to hydraulically fracture the blocks. The pump is set to deliver a constant flow rate during the experiment. The pressure increases until fracturing occurs, at which time the pressure drops sharply. A solid steel rod 4” long and 3/16” diameter was placed inside the hole of the specimens during the experiment to reduce the volume of pressurized water. A 7500 psi pressure transducer is attached to the packer on the side of the block that is not receiving the water. The air is flushed out of the specimen prior to the experiment.

2.2 Thermal Fracture Experimental Setup

Hydraulically fractured specimens were thermally fractured with liquid nitrogen. The specimens were oriented so that the hydraulic fracture was under the through hole, to allow gravity to assist the liquid nitrogen in creating an elongated cooled zone. Thermal packers were created by brazing 3/16” diameter brass tubing to ¼” diameter copper tubes. Cotton was then superglued to brass tube in increments of 2”. Harsh environment heat shrink tube was then applied over the cotton and also superglued in place. Then silicone plumbers grease was applied to the outside of the packers to for lubrication. The red silicon rubber stopper at the edge of the copper tube is the final seal. As seen in figure 5 the thermal packers are different lengths so that only the part of the hole with the hydraulic fracture in it is thermally cooled. Both hydraulic fractures were off center the same amount. The liquid nitrogen exited the back packer that was bent to apply a 10” head. The liquid nitrogen was applied for 30 minutes.

Figure 5: Thermal Packers

2.3 Fracture Evaluation

The evaluation of 3 dimensional fractures in bench top experiments was accomplished visually with pictures and photo editing software (Gimp). Because of the complicated geometries that were created traditional techniques like strike and dip are insufficient descriptions. Instead a new approach is used by evaluating the projected area of the fractures in the orthogonal directions of the principal stresses.
Many of the fractures are almost invisible when viewed perpendicular to their faces. This caused the need for experimenting with light and hundreds of digital photographs. The different methods used were, florescent (ambient) light; flash; light back ground; dark back ground; no ambient light with flash; and no ambient light with flash light at various angles. Many of these options were combined and all had success and failure depending on each individual fracture. The projected area of the fractures in a given direction was calculated by converting the number of pixels into inches squared. The ¼” through hole was used as the scale for all of the conversions in each individual photograph. The reported areas are an average of the two opposite sides. This method minimizes the error of the fractures actual size being smaller when it is closer to the camera than the ¼” hole and vise versa.

3. RESULTS
The purpose of this work is to validate the concept of creating fractures that have faces perpendicular to the maximum horizontal earth stress. The bench top experimental analog that has been created to accomplish this was uniaxially loaded and therefor only has one principal stress. Regardless of this, fractures were created that have faces perpendicular to the maximum principal stress.

Hydraulic fractures were first created in 2 acrylic specimens, A2 and A4. This was done by injecting water at high pressure. Both hydraulic fractures formed around 4,000 psi. Figure 6 show the three orthogonal views of the hydraulic fracture of A2. A4 is almost identical except it has a lower angle of deviation from the axis of the hole. This is an expected result for hydraulic fracturing under these conditions. The projected area in the direction of maximum principal stress was calculated visually with the photo editing software Gimp. The projected area of the hydraulic fractures of A2 and A4 in the direction of maximum principle stress are 0.707 and 0.256 in^2 respectively.

Figure 6: Hydraulic fracture of A2 in a. axial direction, b. horizontal direction, and c. maximum principal stress direction.
Figure 7: Thermal fracture after hydraulic fracture of; a. A2, and b. A4. Views are intended to highlight the complexity of the fracture geometries.

The hydraulically fractured specimens were then thermally fractured for 30 minutes with liquid nitrogen. The resulting fracture morphology is quite complex as can be seen in figure 7. However it is simplified somewhat by simply looking at the gross area of the fractures projected in the direction of maximum principle stress. The projected area of the thermal and hydraulic fractures of A2 and A4 in the direction of maximum principle stress are 7.162 and 4.82 in² respectively. The pictures used to calculate this are shown in figure 8. This shows a dramatic increase over that of the hydraulic fractures alone and quantifies the surface area that is perpendicular to the maximum principal stress.

Figure 8: Thermal fracture after hydraulic fracture of; a. A2, and b. A4, in the direction of maximum principal stress.
4. CONCLUSION
Fractures were created that have faces that are perpendicular to the maximum principal stress of the isentropic homogeneous bench top acrylic specimens. This result validates the concept that was first presented by Perkins and Gonzalez (1985). This was accomplished by hydraulically fracturing the specimens, then thermally fracturing them with liquid nitrogen for 30 minutes, all while under a uniaxial load of 1,000 psi.

ACKNOWLEDGMENT
Funding provided by U.S. Dept. of Energy award DE-EE0000215.

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