NATURAL RECHARGE FOLLOWING EXPLOITATION OF A VAPOUR-DOMINATED GEOTHERMAL SYSTEM

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ABSTRACT

We examine the natural recharge of vapour-dominated geothermal reservoirs through the migration of groundwater. Vapour-dominated systems are typically overlain by a liquid-saturated region. As vapour is extracted from the lower zone, the pressure within the reservoir decreases and liquid migrates downwards into the reservoir. As liquid invades the hot rock, a fraction of the water vaporises. We show that as the liquid advances into the reservoir, the pressure within the system increases towards the saturation pressure of the reservoir and the fraction vaporising decreases.

INTRODUCTION

Natural recharge of vapour-dominated reservoirs is an important process by which fluid reserves in such systems may be replenished. We examine how a vapour-dominated reservoir responds to vapour extraction through a well. Vapour extraction causes liquid to migrate into the reservoir and we examine the typical time scale over which natural flooding of the reservoir may occur. In order to conduct this analysis we develop a simple one-dimensional model of the process. We use this model to help set a reference for understanding the effects of forced vapour extraction and the effects of liquid injection by industry on these natural systems.

We build upon Schubert and Straus's (1980) model of a natural vapour-dominated system and examine the effect of adding an extraction (production) well to a system that is in equilibrium. Schubert and Straus (1980) showed that a stationary liquid zone can overlie a vapour zone if the permeability is sufficiently low that the heat flux supplied from depth can vaporise any liquid which descends below the equilibrium position of the interface. However, if vapour is extracted from the reservoir then the pressure supporting the overlying liquid decreases and the liquid descends (figure 1).

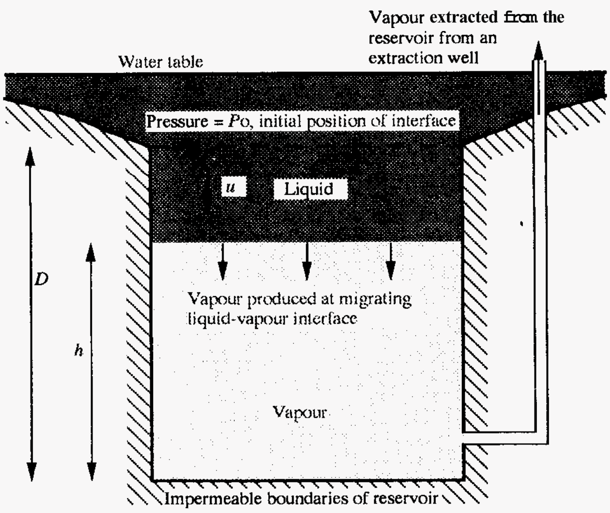

Figure 1 Schema of liquid migration into a superheated geothermal system.

THE MODEL

In this study we consider the introduction of extraction (production) wells which allow vapour to escape at a high rate. We therefore assume that the time scale for liquid to migrate into the superheated zone and the time scale for pressure readjustment within the vapour region is shorter than the time for heat to be conducted from the base of the reservoir to the interface. We subsequently confirm that this assumption is consistent with our results.

Assuming for simplicity that the reservoir is a uniform permeable rock (Schubert et *al.* 1980; Schubert and Straus 1980), the volume flux of liquid into the reservoir per unit area is given by

$$u=\frac{K}{\mu_w}\left(\rho_w g-\frac{(P_r-P_o)}{D-h}\right) \tag{1}$$

where P_o is the initial pressure at the base of the liquid layer, P_r is the pressure within the vapour region, ρ_w is the density of water, g the acceleration due to gravity, D the depth of the system below the initial position of the liquid-vapour interface, h the vertical extent of the vapour zone, K the permeability and μ_w the viscosity of water. We assume that the pressure in the vapour region is nearly uniform. This follows from Fitzgerald and Woods (1994a) who showed that the pressure adjusts across the reservoir with an effective diffusion coefficient $(KP_r/\phi\mu_v)$ where ϕ is the porosity and μ_v the viscosity of vapour. In a reservoir where the vertical extent of the vapour is H, the time for the pressure to adjust is therefore approximately $H^2/(KP_r/\phi\mu_v)$. If this time is much shorter than the rate of migration of the liquid-vapour interface through the reservoir then the pressure in the vapour region is approximately uniform. We show that this is the case in the present situation if the reservoir pressure is sufficiently high and the vertical extent of the vapour zone sufficiently small.

As the liquid front descends, the liquid invades the hot vapour-filled rock and a fraction vaporises. Woods and Fitzgerald (1993) showed that when the vapour pressure is uniform, the fraction vaporising F is given by

$$F=\frac{1}{1+\frac{\phi\rho_w\left(h_{v\infty}-C_{pw}T_{sat}(P_r)\right)}{(1-\phi)\rho_r C_{pr}\left(T_\infty-T_{sat}(P_r)\right)}} \tag{2}$$

where $h_{v\infty}$ is the specific enthalpy of the vapour at the reservoir temperature, C_{pw} is the specific heat of water, C_{pr} is the specific heat of the rock, ρ_w is the density of water, ρ_r is the density of the rock, T_∞ is the reservoir temperature and $T_{sat}(P_r)$ is the saturation temperature of the reservoir pressure. This is dependent upon the reservoir pressure (Woods and Fitzgerald 1995). The vertical scale h of the vapour region decreases at a rate

$$\frac{dh}{dt}=\frac{-u(1-F)}{\phi} \tag{3}$$

and the flux of vapour added to the vapour region Q_{in} by the descent and vaporisation of a fraction of the overlying liquid is

$$Q_{in}=\rho_w AuF \tag{4}$$

where A is the area of the reservoir. The typical flux which may be extracted from a production well Q_{out} in vapour dominated systems is O(10-100) kg/s (Grant *et al.* 1982), and for simplicity in the present model, we take Q_{out} to be a constant. Variations in Q_{out} can readily be incorporated if desired.

