Proceedings 18th NZ Geothermal Workshop 1996

LABORATORY AND THEORETICAL STUDIES OF INJECTION INTO HORIZONTAL FRACTURES

S. D. FITZGERALD[1], C.T. WANG[1] AND K. PRUESS[2]

[1] Geothermal Program, Department of Petroleum Engineering, Stanford University, USA
[2] Earth Sciences Division, Lawrence Berkeley National Laboratory, University of California, USA

SUMMARY - The location of feed points in wells and the transport paths of injected fluid are dominated by the presence of fractures in a geothermal reservoir. As the cold water passes through the hot rock, it is heated, and may be recovered at production wells for power production as hot liquid or steam. It is important that sufficient heat transfer between the fluid and rock occurs before the injected fluid is recovered at a production well in order to prevent premature thermal breakthrough. Several modeling techniques are available for assessing the migration of cold water fronts through geothermal reservoirs (Bodvarsson, 1972; Pruess *et* al., 1987; Bodvarsson and Tsang, 1982; Woods and Fitzgerald, 1993). However, only porous medium type models of fluid flow and heat transfer in geothermal reservoirs have been rigorously tested by laboratory experiments (Fitzgerald and Woods, 1994; Woods and Fitzgerald, 1995, 1996). In this paper we report upon a series of laboratory experiments which have been conducted in order to test the theoretical models for liquid injection and heat transfer within liquid-dominated and vapour-dominated fractured geothermal reservoirs. We find that the analytical solution for the liquid-dominated case of radial flow, and numerical solution for the vapour-dominated case, agree very well with the experimental results.

1. INTRODUCTION

In the early stages of development of geothermal power for electricity, the seperated brine or condensate which was produced was considered to be a waste disposal problem. In some cases the fluid was disposed of in a nearby river such as in Tibet and at Wairakei, New Zealand. Geothermal brine typcially contains toxic substances such as arsenic and boron, and therefore it is not generally permissible nowadays to dispose of the fluid in this way. Injection of this fluid provides an alternative diposal mechanism, and deep reinjection in the peripheral areas of Onikobe, Japan (Home, 1982) and Palinpinon, Philippines (Harper and Jordan, 1985) have been successful. Further strategic changes in the treatment of seperated brine or condensate have arisen following significant pressure reductions in various reservoirs following their exploitation. Severe reduction in reservoir pressure is primarily caused by the net extraction of fluids. Hence, reinjection of reservoir fluid is now considered a major factor in the development plan for geothermal reservoirs since reinjection reduces the net fluid loss from the reservoir. In some cases additional liquid is being considered for injection in order to help maintain the reservoir pressure and provide a solution for the disposal of toxic waste. At The Geysers, contruction has commenced on a $40m pipeline to transport treated waste water froin Lake County to the reservoir in order to provide sufficient fluid for injection. Plans are also being considered for the injection at The Geysers of waste water from the city of Santa Rosa.

Experience has shown that in many cases, the injection of brine or condensate has helped reduce the pressure decline (Enedy, Enedy and Maney 1991; Goyal 1994). However, thermal breakthrough has occurred in some instances (Goyal 1994). Thermal breakthrough associated with large volumes of reinjected brine at Kakkonda caused a reduction in plant performance from 50MW in July 1979 to 37 MW in April 1981. Premature thermal breakthrough resulted from the fracture network linking various injection wells to some of the production wells. Cessation of injection into these particular injection wells enabled the power plant output to return to 41 MW by October 1981 (Nakamura 1981).

Theoretical treatments of fluid migration and heat transfer within geothermal reservoirs based upon porous medium type models are unable to account for the thermal degredation in production wells which arise due to cold water migrating through fractures. Some of the primary benefits of these type of models are that they are relatively simple to use and have been successfully compared with laboratory experiments (Fitzgerald and Woods. 1994; Woods and Fitzgerald, 1996, 1997). In a porous medium type model of cold water injection into a geothermal reservoir, the thermal front associated with the injected liquid lags behind the advancing fluid itself (Bodvarsson, 1972; Pruess et al., 1987; Woods and Fitzgerald, 1993). 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. When liquid migrates along a fracture, conduction of heat along the axis of flow and perpendicular to the direction of fluid flow can be important. In situations where the fractures are spaced sufficiently close together that the time for thermal diffusion between the fractures is much faster than the timescale of interest, the fractured system can be adequately described by an equivalent porous medium system (Bodvarsson and Tsang, 1982; Pruess and Bodvarsson, 1984). However, in many instances this is not tlie case and explicit modelling of the presence of fractures is required.

