

# RECHARGE OF VAPOUR SATURATED GEOTHERMAL RESERVOIRS BY INJECTION OF WATER

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## Summary

In this paper we describe the physical controls upon the rate of vaporisation of liquid as it is injected into a hot porous layer. We show that if liquid is injected at a relatively high rate of injection, then a low fraction of the liquid vaporises and the porous layer becomes filled with hot liquid. However, at low rates of injection, a high fraction of the liquid may vaporise. We also describe a new and fundamental instability that can develop at a migrating liquid-vapour interface if the rate of injection is sufficiently small.

## 1.0 Introduction

Vapour saturated geothermal reservoirs are recharged as liquid invades the pore spaces in the hot rock and vaporises (Truesdell & White 1973).

Active water injection schemes have been designed to regenerate the vapour and hence maintain the vapour pressure in the reservoir (Enezy *et al.* 1991). However, the optimal injection rate depends upon the particular situation. Understanding the underlying physical controls upon the rate of vaporisation of liquid and the mass fraction of liquid which vaporises helps to determine these conditions.

**As** a simple model in this paper we describe results of our analysis of the physical controls upon the rate of vaporisation of liquid as it is injected into a hot porous layer. The paper is divided into two parts. In the next section we analyse the vaporisation of liquid at a planar liquid-vapour interface and describe how both the rate of vaporisation and also the fraction of liquid which vaporises change as the rate of injection of liquid is varied. In the following section, we investigate the stability of such planar vaporising interfaces and show that for sufficiently slow rates of injection the interface actually becomes unstable allowing much more rapid vaporisation.

## 2. Vaporisation of a planar interface

**As** liquid migrates through hot porous rock and vaporises, the rate of vaporisation is governed by the amount of heat released by the rock and also the ability of the vapour to migrate ahead of the interface. In order to quantify the rate of vaporisation and the mass fraction of liquid which can vaporise, equations for the conservation of heat and mass at the moving liquid-vapour interface are coupled with the Clausius-Clapeyron equation, relating the interfacial pressure and temperature, and an equation describing the motion of the vapour ahead of the interface (Woods & Fitzgerald 1993). Furthermore, owing to the thermal inertia of porous rocks (Bodvarsson 1972), the temperature of the liquid behind the interface is close to that at the interface, except near the point of injection.

By solving the relevant system of equations describing the above physical balances we find that as the liquid flow rate increases the interfacial pressure increases (figure 1). **As** a result, the interfacial temperature decreases, and therefore, the heat released by the hot rock for vaporising the liquid decreases. In turn this lowers the mass fraction of liquid which vaporises (figure 2), although the total mass of vapour produced per unit time is greater owing to the greater flow rate (figure 3). Further details of these calculations are presented in Woods & Fitzgerald (1993). Perhaps the most important results are that as the total rate of vaporisation increases, the fraction of liquid which vaporises decreases and the interfacial temperature increases. **As** a result, the water-saturated region of the reservoir is hotter the faster the rate of injection, thereby retaining more of the original thermal energy in the reservoir. In contrast, at **low** rates of injection, a much larger fraction of the liquid vaporises and the residual liquid is much cooler. However, the rate of vapour production is much slower owing to the smaller injection rate.

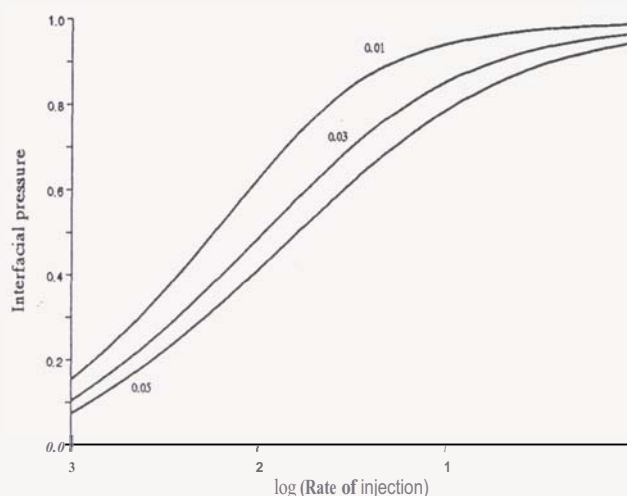


Figure 1 Interfacial pressure as a function of rate of injection from a vertical well. Curves are given for various reservoir porosities.

