EXPERIMENTAL AND THEORETICAL STUDIES OF LIQUID INJECTION INTO VAPOUR-DOMINATED RESERVOIRS

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SUMMARY We analyze the injection of liquid into a depleted geothermal reservoir using numerical, analytical and experimental techniques. We first investigate the injection of liquid at the base of a uniformly heated reservoir and show how an ascending liquid layer develops. Ahead of the liquid-vapour interface the temperature rises sharply and, for cases in which the permeability is sufficiently high, the vapour is approximately isobaric. The region immediately behind the advancing liquid-vapour interface is approximately isothermal and therefore, the fraction vaporizing is dependent on the reservoir superheat. When the reservoir is overlain by a supercooled zone, some of the vapour produced at the ascending liquid-vapour interface condenses. As a result, the amount of newly formed vapour available for subsequent extraction can be significantly reduced.

INTRODUCTION

There is a growing interest in the use of geothermal resources for the production of electricity. Vapourdominated superheated geothermal systems provide one of the most attractive resources for such power generation since the thermal energy stored in the ground may be efficiently harnessed as high enthalpy vapour (Grant et *al.*, 1982). However, as fluids are drawn from a reservoir, natural recharge may be unable to maintain the fluid reserves, and the reservoir pressure falls. This leads to a decline in the production and potential of the reservoir (Enedy, 1989; Kerr, 1991). To compensate for this effect, various schemes for liquid reinjection have been developed (Enedy *et* al., 1991). As liquid migrates into a reservoir, part of the liquid vaporizes thereby restoring the pressure. In order to evaluate the effectiveness of a recharge scheme, it is important to understand the fundamental controls on the mass fraction of the liquid which vaporizes and the temperature distribution in the liquid.

A number of studies have examined the propagation of liquid into geothermal reservoirs under conditions of rapid injection (Pruess et *al.*, 1987; Woods and Fitzgerald, 1993). Under such circumstances, the dynamic pressure associated with the vapour produced at and migrating ahead of the interface has a dominant impact on the vaporization through its control on the saturation temperature at the interface (Woods and Fitzgerald, 1993). As a result, owing to the thermal inertia of the rock, the liquid is heated up to the interfacial temperature long before reaching the interface. When the injection rate is high, or when the permeability is low, the interfacial pressure is relatively large. Consequently, the amount of energy which is released by the hot rock as it cools from the initial temperature to the interfacial temperature is low.

In this study, we concentrate on the situation in which liquid is injected into the reservoir sufficiently slowly that the vapour pressure remains nearly uniform and close to the original reservoir pressure (Fitzgerald and Woods, 1995). We first construct a mathematical model of liquid injection at a constant rate where the migrating liquid-vapour interface is stable and use this result to verify a timedependent numerical formuiation of the problem. The numerical code is then used to investigate the temperature profile in the liquid-saturated zone as liquid is injected at the base of a reservoir. All vapourdominated geothermal reservoirs are overlain by a colder liquid-saturated zone (James, 1968). We therefore consider the problem of injection into a stratified reservoir in which liquid is injected into an initially dry system and describe the formation of a liquid-saturated zone at the top of the vapourdominated region.

1 MODEL OF RECHARGE FROM BELOW

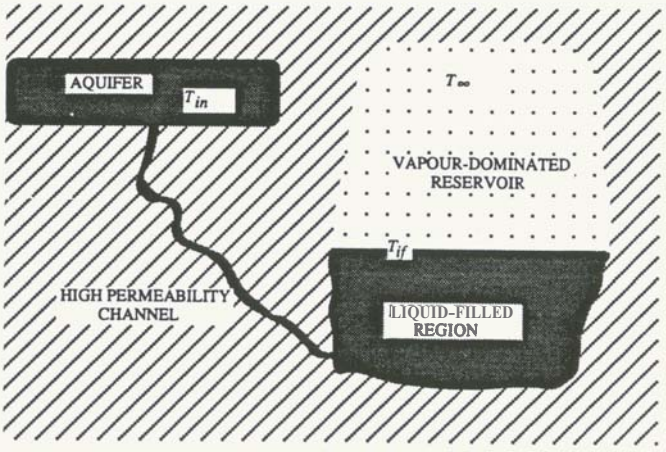


Figure 1. Schematic diagram of a superheated vapour-dominated reservoir supplied at the base from a cold liquid-filled aquifer via a high permeability fissure.