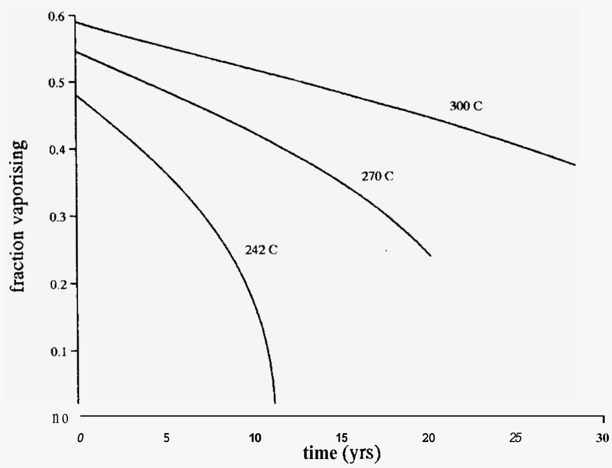

Figure 4 The fraction vaporking F as a function of time as liquid migrates into the vapour-filled zone.

In figure 2 we show how the liquid-vapour interface descends into the vapour zone as a function of time. Initially, the interface is taken to be at a depth of 200 m. After approximately 10 years of continued vapour extraction, the interface has reached a depth of 500 m and the pressure has increased from 5 bar to 3.4 bar (figure 3). At this point the pressure within the vapour zone has increased towards the saturation value for a reservoir at 242°C. As a result of the increase in pressure that occurs, the fraction of liquid that may vaporise decreases with time (figure 4). This is because the amount of superheat that is available for vaporisation decreases as the reservoir pressure increases (4).

Although similar conditions to those found at Kawah Kamojang exist in other reservoirs such as Larderello and The Geysers (Schubert *et al.* 1980), higher temperatures have also been recorded in these other systems (Drenick 1986; Truesdell 1991; Pruess *et al.* 1987). We have therefore also investigated how a migrating liquid-vapour interface may descend following vapour extraction from reservoirs of higher temperature. It is found that when vapour is extracted from higher temperature reservoirs, the rate of descent of the liquid front is slower. This is a dircct consequence of the increase in the fraction of liquid that can vaporise (4) at a given reservoir pressure. For temperatures typical of the 'high-temperature' zones(s) of The Geysers (approx. 300°C) (Drenick 1986), it is found that it takes approximately 30 years for liquid to migrate a distance of 300 m. Thus, liquid migration into hotter systems is more efficient in that more vapour is produced per unit mass of liquid supplied and the quenching of the reservoir occurs over a longer time scale.

These results are only valid for cases in which the assumptions regarding the separation of time scales of descent of the interface, conduction of heat from depth and adjustment of pressure within the vapour zone are satisfied.

In order that the pressure within the vapour zone may be considered uniform, the time scale for the rate of migration of the interface should be much longer than the time scale for the diffusion of pressure signals across the reservoir. From figure 2 the maximum velocity of the interface in any example considered herein is approximately 300 m/year. (The average velocity is considerably less than this, ~100 m/year). Thus the shortest time scale τ_{des} for the descent of the interface through the vapour zone is 1.7 year since the initial depth of the vapour zone is taken to be 500 m. The time scale for the pressure to adjust τ_{adj} is given by $D^2/(KP_r/\phi\mu_v)$~0.12 year. Hence, the vapour pressure is approximately uniform. We also assumed that the time scale for heat to be conducted from depth was less than the time scale of interest. If we take the mean conductivity λ of the rock-fluid to be 4 J/msK then we find that the time taken to diffuse heat τ_{heat} over the depth of the vapour zone is approximately $D^2/(\lambda/\rho_r C_{pr})$~4000 years. Hence, heat transfer from depth may be neglected in the present ease. These results are also only strictly valid if the system remains one-dimensional. Although the case of a stationary interface has been shown to he stable under certain conditions (Schubert *et al.* 1980), the stability of a descending liquid-vapour interface has not been investigated thoroughly. Recent work has shown that a migrating vaporising interface may indeed be unstable in the absence of gravity if the fraction vaporising is sufficiently high (Fitzgerald and Woods 1994b). The inclusion of the effects of gravity upon the stability of a migrating vaporising interface is the subject of current research.

CONCLUSIONS

The migration of meteoric water into vapour-dominated systems is an important process by which new vapour may be supplied following the extraction of fluid for industrial use. We have shown that the pressure within the vapour zone of vapour-dominated systems is governed by the hydrostatic head of liquid that overlies the vapour region. As a consequence of vapour extraction, liquid migrates downwards into hot vapour-filled rock and a fraction of it vaporises thereby replenishing the reservoir. It is found that if vapour is extracted from a superheated vapour region then the liquid-vapour interface will descend and the reservoir pressure will increase towards the saturation value. For systems at 242°C, saturation conditions (P_r~3.4bar) are attained within a period of about 10 years if the extraction rate is 30 kg/s/km^2, though this time may be somewhat shorter if the initial pressure is greater than 5 bar. For hotter systems, the time scale is somewhat greater; approximately 30 years may elapse before the reservoir pressure has increased to 3.4 bar.

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