

## INJECTION INTO GEOTHERMAL SYSTEMS

Shaun D. Fitzgerald<sup>1</sup>, Andrew W. Woods<sup>1</sup> and Catherine Tsui-Ling Wang<sup>2</sup>

<sup>1</sup>Geothermal Program  
Stanford University  
Stanford, CA, 94305, USA  
shaun@stanford.edu

<sup>2</sup>School of Mathematics  
University of Bristol  
Bristol, BS8 1TW, England  
a.w.woods@bris.ac.uk

### ABSTRACT

We present the results of a suite of experiments which have been performed in order to determine the effects of injection into geothermal reservoirs. The results obtained from the experiments are compared with theoretical predictions of the evolution of temperature profiles within a geothermal reservoir following the injection of supercooled liquid. For the case of constant rate liquid injection in an axisymmetric geometry into a liquid-filled porous medium, we find that at slow rates of injection heat is conducted from the far-field towards the source. However, at higher rates of injection, an isothermal zone develops close to the injection well.

We then present the results of an experiment in which liquid was injected into a porous slab initially filled with superheated vapour. We compare the evolution of the temperature profile within the system with the theoretical prediction (Woods and Fitzgerald, 1997) and find that a sharp interface may develop between the liquid- and vapour-filled regions.

Finally, we investigate the injection of liquid into a fracture which initially contains superheated vapour. We compare the evolution of the temperature profile within the fracture with a numerical prediction obtained from TOUGH2 (Pruess, 1991). It is found that a broad two-phase region exists between the completely liquid-filled and vapour-filled zones of the system.

### INTRODUCTION

As geothermal reservoirs are exploited for power production or district heating, they become depleted and reservoir pressures fall. As a result of the potential significant reduction in well flow rates, injection is now viewed as a strategic element of an exploitation program for a geothermal reservoir. The additional pressure support that is possible through the reinjection of spent brine can help minimize the reduction in pressure. However, although the potential benefits of additional pressure support by injection are large, there is a risk of breakthrough of

cooler injected fluid at the production wells. If cold fluid reaches a production well the effects can be devastating. The specific enthalpy of the produced fluid falls. This leads to an increase in the average density of fluid within a production well, and therefore, the flowrate also decreases. The ability to predict the time at which injected cold fluid reaches a production feed zone is important and a number of modelling studies have been performed aimed at determining the evolution of the temperature profile within a reservoir following the onset of injection (Pruess *et al.*, 1987; Woods and Fitzgerald, 1993, 1996, 1997).

In this paper we present the results obtained from a series of analogue laboratory experiments which were performed to investigate liquid injection into geothermal reservoirs. We first discuss the case of liquid injection into a liquid-filled porous medium and compare the experimental findings with the predictions obtained from a theoretical model (Woods and Fitzgerald, 1996). We then present the results obtained from an experiment in which liquid was injected into a porous medium initially filled with superheated vapour. The evolution of the temperature profile within the system is found to agree with the theoretical model proposed by Woods and Fitzgerald (1996). Finally, we consider the case of liquid injection into a fractured system. The experimental findings are compared with predictions obtained from a numerical model TOUGH2 that was modified to enable us to model the boiling of ether within the fracture.

### LIQUID INJECTION INTO A LIQUID-FILLED POROUS MEDIUM

We have performed a series of experiments to test the model of liquid injection into a porous layer developed by Woods and Fitzgerald (1996). In the first suite of experiments, the apparatus consisted of a cylindrical bed of consolidated permeable sand, of radius 35cm and 3cm deep enclosed between two impermeable layers of epoxy resin. The sand bed consisted of 82% 30 mesh sand and 18% Portland

cement. Twelve thermocouples were embedded into the sand layer at approximately 1cm radial intervals from the central injection port and these were connected to a digital data recorder. Before each experiment, carbon dioxide was injected into the centre of the apparatus in order to displace the air. Cold de-ionized water was subsequently injected in order to displace the carbon dioxide. Any remaining CO<sub>2</sub> dissolved in the water. Insulating material was then placed on the upper and lower surfaces of the epoxy boundaries and the apparatus was connected to a water pump and heater.

