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THE INJECTION OF WATER INTO AND EXTRACTION OF VAPOUR FROM BOUNDED GEOTHERMAL RESERVOIRS

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ABSTRACT

When liquid is injected into a geothermal reservoir, a fraction of the liquid may vaporise if the reservoir is sufficiently hot. The vapour forms at an approximately planar liquid-vapour interface and diffuses towards the far boundary of the reservoir. If vapour is extracted from the far boundary, then once the new vapour has diffused across the reservoir, the rate of production of vapour at the liquid-vapour interface approximately balances the rate of extraction. We find that if the pressure at the injection pump and extraction well is fixed, then the fraction of the liquid which vaporises and the rate of extraction of vapour from the reservoir increase with time. However, the rate at which liquid is pumped into the reservoir may initially decrease but subsequently increases with time, if a sufficient fraction of the liquid vaporises. If the mass flux of liquid injected into the reservoir is fixed, then again both the fraction of the liquid which vaporises and the mass flux of vapour which may be extracted increase with time. In this case, the pressure at the injection pump may increase but subsequently decreases with time, again if a sufficient fraction of the liquid vaporises.

INTRODUCTION

Fluids extracted from vapour-dominated geothermal reservoirs such as The Geysers, California and Larderello, Italy have for many years been used to generate electricity. The successive developments of these geothermal reservoirs through the installation of new power plants and wells has increased the rate of extraction of the hydrothermal fluids. However, the exploitation of these reservoirs and the subsequent decrease in fluid levels has caused the average vapour pressures to fall. Consequently, the rate of extraction of vapour from the wells to supply power plants has also decreased (Kerr, 1991; Enedy, 1989). The rate of vapour extraction can be enhanced through the injection of water (Schroeder *et al.*, 1982; Bertrami *et al.*, 1985; Pruess *et al.*, 1987). Previous studies have investigated the production of vapour through the injection of water into an unbounded reservoir (Pruess *et al.*, 1987; Woods & Fitzgerald, 1992). It has been shown that as the rate of injection of liquid increases, the fraction of this liquid which can vaporise decreases but the total mass of vapour produced increases.

In this paper, we examine the behaviour of water injected at one boundary of a closed region as vapour is simultaneously extracted from a far boundary. Once the new vapour has diffused across the reservoir, the system typically attains a quasi-steady state if the vapour produced at the moving liquid-vapour front migrates across the reservoir more rapidly than the liquid-vapour front itself. We develop a simple model which may be used to investigate how the mode of injection of water affects the subsequent rate of extraction of vapour. We use this model to examine the long time response of the system if water is injected at a constant rate or with a constant pressure.

THE MODEL

As a highly simplified model, we consider the injection of water from a planar source into a one-dimensional porous rock of length L, porosity ϕ and permeability k. We restrict attention to flows in which the imposed pressure gradients exert much larger forces than the gravitational acceleration, and we also neglect the effects of surface tension.

Just ahead of the point of injection, there is a liquid region of length $l(t)$ (figure 1) which advances into the reservoir with mass flux Q per unit area according to Darcy's Law

$$\rho_w u_w = Q = \left(\frac{k(P_p - P_I)}{\mu_l l}\right) \quad (1)$$

where P_p is the pressure at the pump, P_I is the pressure at the liquid-vapour interface, μ_l is the liquid viscosity, ρ_w the liquid density and u_w the liquid velocity.

Woods & Fitzgerald (1993) showed that the isotherms within the liquid region lag the advancing liquid-vapour interface so that the fluid is supplied to the liquid-vapour interface with the temperature of the interface. A fraction of this liquid vaporises at the interface and the vapour produced diffuses away from the migrating interface towards the far boundary where vapour is extracted (figure 1). We assume that the liquid and vapour are in thermodynamic equilibrium at the liquid-vapour interface and that the pressure and temperature are coupled by an empirical form of the Clausius Clapeyron relation

$$T_{sat}(P) = 6.7P^{0.23} \quad (2)$$

in the temperature range $150 < T < 240°\mathrm{C}$ (Haywood, 1972). The fraction of injected water which vaporises, F, is given by the Stefan condition across the moving interface

$$F = 1 - \frac{\phi\rho_w(h_{v\infty} - C_{pw}T_i)}{\phi\rho_w(h_{v\infty} - C_{pw}T_i) + (1-\phi)\rho_r C_{pr}(T_\infty - T_i)} \quad (3)$$

where h is taken to represent the specific enthalpy, C_p the specific heat capacity, ρ density, T_i the saturation temperature associated with the pressure at the liquid-vapour interface, subscript r a property of the rock and subscript ∞ to denote a property of the vapour at the far boundary (Woods & Fitzgerald, 1993). Since a fraction F of the liquid vaporises, the liquid interface moves with velocity $dl/dt = (1-F)u_w$. The maximum fraction of liquid which may vaporise occurs when the interfacial temperature attains the minimum value $T_{sat}(P_o)$ where P_o is the pressure at the site of extraction.

