

LABORATORY STUDIES OF INJECTION INTO HORIZONTAL FRACTURES

Shaun D. Fitzgerald¹, Karsten Pruess² and Diederik M. van Rappard¹

¹Geothermal Program
Department of Petroleum Engineering
Stanford University
Stanford, CA, 94305

²Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA, 94720

ABSTRACT

Most geothermal reservoirs are extensively fractured and injected fluids usually enter the reservoir formation at distinct feed points. As the cold water passes through the hot rock, it is heated, and may be recovered at production wells for power production. The influence of fractures is two-fold. Firstly, preferential pathways exist along major faults and the general motion of fluids away from injection wells is controlled by the effective permeability structure. Secondly, since fractures can be spaced several metres or more apart and the flow rates within each fracture can be relatively high, the injected fluid does not necessarily attain thermal equilibrium with all of the host rock at a given distance from the injection well. It is important that sufficient heat transfer between the fluid and rock occurs before the injected fluid is recovered at an injection well in order to prevent thermal breakthrough. In this paper we present preliminary results of an experimental research program examining the effects of injection into fractures. We build upon previous theoretical work by seeking to confirm the results and then discuss the initial results of injection into superheated reservoirs.

INTRODUCTION

Injection into geothermal reservoirs was initially considered as a mechanism for the disposal of spent brine (Bodvarsson 1972). However, it is now used extensively as a method to help supply additional fluid to the reservoir and to provide pressure support at production wells (Enezy, Enezy and Maney 1991; Enezy *et al.* 1993; Klein and Enezy 1989; Acuña 1994). Experience has shown that in many cases, the injection of condensate has helped reduce the pressure decline (Enezy, Enezy and Maney 1991; Goyal 1994). However, thermal breakthrough has occurred in some instances (Goyal 1994). Indeed, as a result of the financial risks associated with thermal breakthrough, no large-scale injection has been conducted at Wairakei; it is planned that injection should commence within the next year.

The study of injection into geothermal reservoirs has primarily involved the use of analytical and numerical methods. Many previous studies of injection into geothermal reservoirs have focused on the case where the host rock may be suitably modelled as a porous medium; that is, the rock and fluid may be assumed to be in thermal equilibrium at a given distance from the point of injection. Bodvarsson (1972) presented a solution to the problem of injection into a liquid-saturated porous medium. As a result of the heat capacity of the porous medium, the thermal front associated with the injected liquid lags behind the advancing fluid itself. This analytical work was extended by Pruess *et al.* (1987) and Woods and Fitzgerald (1993) who developed solutions to describe injection into a vapour-dominated porous rock. The analysis of injection into discrete fractures is more difficult to perform as a consequence of the three-dimensional heat and mass transfer which results. However, Bodvarsson (1972) presented a solution to the special cases in which the rock bounding the fracture is impermeable and of infinite extent. Subsequent studies of injection into fractured media have involved the use of numerical techniques (Bodvarsson and Tsang 1982; Pruess and Bodvarsson 1984). These studies have isolated the limits in which the fractured rock may be adequately modelled as a porous media.

It is important that the theoretical developments are verified where possible by experiments. Although field scale results have been obtained, the detailed nature of the host rock is not known and therefore, it is difficult to use such results to rigorously test the various theoretical treatments of the problem. As a result, we have commenced a series of laboratory experiments in order to investigate the heat transfer and boiling processes which arise as liquid is injected into a fractured rock. In order to isolate the flow within a fracture, we are at present examining the injection of water into a fracture bounded by impermeable rock. In subsequent studies we shall investigate the matrix-fracture flow which ensues when the rock bounding the fracture is permeable.

We first describe the general experimental procedure, describing the problems encountered during liquid

injection into liquid-saturated and superheated systems. We then describe the primary differences between flows within rough-walled and smooth fractures. The heat transfer which occurs as liquid is injected into a rough-walled fracture is then discussed and the results compared with the theoretical findings. Finally, we describe the preliminary results obtained for injection into a superheated environment.

EXPERIMENTAL PROCEDURE

The smooth-walled fracture apparatus was constructed of two transparent polycarbonate sheets, 18" diameter and 1" thickness. An injection port was drilled into the centre of one of the plates. The rough-walled fracture apparatus was constructed using two sheets of 3/4" thick toughened glass and two sheets of shower door glass. The shower glass sheets were glued to the toughened glass in order to increase the heat capacity of the glass bounding the fracture. It was important that both sets of apparatus were made of transparent material in order that the migration of the front of injected water within the fracture could be followed.