In each experiment water was supplied at a constant rate, which was varied from experiment to experiment in the range 5-50 ml/min. For convenience, hot water was injected into a cold liquid-filled sand bed and several experiments were conducted using different flow rates and injection temperatures. The primary advantage of using a sand bed filled with liquid at room temperature, rather than at an elevated temperature, was that the risk of exsolution of any dissolved gases at room temperature was minimized. After completion of the experiments two CT scans of the sand layer apparatus were taken, one with the core fully dry and one with the core fully saturated with liquid. Using these measurements, the porosity  $\phi$  was estimated to be 35+/-3%. Using this estimate together with the known properties of the sand, the effective thermal diffusivity of the porous medium was calculated to be 1.3+/-0.1E-06m<sup>2</sup>/s. During each experiment, temperature measurements were recorded every 5s.

We wish to use the results obtained from these experiments in order to test the theoretical prediction proposed by Woods and Fitzgerald (1996). In this paper we developed a similarity type solution for the evolution of the temperature profile as a function of radius and time for the case in which liquid is injected at a constant rate  $2\Pi Q$  from a central source in an axisymmetric geometry. Following the theory of Woods and Fitzgerald (1996, 1997), the temperature profile is expected to develop according to

$$T(\eta) = T_o + \Delta T \int_0^\eta \eta^{\lambda_w \beta - 1} \exp(-\eta^2) d\eta \quad (1)$$

where  $\beta = Q/\kappa$ ,

$$\Delta = (T_2 - T_0) / \int_0^\infty \eta^{\lambda_w \beta - 1} \exp(-\eta^2) d\eta \quad (2)$$

$T_0$  is the source temperature,  $T$ , is the far-field temperature,  $\lambda_w = \rho_l C_{pl} / (\phi \rho_l C_{pl} + (1-\phi) \rho_r C_{pr})$ ,  $\rho_l$  and  $\rho_r$  are the densities of liquid water and rock respectively,  $C_{pl}$  and  $C_{pr}$  are the specific heat capacities of liquid and rock, and  $\kappa$  is the average thermal diffusivity of the liquid-filled porous medium.

In Figure 1 we compare the temperature profiles obtained in an experiment with the theoretical predictions for the case  $\beta=0.67$  and  $\beta=3.4$ . The radial

locations of these measurements have been non-dimensionalized  $\eta = r/(2\kappa t)^{1/2}$  and the temperature profiles are shown as a function of  $\eta$ . For both the fast injection case  $\beta=3.4$  and the slower injection case  $\beta=0.67$ , the experimental results collapse accurately onto the theoretical temperature profiles.

The experimental data confirms the theoretical prediction that at low flow rates ( $\beta < 1/\lambda_w$ , Figure 1(i)), the isotherms are advected more slowly than the rate of conduction, so the internal boundary layer extends back to the source. However, at high flow rates ( $\beta \lambda_w > 1$ , Figure 1(ii)), the liquid is heated to the far-field temperature by cooling the rock near the source.