Woods and Fitzgerald (1993) have shown that ahead of the interface, the vapour is isothermal and of temperature equal to the far field of the rock. By coupling the Darcy equation with the equation of state for the vapour (Young, 1988), we obtain the nonlinear diffusion equation describing the vapour pressure

$$P_t = \alpha(PP_x)_x \quad (4)$$

where $\alpha = k/\phi\mu$ and μ is the dynamic viscosity of the vapour (Elder, 1981). Fitzgerald and Woods (1993a) have shown that for times longer than the typical diffusion time $\tau_d = \phi\mu L^2/kP_r$, where P_r is a reference pressure, the vapour distribution through the rock becomes quasi-steady, with the rate of production of vapour approximately equal to the rate of extraction. Typically, τ_d is of the order of 1 day - 1 month. In this quasi-steady regime, the mass flux of vapour produced from the vaporising liquid, FQ, is given by the first integral of the right hand side of (4), integrated from the liquid-vapour interface $x = l$ to the far-boundary of the reservoir, $x = L$ (figure 1),

$$FQ = \frac{k\rho_v(P_I^2 - P_o^2)}{(2\mu(L-l)P_o)} \quad (5)$$

Here ρ_v is the density of the vapour at pressure P_o and at the temperature of the rock, T_∞. This quasi-steady model, which we investigate below, is valid for times longer than the diffusion time τ_d. Furthermore, it requires that the rate of migration of the liquid-vapour interface is much slower than the rate of migration of vapour

$$F \gg \frac{1}{1+\rho_w/\rho_v} \quad (6)$$

In all the calculations we present, condition (6) is satisfied.

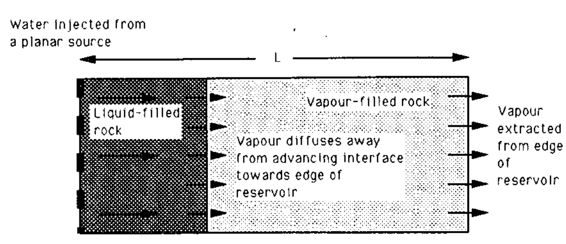

Figure 1. Schematic showing the flow configuration considered.

INJECTION AT A CONSTANT RATE

If water is injected at a constant rate into a bounded domain while vapour is simultaneously extracted from the far boundary at a constant pressure then, as the liquid-vapour interface advances further towards the far boundary, the distance that the liquid has to traverse increases. As a result, the difference in pressure between the liquid-vapour interface and the point of injection increases. In fact, the interfacial pressure decreases, and so the fraction of the injected liquid which vaporises actually increases, thereby producing a greater flux of vapour. This is a consequence of maintaining a fixed pressure at the point of extraction and may be understood in terms of the contradiction which arises if instead the interfacial pressure were to remain constant or increase - in this situation, the mass fraction of the injected liquid which vaporised would remain constant or decrease (equation 3); however, the flux of vapour required to satisfy Darcy's Law would increase, owing to the greater pressure gradient acting over the ever shrinking vapour region.

In figure 2 we show how the fraction of injected water which vaporises varies with time as water is injected at three different rates. After the initial diffusion time τ_d, the quasi-steady model calculations (solid lines) are indistinguishable from those obtained using a full numerical model in which the time-dependent diffusion equation for the vapour has been solved (see Fitzgerald and Woods, 1993b) (dashed lines). At low rates of injection, the pressure required to drive the vapour away from the liquid-vapour interface is relatively small. Consequently, the fraction of water which vaporises is initially larger than for high rates of injection. However, at high flow rates, the interfacial pressure falls more rapidly and so the mass fraction of water which vaporises increases towards the maximum value more rapidly. Eventually, there is a time at which a greater fraction of water vaporises at higher rates of injection.

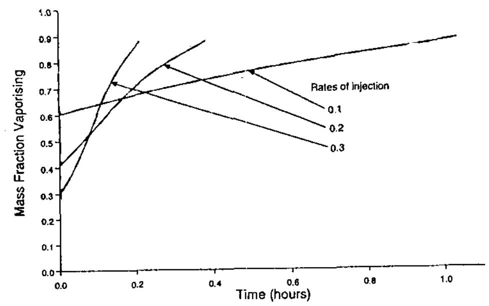

Figure 2. Mass fraction of injected water which vaporises as a function of time (hours). Water is injected from a planar source at a constant rate of 0.1, 0.2 and 0.3 kg/m^{2}s into the liquid region, intially of length 1 m, of a bounded rock of length 10 m while vapour is simultaneously extracted from the far boundary at a pressure of 6 bar. Quasi-steady model (solid) and full numerical model (dashed).