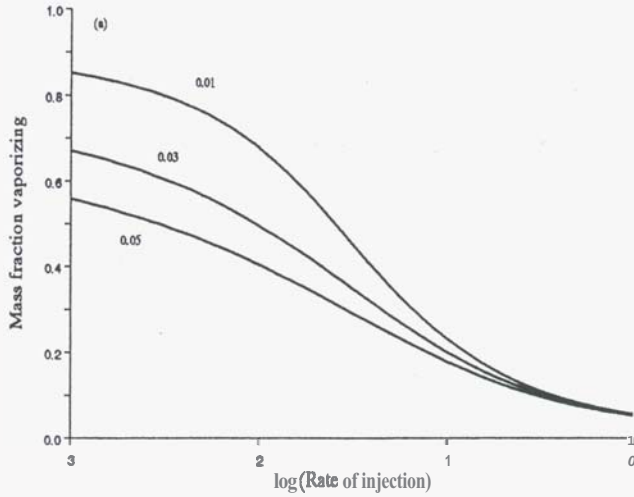


Figure 2 Mass fraction vaporising as a function of rate of injection from a vertical well. Curves are given for various reservoir porosities.

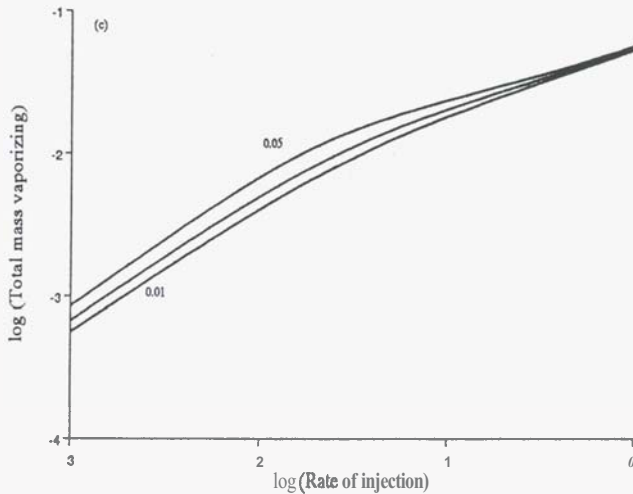


Figure 3 Rate of production of vapour as a function of rate of injection from a vertical well. Curves are given for various reservoir porosities.

This identifies a fundamental paradox between the short term need for a high rate of vapour regeneration and the longer term objective of removing the thermal energy from the reservoir through extraction of vapour. However, in the next section we show that at low flow rates, for which the mass fraction of liquid which vaporises is high, the situation is somewhat more complex. The assumption that the liquid vapour interface remains planar is not always satisfied. This affects the above results concerning the fraction of the liquid which vaporises, the rate of vaporisation and the residual thermal energy stored in the reservoir.

### 3. Interface Stability

The results we described above following Woods & Fitzgerald (1993) hinge upon the assumption that the liquid vapour interfaces remains planar. However, this need not be the case if the pressure gradient in the vapour ahead of the

interface exceeds that in the liquid just behind the interface. This effect is somewhat analogous to the Saffman-Taylor instability which develops in a porous layer when a more viscous fluid is displaced by a less viscous fluid (Saffman & Taylor 1958). The instability arises when a finger of the fluid behind the interface advances ahead of the interface. Because the pressure gradient in this finger is smaller than that of the surrounding fluid, the finger advances.