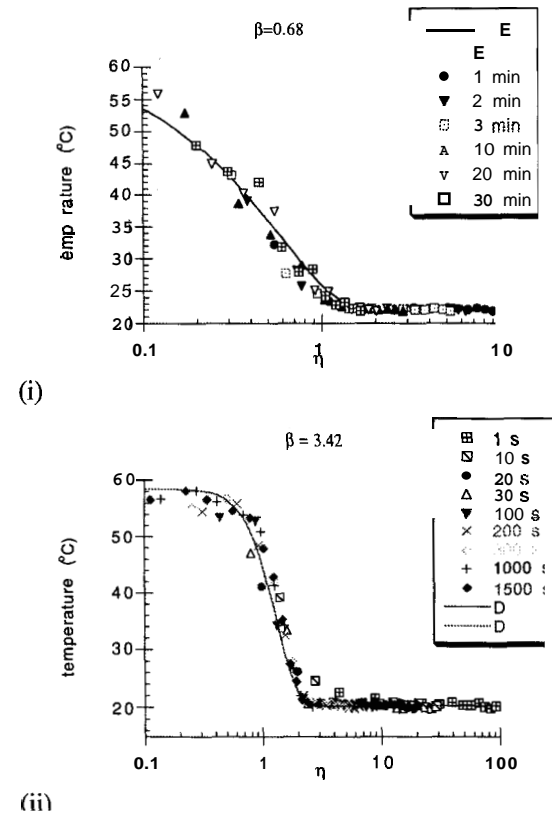


Figure 1 Comparison of the model predictions with experimental measurements of temperature as a function of distance from the source. Distances are shown in dimensionless form  $\eta = r/(2\kappa t)^{1/2}$ . Results are shown for two experiments in which hot liquid is injected into a cold water saturated layer. (i)  $\beta=0.67$ ,  $T(\text{input})=63$  C and  $T(\text{initial})=20.2$  C and (ii)  $\beta=3.42$ ,  $T(\text{input})=59$  C and  $T(\text{initial})=21$  C. Symbols show the temperature at different times during the experiment. The solid lines correspond to the theoretical prediction.

We now extend our discussion to investigate the case of liquid injection into a porous medium initially containing superheated vapour.

### **LIQUID INJECTION INTO A VAPOUR-FILLED POROUS MEDIUM**

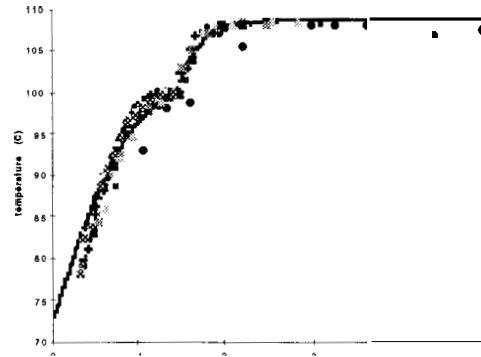
Following the exploitation of a number of geothermal reservoirs such as The Geysers, there now exist zones in which the reservoir pressure is below the local saturation pressure corresponding to the reservoir temperature. These regions are prime candidates for the injection of liquid since it is in these regions that the pressure has usually declined most significantly, thereby leading to dramatic decreases in flow rate from the production well. In addition, the reduction in pressure and formation of reservoir superheat has created the possibility for injection of fluid and subsequent vaporization of this fluid. We now extend the experimental techniques developed in the previous section to the case in which an analogue reservoir initially contains superheated vapour.

The apparatus used in these experiments consisted of a slab of 500 md, 15.5% porosity Berea sandstone, 12in in diameter and 0.95in thickness. The sandstone core was initially heated in an oven to 500°F for 24 hours in order to deactivate the clays. This was performed in order that during the injection experiments, the clays did not swell and thereby block the pores. 12 thermocouples were then placed at various distances from the centre of the disk and a central injection port was also drilled. The thermocouple holes were aligned along three radial transects and were drilled to a depth of 0.475in so that the thermocouples recorded the temperatures at the centre of the slab. Epoxy resin was applied to the upper and lower surfaces of the sandstone core to form impermeable boundaries and the core was then flooded with carbon dioxide.

In order to study the boiling of liquid within the porous medium, the apparatus was heated in an oven at 108°C for several hours. The apparatus was then removed from the oven, laid horizontally on insulating material and covered with additional pieces of insulation. Deionized water which had been heated to approximately 75°C was then pumped through the injection port at a rate of 10ml/min. Temperatures were recorded every 5s by a digital data recorder.

Woods and Fitzgerald (1996, 1997) presented a theoretical model for the evolution of the system as liquid is injected at a constant rate into a porous medium in an axisymmetric geometry. In this model, the temperature profile is also described by a similarity solution in terms of the variable  $\eta = r/(2\kappa t)^{1/2}$ . The theoretical prediction obtained from

Woods and Fitzgerald (1996, 1997) is plotted in Figure 2 with the experimental data.