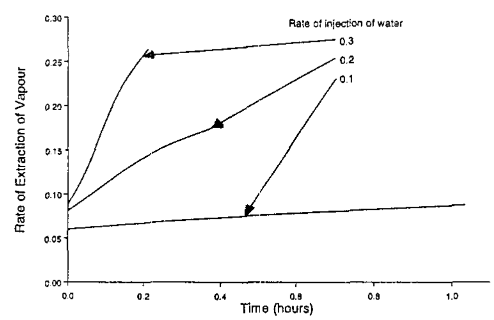

Figure 3. Rate of extraction of vapour (kg/m^{2}s) as a function of time (hours). Water is injected from a planar source at a constant rate of 0.1, 0.2 and 0.3 kg/m^{2}s into the liquid region, intially of length 1 m, of a bounded rock of length 10 m while vapour is simultaneously extracted from the far boundary at a pressure of 6 bar.

In our quasi-steady model, the mass flux of vapour extracted from the reservoir equals the rate of production of vapour at the liquid-vapour interface; this flux depends upon the rate of injection of water and the fraction of the injected water which vaporises. In figure 3 we show how the rate of extraction of vapour varies with time for the three injection rates used in figure 2. The rate of extraction of vapour increases with time as the mass fraction vaporising increases and is greater at higher flow rates, even though at early times, the mass fraction which vaporises is smaller (figure 2). Although the efficiency of injection may be low during early times, the rate of vapour production at the liquid-vapour interface is dependent primarily upon the rate of injection of water.

The pressure at the point of injection may vary non-monotonically with time as shown in figure 4. During early times, $t \sim \tau_d$, the increase in pressure difference across the liquid region occurs more rapidly than the decrease in interfacial pressure. Consequently, the pressure at the plane of injection rises. However, for times $t \gg \tau_d$, the decrease in interfacial pressure is more rapid than the increase in the pressure difference across the liquid region (as is required to maintain the constant liquid flow rate) and so the injection pressure falls.

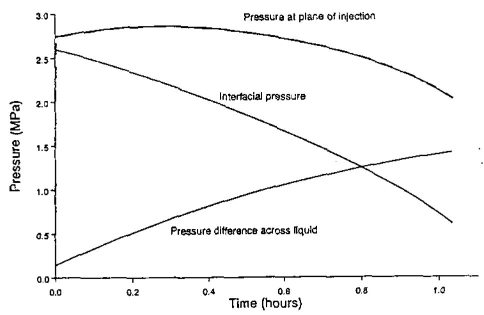

Figure 4. Pressure (MPa) as a function of time (hours). Water is injected from a planar source at a rate of 0.1 kg/m^{2}s into the liquid region, initially of length 1 m, of a bounded rock of length 10 m while vapour is simultaneously extracted from the far boundary at a pressure of 6 bar.

Note that in geothermal reservoirs of length scale 10^3 m and diffusivity 10^{-1}m^2/s, the transient diffusion-controlled period may last for up to several months. In these cases, the evolution towards the quasi-steady state is also of interest and recourse to a full numerical model is necessary (Fitzgerald and Woods, 1993b). During the transient period, the rate of extraction of vapour decreases significantly with time if the pressure at the extraction well is lower than that originally in the reservoir. However, as the new vapour advances into the reservoir and compresses the vapour originally in place, the rate of extraction increases towards those predicted by the quasi-steady model.

INJECTION AT A CONSTANT PRESSURE

The quasi-steady model of the simultaneous injection of water and extraction of vapour may be used to investigate the situation in which water is injected at a constant pressure. We again consider the injection of water from a planar source into a bounded domain. During early times, the pressure difference across the liquid region is relatively small and therefore, the interfacial pressure is approximately equal to the pressure at the point of injection. Consequently, the energy available for vaporisation is relatively small and the mass fraction which vaporises is low (equation 3; figure 5). As in the previous case of injection at a constant rate, the mass fraction which vaporises increases as the size of the liquid region increases and the interfacial pressure decreases. The mass fraction which vaporises during early times is lower when the pressure at the plane of injection is high. However, the rate of addition of water is greater when the injection pressure is high and thus the liquid-vapour interface advances more rapidly. This causes the interfacial pressure to decrease more rapidly with time and the mass fraction which vaporises increases more rapidly at high injection pressures (figure 5).