We have perfonned a series of laboratory experiments designed to test the theoretical treatments of liquid injection into liquid-dominated and vapour-dominated reservoirs (Bodvarrson, 1972; Mossop, 1996; Pruess et *al.* 1987). Experiments have been performed in which liquid was injected at a constant rate into an impermeable transparent glass-walled fracture. The temperature changes due to heat transfer were recorded using thermocouples and the migration of the front by video.

We first describe the experimental procedure, describing the problems encountered during liquid injection into liquid-saturated and superheated systems. Wc then discuss the lieat transfer which occurs **as** liquid is injected into a rough-walled fracture and compare the results with the theoretical predictions.

These results build upon the earlier experimental work of Fitzgerald, Pruess and van Rappard (1996).

2. EXPERIMENTAL PROCEDURE

The fracture apparatus was constructed using two 18" diameter 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 the apparatus was made of transparent material in order **that** the migration of the front of injected water within the fracture could be followed. An injection port was drilled into the centre of one of **the** fractures and a brass injectioii fitting was glued to the outer surface. **Tlie** glass plates were laid on top of one another in order to create the fracture and the surface disparities formed the pathways for the migration of fluid. Tlie plates were sufficiently heavy that the fi-acture remained at the same aperture for the flow rates used without the use of clamping devices.

The apparatus was laid horizontally and the fluid injected at either constant rate or pressure into the port from the base. For the experiments in which liquid was injected into a liquid-filled fracture deionized water was used as the working fluid. However, tlie experiments investigating boiling used ether since it has a considerably lower boiling point **(34°C** at atmospheric pressure). In order to track tlie front of the injected fluid, a video camera was placed above the vessel and the injected fluid was **died** with ink. As the fluid migrated through the fracture the position of the front **marked** by the ink was clearly visible. In the case of Iiquid injection into a liquid-filled fracture, the ink front conresponded to the front of new fluid. However, in the case of boiling within the fracture, the ink front marked the leading edge of a two-phase zone since the dye was only soluble in the liquid phase. As a result, injected fluid existed ahead of the front **as** vapour. The evolution of the temperature profile within tlie fracture was recorded by using an array of thermocouples within the fracture. Although the leadwircs wcre drawn **across** the fracture, no disturbance to tlie flow was observed. The thermocouples were connected to a digital recorder and tlic temperatures recorded every **10s.** A schematic diagram of tlie experimental set up is **shown** in Figure 1.

The investigation of tlie 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 plates were then placed together and taken from the water bath in order to perform the experiment.

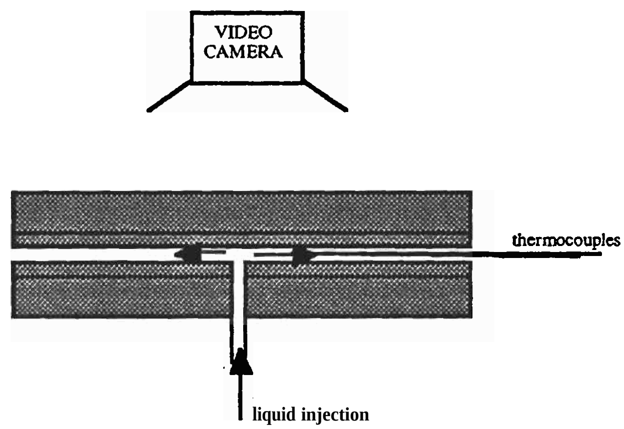

Figure **1** Schematic diagram of the apparatus. Liquid is pumped through the inlet port and migrates through **the** fracture spreading axisymmetrically.

Tlie formation of air bubbles during the heating phase of tlie liquid-filled fracture experiments caused the front of newly-injected liquid to be inregular, with air trapped in the fracture by surface tension. In order to overcome **this** problem it was necessary to remove all **air** bubbles from the surfaces and pipes whilst the apparatus was in **the** water bath.

A further problem became apparent during the boiling experiments. During **the** initial series of experiments Ue leading edge of the two-phase zone was elliptical. This was found to be a consequence of the support mechanism for the glass plates. The glass plates **tended** to deform when heated overnight in the oven and supported **at** the edges. In order 'to prevent this, the support mechanism was altered and the boiling front propagated in a roughly circular manner in subsequent experiments.