*Figure 2 Temperature as a function of  $\eta$  for an experiment in which water was injected at 73°C into a sandstone core initially at 108°C. The injection rate of 10ml/min into a core 0.95in thick corresponded to the case  $\beta=0.67$ . Symbols represent the experimental data and the solid line indicates the theoretical prediction. Each set of symbols corresponds to temperatures obtained from one thermocouple.*

The temperature profiles within both the liquid- and vapour-filled regions are in close agreement with those predicted from the theory. Furthermore, the interface between the liquid- and vapour-filled zones is found to be sharp, in accord with the theoretical model. However, there are some noticeable discrepancies. In particular, the experimental data indicates that the temperature does not necessarily increase monotonically with radius away from the injection port. 12 thermocouples were used in the experiment, 4 thermocouples aligned along 3 different radial segments. The variation in temperature along each line of 4 thermocouples indicated that the boiling interface did not propagate as a circular front. If the apparatus was not perfectly level, then a non-circular front would be expected. However, we are reasonably confident that the apparatus was level. Propagating boiling fronts can become unstable if the fraction  $F$  which boils is sufficiently high (Fitzgerald and Woods, 1994). However, in the present experiment the fraction which boiled was approximately 7% which is much less than the critical value. As a result, it is likely that the departures in temperature away from the theoretical prediction were caused by heterogeneities in the permeability of the sandstone core. Even though the scatter in the data indicates that the interface did not propagate uniformly, the general agreement between the experimental data and the theory suggests that the theory is valid over length scales greater than the scale of non-uniformity of the front.

The close agreement between the experimental data and model predictions for injection into porous media is comforting. However, geothermal reservoirs can also contain extensive zones of fractured rock. We have therefore extended our study of liquid injection into superheated rock to investigate the effects of injection into an isolated fracture.

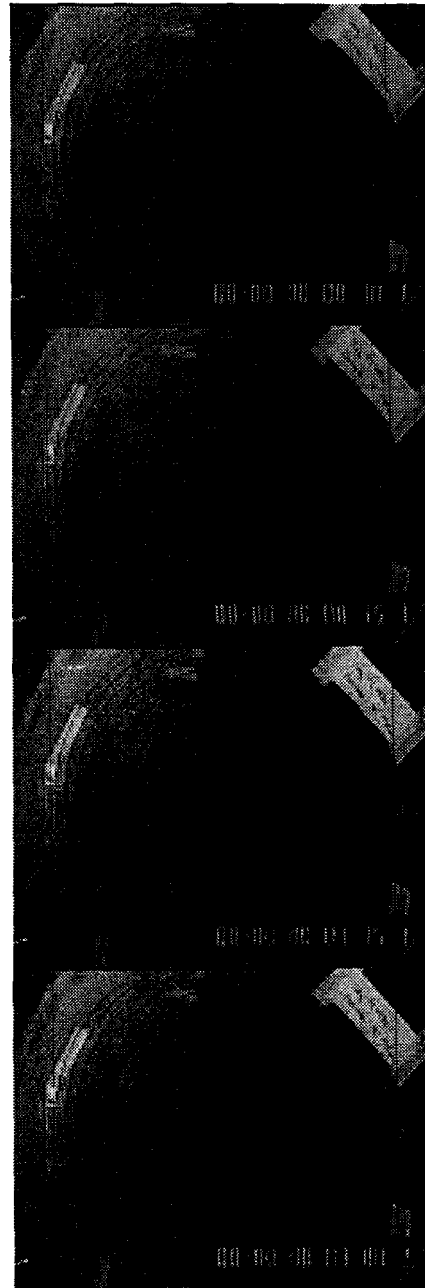
### **LIQUID INJECTION INTO A VAPOUR-FILLED FRACTURE**

In the case of liquid injection into a porous medium filled with superheated vapour, 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 and the amount of heat which is conducted towards the point of injection. 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 at low degrees of superheat, where the liquid-vapour transition zone can be a narrow interface.