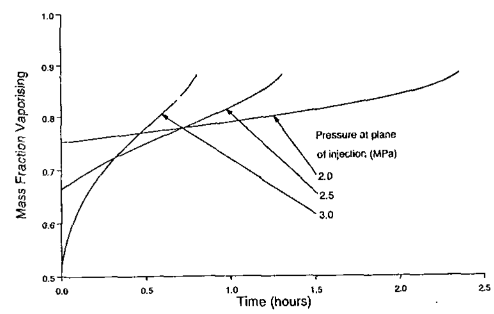

Figure 5. Mass fraction of injected water which vaporises as a function of time (hours). Water is injected from a planar source at a constant pressure of 2, 2.5 and 3 MPa into the liquid region, initially

of length 1 m, of a bounded rock of length 10 m while vapour is simultaneously extracted from the far boundary at a pressure of 6 bar.

For injection at a large constant pressure, the rate of injection of water initially decreases with time as the size of the liquid region, and hence pressure difference across the liquid, increases (figure 6).

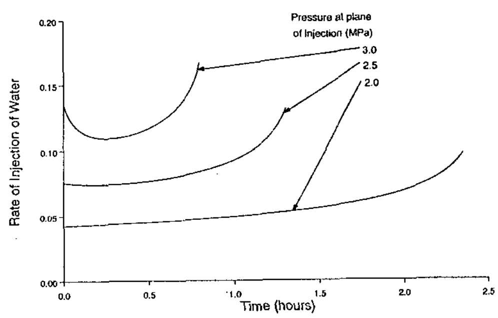

Figure 6. Rate of injection of water (kg/m^{2}s) as a function of time (hours). Water is injected from a planar source at a constant pressure of 2, 2.5 and 3 MPa into the liquid region, initially of length 1 m, of a bounded rock of length 10 m while vapour is simultaneously extracted from the far boundary at a pressure of 6 bar.

However, as the liquid-vapour interface approaches the far boundary, the interfacial pressure decreases rapidly since the mass transfer ceases to be rate limited by the diffusion of vapour. This results in an increase in the flux of water into the system and also the mass fraction which vaporises. At low injection pressures, the flux of water injected into the reservoir increases monotonically with time because the transport of a relatively small flux of vapour across the reservoir does not suppress the vaporisation process as much, and so the interface pressure is smaller *ab initio*.

The rate of extraction of vapour is a function of both the rate of injection of water and the mass fraction which vaporises (figure 7). It increases monotonically with time for all cases considered.

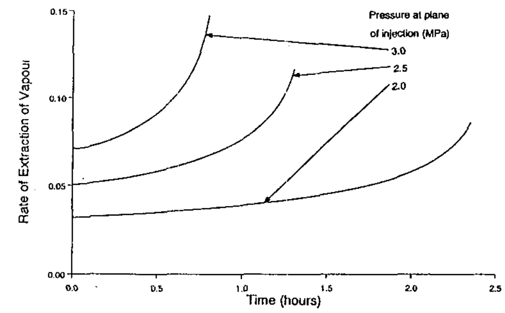

Figure 7. Rate of extraction of vapour (kg/m^{2}s) as a function of time (hours). Water is injected from a planar source at a constant pressure of 2, 2.5 and 3 MPa into the liquid region, initially of length 1 m, of a bounded rock of length 10 m while vapour is simultaneously extracted from the far boundary at a pressure of 6 bar.

Again, these results are valid only for times greater than the timescale of diffusion of vapour across the reservoir. As in the case of injection at a constant rate, during the transient period before the quasi-steady state has been attained, the rate of vapour extraction may decrease significantly with time if the pressure at the extraction well is lower than that originally in the reservoir.

CONCLUSIONS

The rate of extraction of vapour from a geothermal reservoir can be significantly increased through the injection of water. In quasi-steady state, the rate of production of vapour from the liquid is approximately equal to the rate of extraction. If water is injected at one point while vapour is simultaneously extracted from a second point (figure 1), then the rate of production of vapour increases with time, particularly at high pressures or high rates of injection. In contrast, if liquid is injected into a bounded reservoir and vapour is *not* extracted then the production of vapour is suppressed as the interfacial pressure increases.

The mass fraction which vaporises increases with time for both injection at a constant pressure and with a constant liquid flow rate. In both cases, the total flux of vapour extracted from the reservoir increases with time. Initially, most of the pressure drop across the reservoir occurs across the new vapour, since this must migrate across a large fraction of the reservoir; however, with time, the ever increasing efficiency of vaporisation causes a rapid decrease in the interface pressure, changing the dynamic response of the system. For injection at constant pressure, the mass flux of liquid may initially decrease but then increases as the vaporisation efficiency increases. In contrast, for injection with constant liquid flux, the pump pressure may initially increase but then decreases as the vaporisation efficiency increases. Only in the extreme case in which a very small fraction of the liquid vaporises is the process rate-limited by the migration of the liquid (Fitzgerald and Woods, 1993).

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