3. LIQUID-FILLED FRACTURE

In this section we examine the injection of liquid into a liquid-filled fracture. We have conducted a series of experiments in which water of temperature 20 "**C** was injected at rates of **3,** 6 and 10ml/min into a fiacture bounded by rough-walled glass varying in temperature between 40-90°C. Thermocouples were placed witliin tlic fracture at various distances from the inlet port.. **As** liquid water was injected into the fracture, the temporal changes in temperature were recorded.

As liquid migrated through the fracture, the initially cold injected fluid became heated as heat was transferred from the fracture walls to the fluid. A theoretical model of the problem of injection into a liquid-filled fracture bounded by impermeable rack 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. In reality, the injected fluid accumulates heat and the cold zone which develops around the injection port is of greater extent than that predicted by Bodvarsson (1972). If one includes the effects of accumulation of heat by the fluid then one obtains the following expression for tlie temperature of the fluid as a function of radial distance r and time t (Mossop, 1996)

$$\eta = erf(\xi) \quad (1)$$

where

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

and k is tlie thennal conductivity of the rock (glass), Q is tlie injection mass flux, C_{pw} is the specific heat capacity of water, κ is the thermal diffusivity of the rack (glass), h is tlie fracture aperture and ρ is the density of water. η is the dimensionless temperature defined as

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

where T_{inj} is the temperature of the injected fluid and T_o is the initial temperature of the rock. This expression is valid only for intermediate times in which the conduction of heat in the radial flow direction may be neglected. Values used in tlie experiments were as follows: k=0.937W/mK, Q=5-10g/min, C_{pw}=4180J/kgK, κ=4.21e-7m^2/s, h=0.18mm and ρ=1000kg/m^3. The theoretical prediction for tlie variation of temperature η with dimensionless time ξ at a given distance from the injection port is shown by the solid line in Figure 2.

The data obtained from the experiments is also plotted in Figure 2. 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 rack of infinite extent. In our experiments the glass sheets were 1.9cm thick. We tlius expect tliat tlic cooling of tlic 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 κ =4.21e-7 m^2/s we find tliat 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 tlie experiments were completed within this time frame.

A further possible discrepancy between the experimental results and theoretical predictions arose from the heat capacity of the brass injection port which is not included in the theory. The field scale equivalence of this is the additional heat transfer which occurs due to heat transfer along an injection well bore prior to tlie liquid entering a fracture. The additional heating of the fluid by tbe brass injection port was more significant during the early stages of the experiment. As the experiment proceeded the brass port cooled more rapidly than tlie extensive glass plates. As a result the discrepancies between the theoretical prediction (Mossop, 1996) and experimental results are greatest for larger values of ξ (smaller values of time) where the measured temperatures are greater than the predicted values. The experiments therefore support the theory for times sufficiently long tbat the effects of well bore heat transfer are negligible.

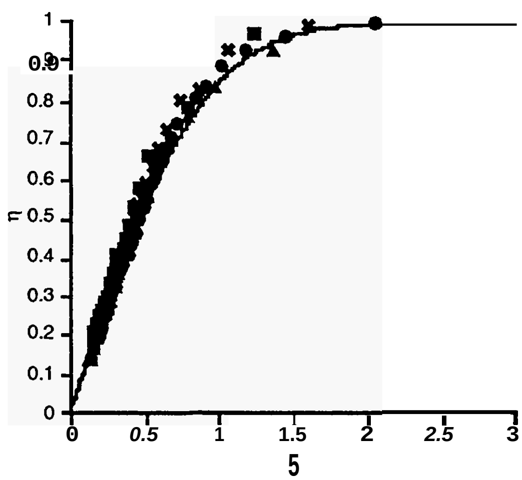

Figure 2 The variation of dimensionless temperature η as a function of tlie similarity variable ξ. The solid line represents tlie theoretical prediction and the symbols represent tlie results obtained from a series of experiments io rough-walled fractures.