In the case of the smooth-walled fracture, the plates were separated by spacers located at the perimeter of the vessel. In the case of the rough-walled fracture, the plates were clamped together since the surface disparities formed the pathways for fluid to migrate through the fracture. The apparatus was laid horizontally and the fluid injected at either constant rate or pressure into the port from the base. Most of the experiments conducted thus far have used water as the working fluid. However, the preliminary experiments investigating boiling have used ether, which has a considerably lower boiling point (34°C at atmospheric pressure). In order to track the front of the injected fluid, a video camera was placed above the vessel and the injected fluid was dyed with ink. The evolution of the temperature profile within the fracture was recorded by using an array of thermocouples within the fracture. Although the leadwires were drawn across the fracture, no disturbance to the flow was observed. The thermocouples were connected to a digital recorder and the temperatures recorded every 10s. A schematic diagram of the experimental set up is shown in Figure 1.

The investigation of the heat transfer between the rock and fluid was conducted by heating the apparatus overnight in an oven to temperatures varying between 50-90°C. In order to analyze water injection into a liquid-filled fracture, the apparatus was contained in a water bath during the heating stage. The air bubbles which accumulated overnight were removed while the apparatus was submerged. The plates were then clamped together and taken from the water bath in order to perform the experiment.

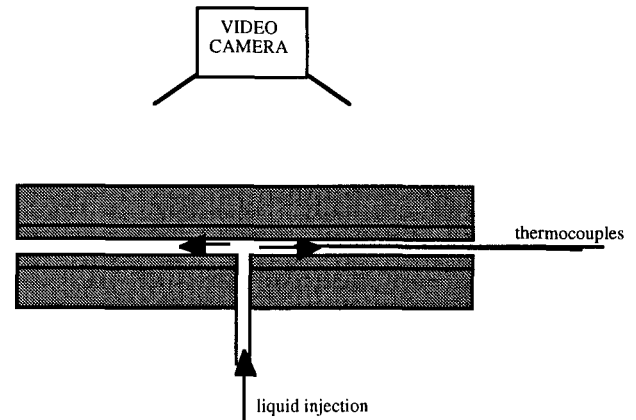


Figure 1 Schematic diagram of the apparatus. Liquid is pumped through the inlet port and migrates through the fracture spreading axisymmetrically.

LIQUID-FILLED FRACTURE

In the first suite of experiments, we compared the injection of dyed liquid into rough-walled and smooth-walled fractures. Experiments were conducted using flow rates of 3, 6 and 10 ml/min. In the smooth-walled fracture, the displacement front consisted of an apparently uniform diffusive boundary layer. A typical flow visualization is shown in Figure 2.

The effective dispersion of the tracer was caused primarily by the difference in fluid velocities close to the fracture wall and mid-channel. In contrast, when dyed liquid was injected at a constant rate into the rough-walled fracture, the displacement front developed fingers of dyed liquid lying approximately parallel with the flow. The length scale of the surface roughness of the shower glass was estimated to be 1mm. It is seen in Figure 3 that the typical length scale of the fingers of dye is several mm. Thus, the effective dispersion of the tracer is considerably greater in the case of rough-walled fractures.

We now examine the additional effects of heat transfer as cold water is injected into a fracture bounded by hot rock. The problem of injection into a fracture bounded by impermeable rock of infinite extent was investigated by Bodvarsson (1972). In his analysis, radial conduction of heat was considered to be negligible, the fluid was assumed to be well mixed across the fracture aperture and at the same temperature as the rock face, and the accumulation of heat by the fluid was ignored. If one includes the accumulation of heat by the fluid then one obtains the following expression for the temperature of the fluid as a function of radial distance r and time t (Mossop 1996)