We consider the migration of a planar liquid front, supplied with liquid at constant Darcy speed u through a porous rock of porosity ϕ and permeability K (figure 1). The temperature -

of the liquid on injection is T_{in}, the initial rock temperature is T_∞ and the vaporization temperature of the reservoir is assumed to be T_{if}. In the liquid-filled zone, the temperature is approximately uniform immediately behind the migrating interface and equal to T_{if} (Woods and Fitzgerald, 1993).

In the vapour region, the isotherms migrate according to the relation

$$\frac{\partial T}{\partial t} + \lambda_v f u \frac{\rho_l}{\rho_v} \frac{\partial T}{\partial x} = \kappa \frac{\partial^2 T}{\partial x^2} \qquad (1)$$

where T is temperature, t is time, f is the fraction vaporizing, x is distance, κ is the thermal diffisivity of the vapour-filled rock, $\lambda_v=\rho_v C_{pv}/(\phi\rho_v C_{pv} +(1-\phi)\rho_r C_{pr})$, ρ is density, Cp is the specific heat capacity, and subscripts v and r denote a properties of the vapour and rock respectively. The fraction vaporizing is given by

$$f = \frac{(1-\phi)\rho_r C_{pr}\left(T_\infty - T_{if}\right)}{(1-\phi)\rho_r C_{pr}\left(T_\infty - T_{if}\right) + \phi\rho_l\left(C_{pv}\left(T_\infty - T_{if}\right) + L\right)} \qquad (2)$$

where L is the latent heat of vaporization. When liquid is supplied at a constant rate, the temperature within the vapour-filled zone ahead of the migrating liquid-vapour interface has the form

$$T(x-vt) = T_\infty + \left(T_{if} - T_\infty\right)\exp(\gamma[x-vt]) \qquad (3)$$

where $v=(1-f)\,u\,/\,\phi$ and $\gamma = (\phi\,\lambda_v f\rho_l/\rho_v+f-1)u\,/(\phi\,\kappa)$

In practice the steady state solution requires some time to become established; the steady state represents a balance between the advection and diffusion of heat and this balance becomes established over the time scale $T = (\rho_v / \rho_r \lambda_v)^2\,\kappa\,/\,u^2$. In order to show that the steady solutions do indeed become established, we have developed a numerical scheme to model the injection of liquid into the region $x>0$ for times $t>0$. At $x=0$, we impose the boundary condition that the conductive heat flux equals the heat required to vaporize all the liquid and to heat the newly formed vapour to the inlet temperature

$$k\frac{dT}{dx} = \rho_l u\left[C_{pl}\left(T_{if} - T_{in}\right) + L + C_{pv}\left(T_1 - T_{if}\right)\right] \qquad (4)$$

where T_1 is the temperature at the inlet $x=0$, k is the thermal conductivity of the fluid-filled rock and subscript l refers to a property of the liquid. Once the inlet has reached temperature T_{if} we apply a modified boundary condition at the inlet to the liquid saturated zone; the conductive heat flux equals the heat required to raise the liquid from the injection temperature to the inlet temperature

$$k\frac{dT}{dx} = \rho_l u C_{pl}\left(T - T_{in}\right) \qquad (5)$$

At the migrating interface, the temperature is fixed to be the saturation temperature corresponding to the reservoir pressure and the fraction vaporizing is obtained by applying the heat balance,

$$k\left[\left.\frac{dT}{dx}\right|_v - \left.\frac{dT}{dx}\right|_l\right] = \rho_l u f L \qquad (6)$$

Figures 2*a* and b show the adjustment to the steady state. In figure 2 a we show how the mass fiaction vaporizing decreases towards the steady state value (2) and in figure 2b we plot the temperature profile at dimensionless times 0.1, 1 and 10. For times $\tau>10$, the travelling wave solution accurately describes the temperature profile in the vapour zone and the fraction vaporizing; the liquid is isothermal immediately behind the interface and adjusts from the source temperature T_{in} to the interfacial temperature T_{if} across an internal boundary layer.