VAI'OUR-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 a steam cap has formed, even though the fiactures were originally liquid-filled. Alternatively, systems in whicli fractures are vapour-filled can occur naturally such as at The Geysers, Larderello and Kawah Kamojang. Injection of liquid into systems such as these is also conducted in order to provide pressure support for the production wells. As the liquid migrates into the reservoir along fractures it is heated and a fraction of it boils. The newly generated vapour can migrate to production wells and lead to increased production. In addition to the increase in reservoir pressure, the productivity of the wells can improve since the newly generated vapour within tlie reservoir generally has a lower non-condensible gas content (Klein and Enedy, 1989; Enedy et *al.* 1993). Thus, the power plant output per unit mass of extracted fluid can increase. The fraction of liquid which actually boils depends on the amount of heat which can be transferred to the fluid and the pressure witliin the fractured reservoir. A number of theoretical and laboratory studies of liquid injection into a superheated reservoir consisting of a porous rock have been conducted (Pruess et *al.* 1987; Woods and Fitzgerald 1993, 1996, 1997). These studies showed that the amount of heat which can be extracted from tlie rock and used for vaporization is a function of tlie extent of cooling which occurs at tlie vaporization front and the amount of heat which is conducted towards the point of injection. The laboratory experiments support the theoretical predictions for the evolution of the system as liquid flows into a vapour-filled porous medium type reservoir (Woods and Fitzgerald 1996). In this case, 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 lieat 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. However, it is similar to the case in which a porous medium type reservoir is sufficiently superheated that the propagating liquid-vapour interface may become unstable and break up into fingers (Fitzgerald and Woods, 1994).

Having established that boiling must occur over a two-phase zone, it is of interest to determine how tlie temperature and liquid- and vapour-saturations vary with radial distance since the migration of cold liquid along a fracture can lead to premature thennal breakthrough at nearby production wells (Nakamura, 1980). As liquid is injected into the fracture, we expect that the pressure will decrease monotonically away from tlie inlet port as fluid migrates into the far-field. After a period of injection we anticipate that the fluid within the fracture close to tlie inlet port will be liquid since the pressure is highest at this point and tlie rock closest to the injection point will have undergone the most cooling. In the far-field, we expect that tlie fracture will be filled with vapour at relatively low pressure and at a temperature close to tlie 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 tlie boiling zone if steam and water are in thermodynamic equilibrium. 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 geothennal reservoir.

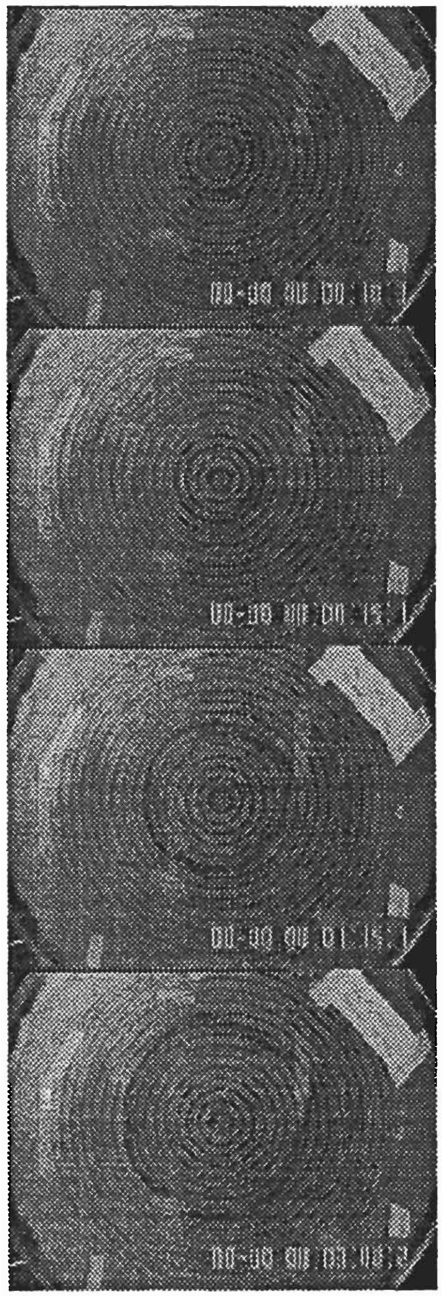

Figure 3 The spreading of dyed ether as it is injected at 20ml/min. The times shown correspond to times 10, 15, 75 and 180s after tlie onset of injection. The region of concentrated dye indicates the leading (front) edge of tlic two-phase boiling zone.