$$\eta = \text{erf}(\zeta) \quad (1)$$

where

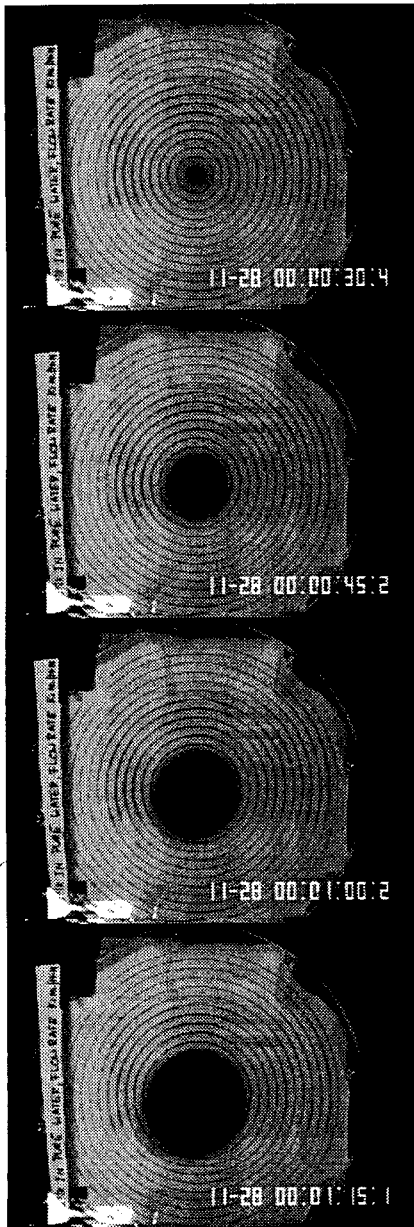


Figure 2. The radial spreading of dyed liquid as it is injected at 10 ml/min into a smooth-walled fracture. The circles drawn are spaced at 1 cm intervals. Photographs are taken at 15 s intervals

$$\zeta = \left(\frac{\Pi k r^2}{Q C_{pw} \sqrt{\kappa \left(t - \frac{\Pi h \rho r^2}{Q} \right)}} \right)^{(2)}$$

and k is the thermal conductivity of the rock (glass), Q is the injection mass flux, C_{pw} is the specific heat

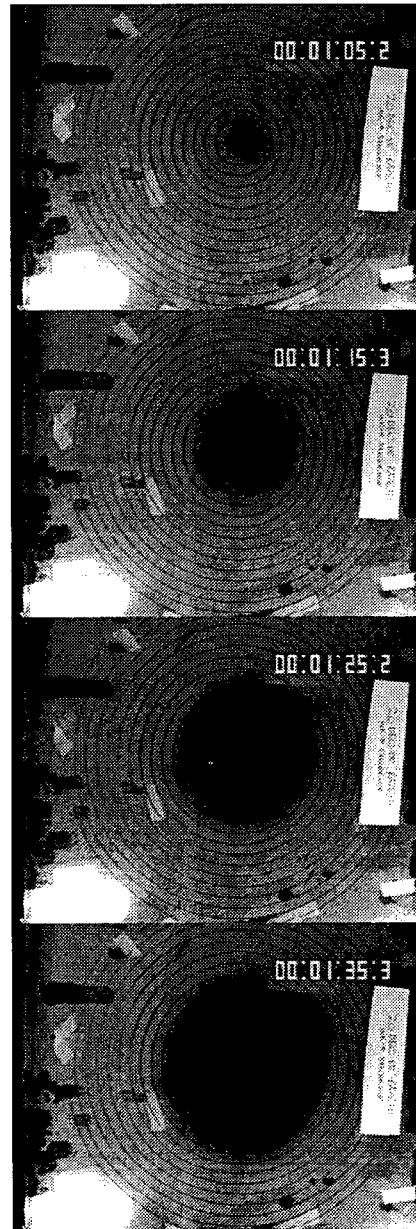


Figure 3. The radial spreading of dyed water as it is injected at 10 ml/min. The interface between the injected (dark) water and water in place consists of strands of dye caused by heterogeneities in the liquid velocity around the disparities of the fracture surface.

capacity of water, κ is the thermal diffusivity of the rock (glass), h is the fracture aperture and ρ is the density of water. η is the dimensionless temperature defined as

$$\eta = \frac{T - T_{inj}}{T_0 - T_{inj}} \quad (3)$$

where T_{inj} is the temperature of the injected fluid and T_0 is the initial temperature of the rock. Values used in the experiments were as follows: $k=0.937\text{W/mK}$, $Q=5\text{-}10\text{g/min}$, $C_{pw}=4180\text{J/kgK}$, $\kappa=4.21\text{e-}7\text{m}^2/\text{s}$, $h=0.18\text{mm}$ and $\rho=1000\text{kg/m}^3$. The theoretical prediction for the variation of temperature η with dimensionless time ξ at a given distance from the injection port is shown by the solid line in Figure 4.

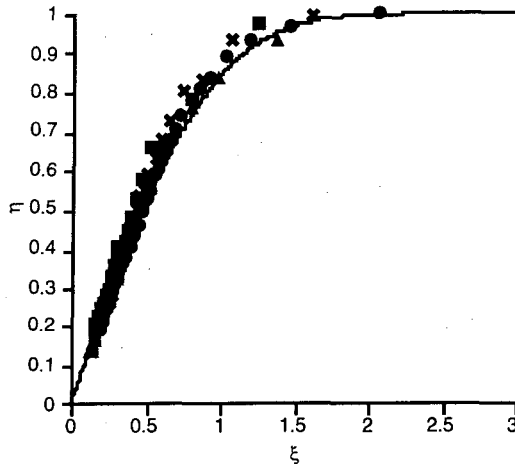


Figure 4. The variation of dimensionless temperature η as a function of the similarity variable ξ . The solid line represents the theoretical prediction and the symbols represent the results obtained from a series of experiments in rough-walled fractures.