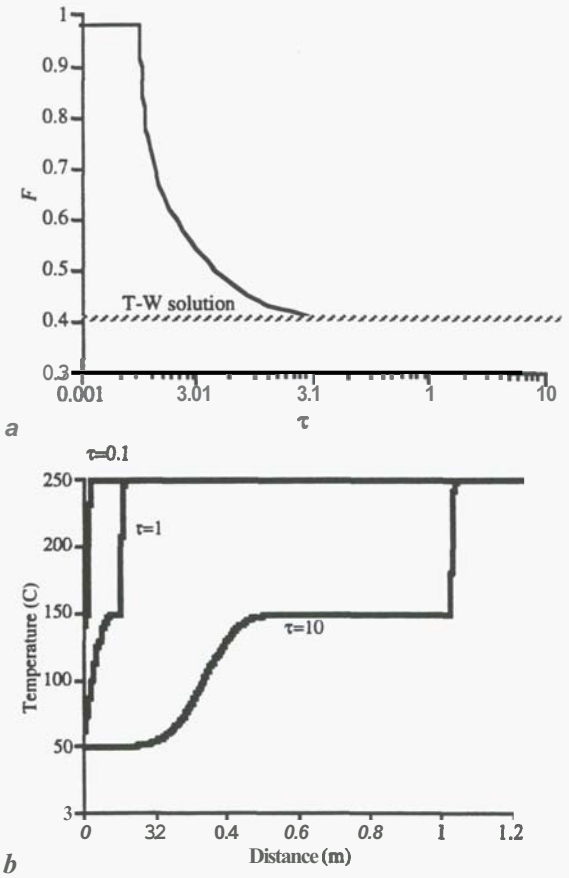


Figure 2. *a* The fraction f vaporizing as a function of time $\tau=t/T$. The broken line indicates the value expected from the travelling wave solution (2). b Temperature profiles at times τ=0.1, 1 and 10 after the onset of injection. In this example, u=1e-04 m/s, ϕ=0.2, T_∞=250°C, T_{if}=150°C, T_{in}=50°C, L=2.8e6J/kg, ρ_l=1000 kg/m^3, ρ_v=4.3 kg/m^3, ρ_r=2600 kg/m^3, C_{pl}=4200 J/kgK and C_{pv}=2200 J/kgK.

2 EXPERIMENTAL OBSERVATIONS. OF INJECTION FROM BELOW

We have carried out a series of experiments to test the model predictions. In the first suite of experiments liquid ether was

injected into the base of a vessel containing superheated sand (figure 3)

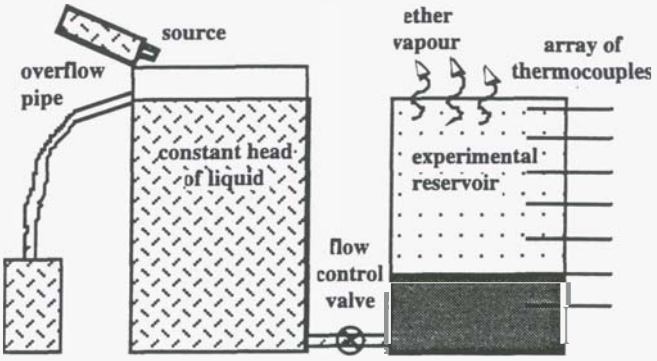


Figure 3. A schematic of the experimental apparatus configured for the injection of liquid at a constant pressure into the base of a hot sand layer. The vessel could be sealed at the top in order to simulate injection into a closed system or left open to allow vapour to vent freely. The vessel containing the sand was approximately 10x10x40 cm.