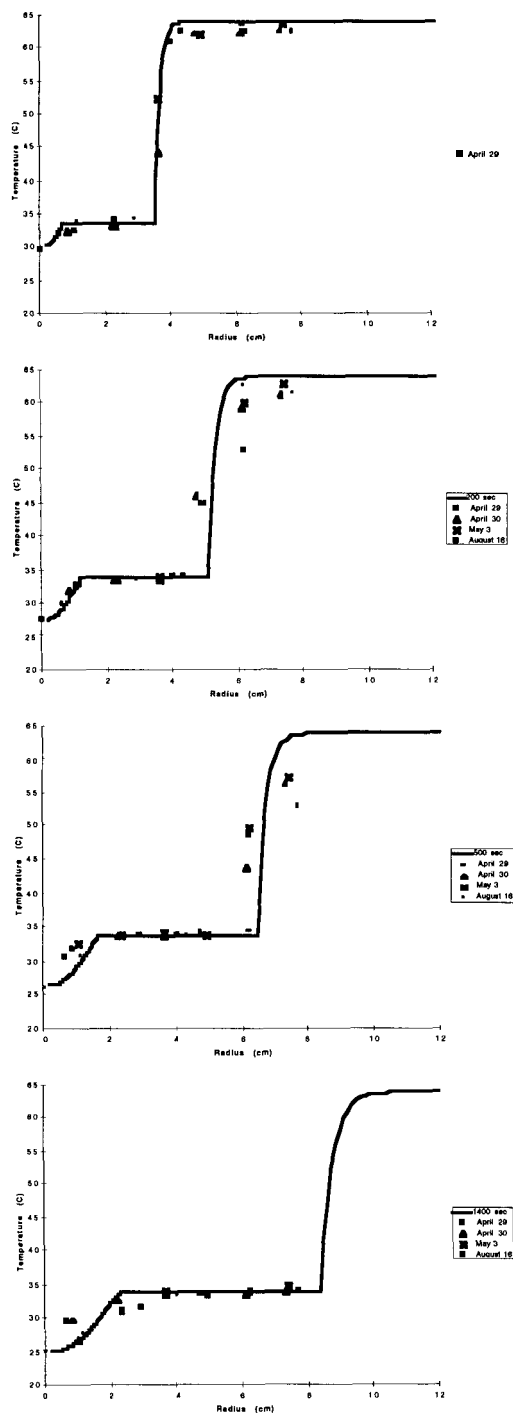
In order to develop a quantitative model of this scenario we have used the TOUGH2 general purpose numerical code (Pruess, 1991) for solving the coupled equations of heat and mass conservation in a fractured-porous type geothermal reservoir.

In addition we have conducted a series of experiments in which liquid ether was injected at rates of 10-20 ml/min into a horizontal rough-walled fracture in order to determine whether a two-phase zone does indeed develop as predicted. Ether was chosen as the working fluid since it boils at 34.5°C at atmospheric pressure thereby enabling us to study the boiling process using fracture temperatures of 50-90°C. In Figure 3 we show a series of photographs taken at various times during the course of one experiment as ether was injected at constant rate. As the ether migrated radially out into the fracture, a liquid zone developed close to the injection port. Ahead of this zone a two-phase region developed. The leading (front) edge of the two-phase zone is shown in Figure 3 by the region of concentrated dye. The orange dye used was only soluble in the liquid phase of ether and therefore accumulated at the edge of the boiling zone as shown. The front was observed to remain roughly circular. The present experimental results provide a reliable data set to test the numerical prediction of TOUGH2. The numerical problem considered for

comparison with the experimental observations was a two-dimensional radial system with semi-infinite fracture walls.



*Figure 3 The spreading of dyed ether as it is injected at 20ml/min. The times shown correspond to times 10, 15, 75 and 180s after the onset of injection. The region of concentrated dye indicates the leading (front) edge of the two-phase boiling zone.*



**Figure 4** Temperature profiles at times 50, 200, 500 and 1400s after the onset of injection of 21°C liquid ether at 10 ml/min into a fracture originally at 64°C. The symbols represent data obtained from different experiments and the solid line indicates the profile obtained from the modified numerical code TOUGH2.

In order to compare the numerical prediction of the code with the experimental results, the code was modified to incorporate the physical properties of

ether rather than water for the reservoir/apparatus fluid. For example, properties of ether at atmospheric conditions include: vapour density 3.33 kg/m<sup>3</sup>, liquid density 713.8kg/m<sup>3</sup>, latent heat of vaporization 377.7kJ/kg, vapour viscosity 8.4e-6 kg/sm and liquid viscosity 1.66e-4 kg/sm (Weast, 1972).