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. Etlier 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-pliasc 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. This is in contrast to the earlier results of Fitzgerald, Pruess and van Rappard (1996) where tongues of liquid were observed to move rapidly and erratically through a smottli-walled fracture. It is believed that the smooth-walled fracture aperture used in the earlier boiling experiments may have increased with radius due to the deformation of the apparatus during heating. Furthermore, the flow rates used in the earlier boiling experiments were sufficiently high that inertial effects were likely to have been important. The present experimental results provide a much more 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 as illustrated in Figure 4.

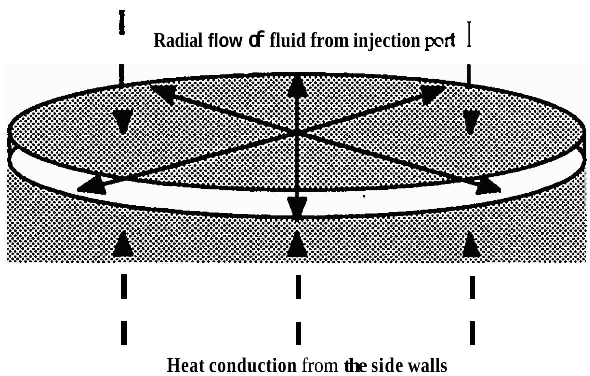

Figure 4 Schematic diagram illustrating the radial flow of fluid through the fracture apparatus and the conduction of heat within the glass walls bounding the fracture.

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 3.331kg/m^3, liquid density 713.8kg/m^3, latent heat of vaporization 377.7kJ/kg, vapor viscosity 8.4e-6 kg/sm and liquid viscosity 1.66e-4 kg/sm (Weast 1972). The problem of heat transfer from the brass injection port arose in the series of boiling experiments, as in the earlier non-boiling series. In order to compare the temperature profiles recorded at various stages in the experiment with the numerical prediction we placed a thermocouple within the fracture at the point of entry of the fluid.