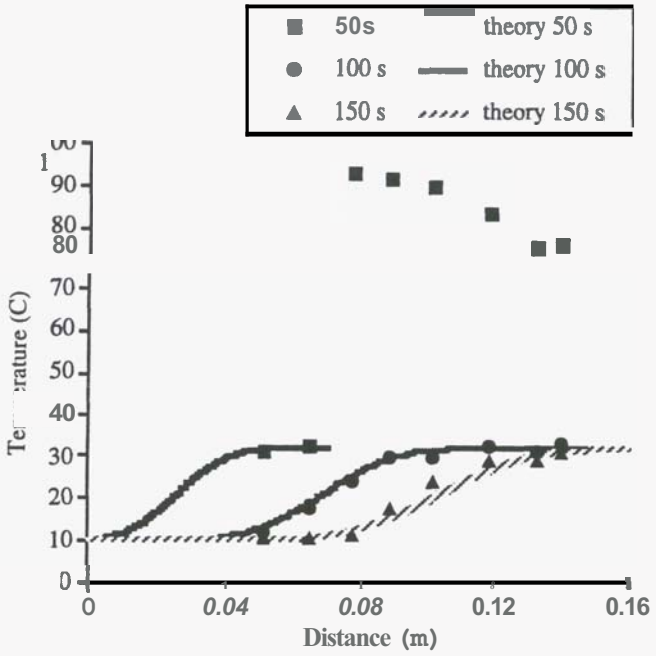


Figure 4. Temperature profiles at times 50, 100 and 150s in the sand bed after the onset of injection into the base of the vessel. Only the liquid-saturated portion is shown for the theoretical curves.

The apparatus was constructed from perspex, which begins to yield at 123°C. In order that a sufficiently large range of model reservoir superheats could be investigated, ether was chosen as the working fluid; ether boils at approximately 34°C at a pressure of 1 bar. Sand was heated over night to a prescribed temperature and then transferred to the vessel. After packing, the porosity of the model reservoir was determined to be 0.45+/-0.05. In order to prevent distortion of the apparatus by the hot sand, the maximum temperature investigated was 110°C. As a result, the maximum fraction vaporizing that could be obtained was approximately 0.4 (2) (Fitzgerald and Woods, 1995). The fraction vaporizing deduced from the experimental results were found to be in excellent agreement with the theory (2) (Fitzgerald and Woods, 1995). In addition to recording the rate of migration of the liquid-vapour interface, we also monitored the evolution of the temperature profile within the sand bed using the array of thermocouples as indicated in Figure 3. The numerical code described in the previous section was modified to account for the decrease in liquid supply rate as the interface migrated into the vessel. Using the appropriate physical properties for sand, the temperature profiles in the liquid and vapour zone were found to be in excellent agreement with the experimental results as shown in figure 4.

The most important observation is that the liquid-saturated region immediately behind the boiling interface is indeed approximately isothermal for a finite distance. As a result, the fraction which vaporizes under conditions of quasi-steady injection in one dimension is dependent only upon the superheat of the reservoir. During the initial stages of injection, $\tau<10$, a temperature gradient exists in the liquid-filled region (Figure 2*a*) and the vaporizing fraction decreases with time (Figure 2*b*).

Vapour-dominated geothermal reservoirs include regions of different pressure and temperature (White *et al.*, 1971) and are typically overlain by a colder liquiddominated region (Dench, 1980; Schubert and Straus, 1980; Schubert, Straus and Grant, 1980; James, 1968). It is therefore of interest to consider how the vaporization process investigated thus far changes when the experimental sand bed is thermally stratified. A number of experiments were conducted in which the superheated sand layer indicated in Figure 3 was overlain by a layer of supercooled sand of initial temperature 10°C. The lower layer evolved as before in the case of no thermal stratification. However, as superheated vapour rose into the overlying cold sand layer the vapour condensed and the temperature of the overlying sand increased towards the saturation point. As more ether vapour condensed, an intermediate saturated zone formed between the cold upper surface of the sand layer and superheated region below. The zones which developed are shown schematically in figure 5.