We found that heat was transferred from the brass injection port to the liquid ether. In order to account for this additional heat transfer we placed a thermocouple within the fracture at the point of entry of the fluid. As the experiment proceeded the inlet temperature of the liquid ether to the fracture decreased as expected. Therefore, the inlet temperature of the liquid used in the numerical fracture model was reduced at various times in accord with the experimental observations.

Experiments were conducted at flow rates of 10 and 20 ml/min. Typical temperature profiles at various times for 10ml/min are shown in Figure 4. It is seen that the agreement between the experimental observations and the numerical predictions is good. Close to the injection port a liquid-filled region develops as predicted. Within this liquid-filled zone the experimental data is in very close agreement with the numerical prediction. The radial temperature and temperature gradient increase away from the injection site until boiling conditions are attained. Ahead of the liquid zone lies a two-phase zone. The scatter of the experimental data becomes greater towards the leading edge of the two-phase zone. During the course of the experiments it was found that the leading edge of the boiling zone tended to pulse rather than migrate steadily. As a result, the temperature may have fluctuated whereas the numerical prediction did not indicate this phenomenon. These experimental results suggest that the predictions for the evolution of the temperature, pressure and saturation distributions which one may obtain from TOUGH2 are likely to be very accurate for uniform horizontal fractures bounded by impermeable rock.

## CONCLUSIONS

We have conducted a series of laboratory experiments in order to test the theoretical models of liquid injection into a liquid-filled or superheated porous medium type reservoir (Woods and Fitzgerald, 1993, 1996). In the case of liquid injection into a liquid-filled porous medium we found that at low flow rates, the temperature increases immediately from the injection port in accord with the theory. However, at higher flow rates, an isothermal zone develops close to the inlet site. The liquid is heated to the far-field temperature by cooling the rock close to the source.

We have also performed an experiment in which liquid was injected into a porous rock initially filled with superheated vapour. In this case a sharp interface

etween the liquid- and vapour-filled regions develops. The amount of heat available for vaporization depends upon the difference in the amount of heat conducted from the vapour-filled zone towards the interface and heat conducted away from the interface into the liquid-filled zone. The experimental results indicate that the theoretical treatment of injection proposed by Woods and Fitzgerald (1996, 1997) is accurate.

We then investigated the case in which liquid is injected into a fracture bounded by impermeable rock in order to ascertain the primary differences between heat transfer and boiling within porous media and fractured systems. It was found that a broad two-phase zone formed within the fracture in order that boiling would occur. This is in contrast to the case of boiling in a porous medium where a sharp interface formed between the liquid- and vapour-filled zones.

We are in the process of developing this work further and will examine experimentally how an injection plume migrates under gravity and how the rate of propagation of the cold water changes when the rock bounding the fracture is permeable.

#### **ACKNOWLEDGEMENTS**

Our work is supported by USDOE, PG E. JNOCAL and Caithness Corp.

#### **REFERENCES**

Fitzgerald, S.D. and Woods, A.W. 1994 The instability of a vaporization front in hot porous rock. *Nature* **367**, 450-453.

Pruess, K. 1991 *TOUGH User's Guide*. Earth Sci. Div., Report LBL-20700, Lawrence Berkeley Laboratory.

Pruess, K., Calore, C., Celati, R. and Wu, Y.S. 1987 An analytical solution for heat transfer at a boiling front moving through a porous medium. *Int. J. Heat Mass Transfer* **30**(12), 2595-2602.

Weast, R.C. 1972 *Handbook of Chemistry and Physics*. Chemical Rubber Co.

Woods, A.W. and Fitzgerald, S.D. 1993 The vaporization of a liquid front moving through a hot porous rock. *J. Fluid Mech.* **251**, 563-579.

Woods, A.W. and Fitzgerald, S.D. 1996 The effects of heat conduction on the vaporization of liquid invading superheated permeable rock. *Proc. Stanford Geothermal Reservoir Engineering Workshop* **21**, 421-425.

Woods, A.W. and Fitzgerald, S.D. 1997 The vaporization of a liquid front moving slowly through a hot porous rock. Part II. *J. Fluid Mech. in press*