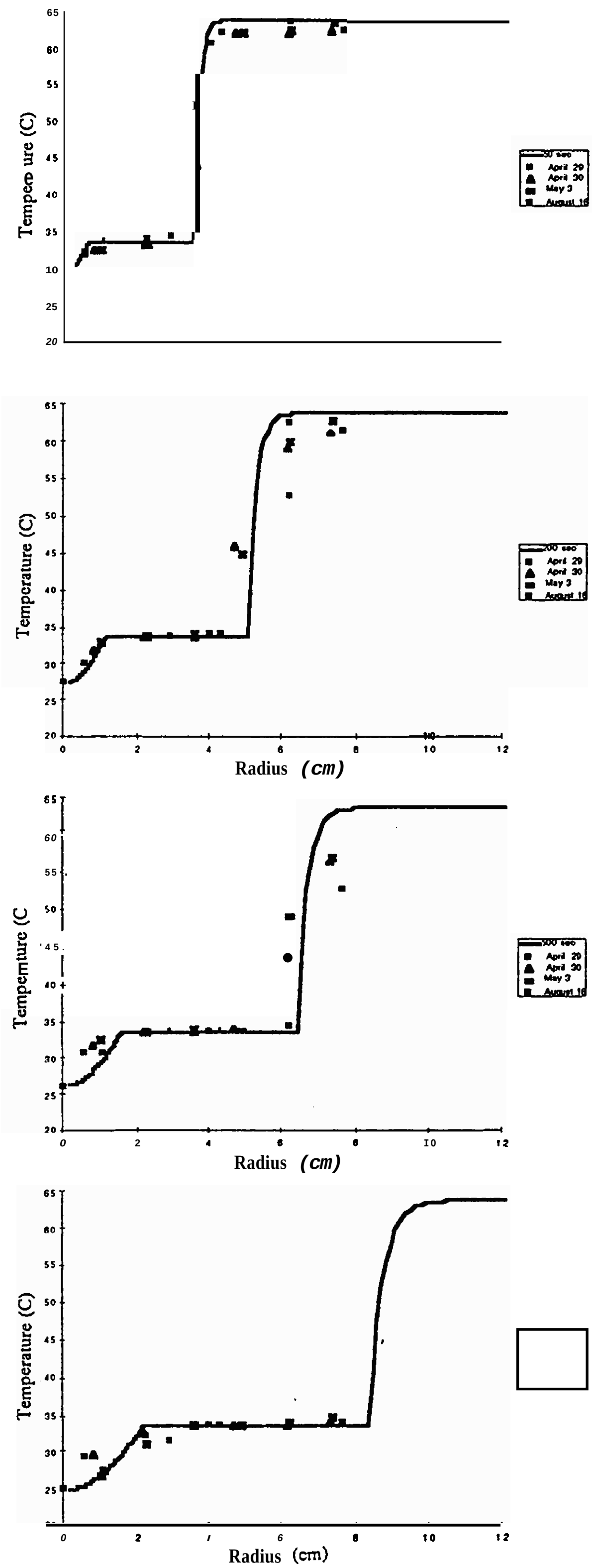

Figure 5 Temperature profiles at times 50, 200, 500 and 1400s after the onset of injection of 21°C liquid ether at 10 ml/min into a fracture originally at 64°C. The symbols represent data obtained from different experiments and the solid line indicates the profile obtained from the modified numerical code TOUGH2.

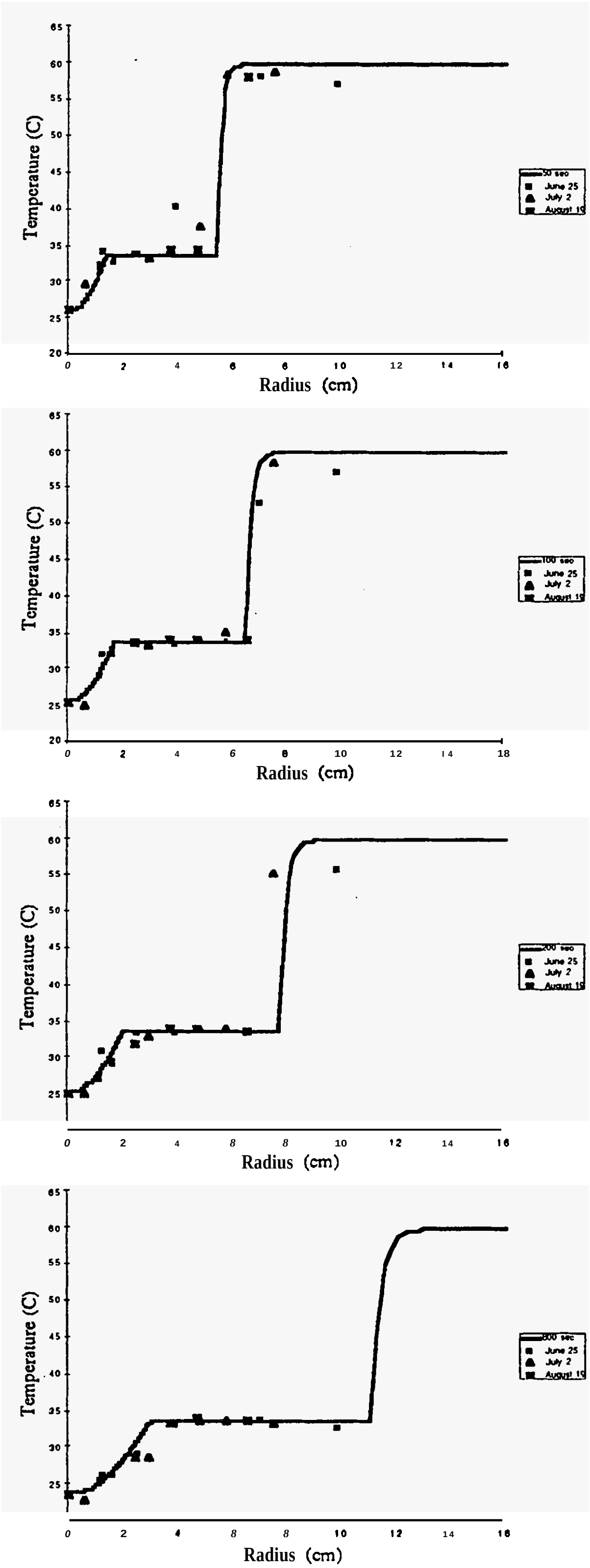

Figure *6* Temperature profiles at times 50, 100, 200 and 800s after the onset of injection of 21°C liquid ether at 20 ml/min into a fracture originally at 60°C. The symbols represent data obtained from different experiments and the solid line indicates the profile obtained from the modified numerical code TOUGH2.