As ether vapour continued to enter the *saturated* layer, the lower boundary of the two-phase zone migrated upwards a small distance (approx. lcm over the course of the experiment). In addition, a small number of fingers of condensed liquid formed and descended into the superheated zone below, partially vaporizing as they came into contact with hot sand. It therefore appears that liquid (condensate) may migrate downwards in some regions of a reservoir even though it is derived from a deep source. The complexities which surround the invasion of liquid into a vapour-dominated reservoir from above are discussed in detail in Woods and Fitzgerald (1995) and the problems associated with the numerical modelling of such injection scenarios are described by Pruess (1991).

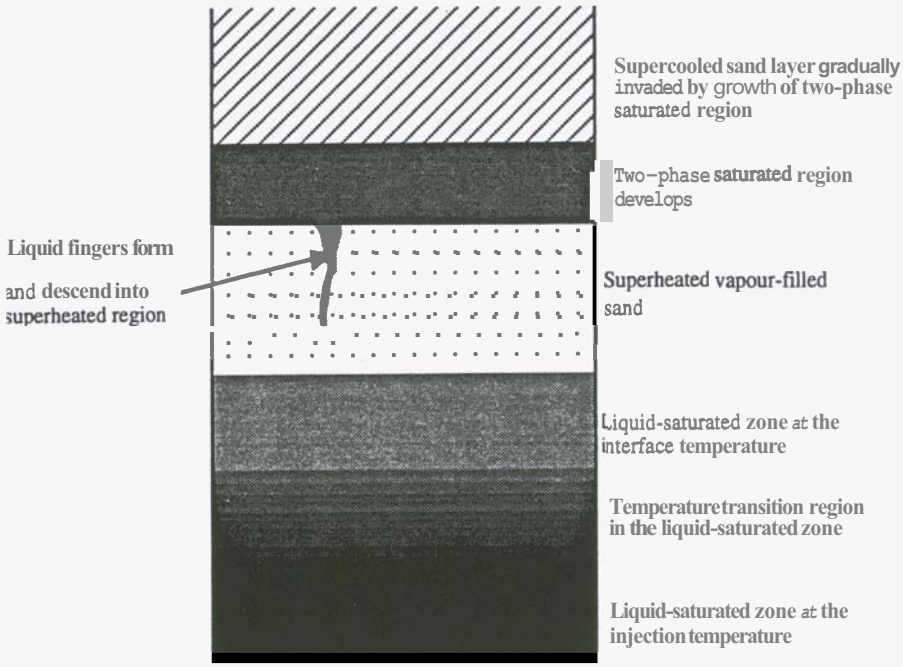


Figure 5. Schematic of the injection of liquid ether into the base of a vessel containing a superheated sand layer overlain by a layer of supercooled sand.

4 CONCLUSIONS

We have analyzed the addition of liquid to a superheated vapourdominated geothermal reservoir using a combination of analytical, numerical and experimental techniques. We have confirmed that the temperature profile which evolves as liquid is injected into a reservoir agrees with the theoretical predictions for cases in which the migrating liquid-vapour interface remains stable.

We have also investigated the effects of temperature variations within a reservoir and demonstrated that complex flows can result from injection. In addition to the vaporization and supply of new vapour to the reservoir for subsequent production (Pruess *et at.*, 1987; Woods and Fitzgerald, 1993), condensation may also occur. Some of the condensate can form liquid fingers which descend into the vapourdominated zone. These fingers partially vaporize as they descend, Since some of the vapour derived from injection can condense if it enters cold rock, the fraction of injectionderived vapour available for power generation can be reduced if the reservoir pressure is allowed to increase significantly; an increase in reservoir pressure may cause some of the injectionderived vapour to invade colder rock at the boundaries of the reservoir.

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