We have conducted a series of experiments in which water of temperature 20°C was injected into a fracture bounded by rough-walled glass varying in temperature between $40\text{-}90^\circ\text{C}$. Thermocouples were placed within the fracture at various distances from the inlet port. As liquid water was injected into the fracture, the temporal changes in temperature were recorded. The results of these experiments are also plotted in Figure 4. Each experimental set of observations are represented by different symbols. We find that the experimental results are in excellent agreement with the theoretical prediction even though the theory is only strictly valid for rock of infinite extent. In our experiments the glass sheets were 1.9cm thick. We thus expect that the cooling of the outer surfaces of the glass to become important after a time of order (D^2/κ) where D is the thickness of the glass. Using the manufacturers value for the diffusivity $\kappa = 4.21\text{e-}7\text{m}^2/\text{s}$ we find that the time which may elapse after taking the glass from the water bath before the effects of cooling become important is approximately 15 mins. All of the experiments were completed within this time frame.

VAPOUR-FILLED FRACTURE

In numerous geothermal reservoirs, some of the fractures are filled with vapour rather than liquid. This

can be the result of large scale depletion such as at Wairakei (Grant 1979), where the fractures were originally liquid-filled, or can occur naturally where the reservoir is vapour-dominated such as The Geysers or Larderello. As liquid is injected into such systems, a fraction of the water boils and may be recovered at nearby production wells for power generation (Enezy *et al.* 1993). However, the fraction of liquid which boils is a function of the amount of heat which can be extracted from the rock as the injected fluid migrates along the fractures. A number of studies of liquid injection into a superheated reservoir consisting of a porous rock have been conducted (Pruess *et al.* 1987; Woods and Fitzgerald 1993). These studies showed that the amount of heat which can be extracted from the rock and used for vaporization is a function of the extent of cooling which occurs at the vaporization front. In the case of injection into a porous medium, the heat required to overcome the latent heat of vaporization is supplied by the rock grains within the vapour-saturated thermal boundary layer immediately ahead of the liquid-vapour interface. However, in the case of a fractured system, the heat is supplied by conduction from the fracture walls perpendicular to the flow. In order that boiling may occur, the heat required to overcome the latent heat of vaporization must be supplied over a finite area. As a result, boiling has to occur over a broad two-phase zone rather than a sharp interface. This is in contrast to the case of injection into a porous medium where the liquid-vapour transition zone can be a narrow interface at low degrees of superheat (Fitzgerald and Woods 1994).

Having established that boiling must occur over a two-phase zone, it is of interest to determine how the liquid- and vapour-saturations vary with radial distance and whether the zone is stable. As liquid is injected into the fracture, we expect that the pressure will decrease monotonically away from the inlet port as fluid migrates into the far-field. After a period of injection we anticipate that the fluid within the fracture close to the inlet port will be liquid since the pressure is highest at this point and the rock closest to the injection point will have undergone the most cooling. In the far-field, we expect that the fracture will be filled with vapour at relatively low pressure and at a temperature close to the initial temperature of the rock. However, if the pressure is prescribed to decrease monotonically away from the inlet port and the boiling zone is to be of finite extent then the temperature must decrease within the boiling zone if steam and water are in thermodynamic equilibrium. This prediction is in agreement with the results obtained from the full numerical solution of liquid injection into a vapour-filled fracture shown Figure 5. The most striking feature of this result is that the temperature is predicted to vary non-monotonically with radial distance away from the injection site. In order to determine whether a two-phase zone does

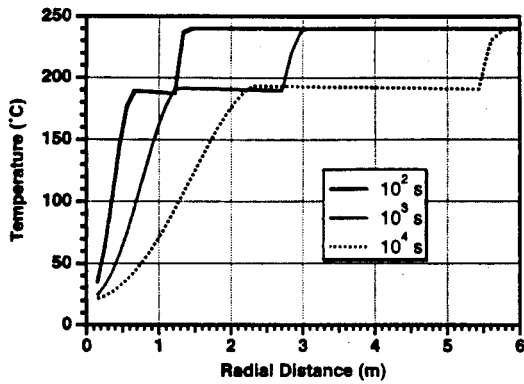


Figure 5. The variation of temperature within a fracture as liquid is injected into a fracture initially at temperature 240°C and pressure 1MPa. In the example shown the injection rate is 0.1kg/s and the effective fracture aperture is 1mm.