As the experiment proceeded the inlet temperature of the liquid ether to the fracture decreased as expected. In order to account for this effect, the inlet temperature of tlie liquid used in tlie 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 the two flow rates are shown in Figures 5 and 6.

It is seen that tlie 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. Duriig the course of the experiments it was found that tlie 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 phenomena.

The average period of the pulses tended to increase as the two-pliase region became larger. This pulsing may representa form of instability at the interface between tlie two-phase region and zone of superheated vapour. Ahead of the two-phase zone the temperature was found to increase sharply across a thermal boundary layer to the far field temperature. The variations in experimental data were less marked further from the boiling zone due to the smaller influence of tlie pulses.

Tlicsc experimental results suggest that tlie predictions for the evolution of tlie 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 shown that the theoretical prediction for heat transfer at intermediate times 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. As the liquid migrates further into the fracture, the surface area of rock available for heating increases significantly. Eventually, the conduction of heat from the far field in the direction of fluid flow will become important and the theoretical expression discussed will break down.

In the case of liquid injection into a depleted reservoir, tlie 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 tliis zone. Our experimental observations suggest that tlie injection and boiling of liquid in a fracture may be accurately described and, modelled using existing numerical techniques (Pruess, 1991). These results are extremely important since they represent the first laboratory experiments which have been conducted and confm the validity of the numerical techniques for modelling injection and boiling in a fracture.

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

REFERENCES

Bodvarsson, G. (1972) Thermal problems in the siting of reinjection wells. *Geothernzics* Vol. 1(2), 63-66.

Bodvarsson, G.S. and Tsang, C.F. (1982) Injection and thermal breakthrough in fractured geothermal reservoirs. ***J. Geophys. Res.*** Vol. 87(B2), 1031-1048.

Enedy, S., Enedy, K. and Mancy, J. (1991) Reservoir response to injection in tlie Southeast Geysers. ***Proc. Stanford Geoth. Workshop*** Vol. 16, 75-82.

Encdy, S.L., Smith, J.L., Yarter, R.E., Jones, S.M. and Cavote, P.E. (1993) Impact of injection on reservoir performance in the NCPA steam field at tlie Geysers. ***Proc. Stanford Geoth. Workshop*** Vol. 18, 125-134.

Fitzgerald, S.D., Pruess, K. and van Rappard (1996) Laboratory studies of injection into horizontal fractures. ***Proc. Stanford Geoth. Workshop*** Vol. 21, 113-118.

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

Goyal, K.P. (1994) Injection performance evaluation in Unit 13, Unit 16, SMUDGEO#1, and Bear Cayon areas of the Southeast Geysers. ***Proc. Stanford Geotli. Workshop*** Vol. 19, 27-34.

Grant, M.A. (1979) Interpretation of downhole measurements in geothermal wells. ***Rep. 88 Appl. Math. Div., Dep. Sci. Ind. Res., New Zealand.***

Harper, R.T. and Jordan, O.T. (1985) Geochemical changes in response to production and reinjection for Palinpinon-I geothermal field, Negros Oriental, Philippines. ***Proc. New Zealand Geothermal Workshop*** Vol. 7, 39-44.

Horne, R.N. (1982) Geothermal reinjection experience in Japan. ***J. Petroleunz Teclz.*** Vol. March, 495-503.

Klein, C. and Enedy, S. (1989) Effect of condensate reinjection on stem chemistry at The Geysers field. ***Trans. Geotlz. Res. Counc.*** Vol. 13,409-413.

Mossop, A. (1996) Induced seismicity at The Geysers geothermal field, California I-A thermoelastic injection model. ***in prep.***

Nakamura, H. (1981) Development and utilization of geothermal energy in Japan. ***Trans. Geothemzal Resources Council*** Vol. 5, 33-35.

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

Pruess, K. and Bodvarsson, G.S. (1984) Thermal effects of reinjection in geothermal reservoirs with major vertical fractures. ***J. Pet. Tech.*** Vol. Sep, 1567-1578.

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*** Vol. 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.*** Vol. 251, 563-579.

Woods, A.W. and Fitzgerald, S.D. (1996) Laboratory and theoretical models of fluid recharge in superheated geothermal systems. ***J. Geophys. Res. in press***

Woods, A.W. and Fitzgerald, S.D. (1996) The vaporization of a liquid front moving slowly through a hot porous rock. Part II ***J. Fluid Mech. submitted***