Appealing to the analogy with the Saffman-Taylor instability, we can derive a simple condition which identifies the flow rates for which the interface may be unstable. The pressure gradient in the liquid just behind the interface is given by Darcy's Law (Bear 1972)

$$p_{lx} = -(k/\mu_l) u_l \quad (1)$$

where  $U$  is the Darcy velocity of the liquid,  $k$  the permeability of the rock and  $\mu$  the dynamic viscosity of the liquid. Similarly in the vapour, the pressure gradient is given by

$$p_{vx} = -(k/\mu_v) u_v \quad (2)$$

We can relate these pressure gradients by noting that if the mass fraction which vaporises is  $F$ , then the mass flux of vapour  $\rho_v u_v = F \rho_l u_l$  and so

$$(p_{vx}/p_{lx}) = F (\rho_l \mu_v / \rho_v \mu_l) \quad (3)$$

Typically, the ratio  $(\rho_l \mu_v / \rho_v \mu_l) \approx 10$  for water and water vapour at pressures of 6 - 30 atmospheres and temperatures of 150 - 250°C. Therefore, if the typical mass fraction vaporising  $F$  exceeds about 10 - 20%, we expect that the liquid-vapour interface will be unstable.

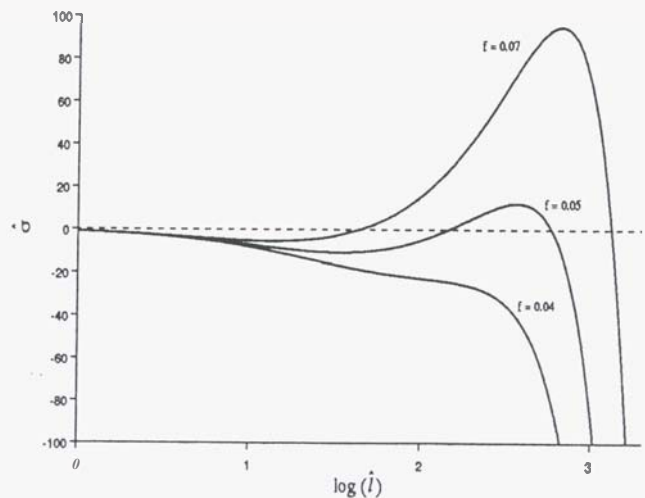


Figure 4 Exponential growth rate of a finger as a function of wavenumber. Curves are given for three values of the mass fraction vaporising. In these calculations the thermal diffusivity  $\kappa = 3 \times 10^{-6}$ ,  $\kappa/\alpha = 5 \times 10^{-4}$  and  $v_l/v_v = 0.042$ .

A more detailed calculation including the effects of thermal diffusion, and the differential rate of vapour production between the crests and base of the fingers shows that very short and very long wavelength perturbations may be stabilised. Therefore, there is typically a band of wavelengths which are linearly unstable if  $F$  is sufficiently large (figure 4).

From figure 2, we see that the instability may arise for injection rates  $Q < 0.1$  since at such low rates of injection the mass fraction vaporising is sufficiently large.

Once the fingering develops, the surface area of the liquid-vapour interface increases and so the motion of the newly formed vapour ahead of the interface has a smaller rate limiting effect upon the mass fraction which vaporises. As a result, the mass of liquid which vaporises can increase and the injection process becomes more effective.

#### 4. Conclusions

Vapour saturated geothermal reservoirs may be recharged through the active injection and subsequent vaporisation of liquid into the reservoir. As the rate of injection increases, the mass fraction of the liquid which vaporises decreases although the overall rate of production of vapour increases. Furthermore, as the rate of injection increases, the temperature of the liquid vapour interface increases. Therefore owing to the thermal inertia of porous layers (Woods & Fitzgerald 1993) the liquid remaining in the reservoir is hotter, rendering the overall energy extraction through the vapour less efficient.

Finally, we have described how, at low rates of injection, the liquid-vapour interface may become unstable and break up into fingers. This further increases the mass fraction of the liquid which can vaporise at low injection rates.

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