indeed form ahead of a liquid-filled region we have conducted a series of experiments. In order to perform the experiments at temperatures less than 100°C and at atmospheric pressure, ether was chosen as the working fluid. Ether boils at 34.5°C at atmospheric pressure and thus we were able to study the boiling process using fracture temperatures of 50-90°C. In Figure 6 we show a series of photographs taken at various times during the course of one experiment as ether was injected at constant pressure into a smooth-walled fracture. As the ether migrated radially out into the fracture, a liquid zone developed close to the injection port. In Figure 6 liquid-filled regions of the fracture are shown as the darker zones and the vapour-filled regions are shown as the lighter zones. Ahead of the liquid-filled region immediately surrounding the inlet port a two-phase zone was observed to form. The liquid and vapour portions of the two-phase zone were segregated as shown and the liquid 'tongues' moved erratically as they partially boiled. The unstable nature of the flow is evident in the photographs of Figure 6 since the liquid fingers do not remain in the same position during the time series.

The unstable nature of liquid fingers is of great concern since it is important that premature thermal breakthrough of cold injected water at nearby production wells be avoided. When liquid is injected into a superheated porous medium, the liquid-vapour interface may become unstable if the vaporizing fraction is sufficiently high that the pressure gradient within the vapour zone is greater than that within the liquid zone (Fitzgerald and Woods 1994). Liquid fingers can therefore develop and preferential pathways for cold water may be formed. The experimental results shown in Figure 6 suggest that liquid fingers can also form within the fractures of a fractured reservoir. Since fractures provide preferential pathways for injected liquid in geothermal reservoirs,

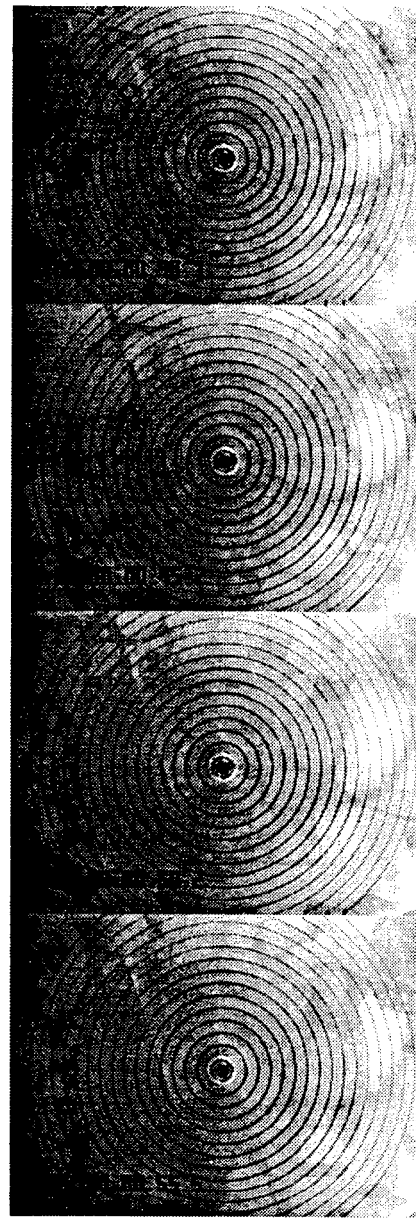


Figure 6. The flow of ether within the fracture as it spreads out from the central source. The dark zones correspond to the liquid-filled portions of the fracture and the lighter areas correspond to the vapour-filled regions. Ether was supplied at constant pressure. The fingers of liquid ahead of the purely liquid-filled zone move rapidly and change position as the experiment proceeds. Photographs are shown at 5s intervals.

the formation of fingers within the fractures suggests that the risk of the production of cold liquid at nearby production wells may be greater than has previously been recognized.

CONCLUSIONS

We have shown experimentally that the dispersion of tracers increases with surface roughness, in accordance

with theoretical predictions (Phillips 1991). We have also shown that the theoretical prediction for heat transfer in a fracture bounded by infinite rock is in good agreement with experimental observations. As liquid migrates out into the reservoir from an injection well feed point, the rock immediately surrounding the injection well is cooled rapidly. In the case of liquid injection into a depleted reservoir, the migration of liquid along the fractures is much more complex. A liquid-filled region develops close to the injection well. A two-phase region develops ahead of this zone. Our experimental observations suggest that the system is unstable since the two-phase region consisted of distinct liquid and vapour zones and the position of the liquid-filled zones changed rapidly.

We are currently developing this work further and are examining liquid injection and phase change within rough-walled fractures.

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