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Vapour Generation in Hot Permeable Rock Through Injection of Water

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Abstract

We present a non-linear model to describe vapour generation in a hot, permeable rock through injection of water. We develop similarity solutions describing the steady injection of fluid from a line source. A systematic parameter study has shown that, with other parameters fixed, as (i) the reservoir pressure increases, the mass fraction vaporised decreases; (ii) the reservoir temperature increases, the mass fraction vaporised increases; (iii) as the mass injection rate increases, the mass fraction vaporised decreases; and (iv) as the porosity increases, the mass fraction vaporised decreases.

We then present similarity solutions which describe injection from (i) a point source, with the mass flux injected proportional to $t^{1/2}$; and (ii) a planar source, with the mass flux injected proportional to $t^{-1/2}$, where t is the time of injection. These results suggest that for steady injection, the vapour production gradually increases for injection from a point source, and gradually decreases for planar injection. We confirm this prediction with numerical calculations describing the vapour production resulting from steady injection from line, point and planar sources.

Introduction

Vapour dominated geothermal reservoirs have great economic potential as an energy source. For example, the Geysers in California has the potential of producing 2000MW and the Larderallo field in Italy also produces much energy. However, a major problem with such a resource is the replacement of fluid, which is extracted through turbines, in order to tap the energy. In the Geysers reservoir, fluid levels have diminished drastically following massive exploitation of this energy resource; today, the reservoir can only provide 1500MW of power, although the turbines were designed to generate 2000MW (Kerr, 1991).

One practical means of recharging reservoirs is through the injection of water, at high pressure, into the reservoir. As the water migrates through the rock, it is heated up and a fraction vaporises. Fundamental understanding of the controls acting upon this vaporisation process is crucial in order to optimise the efficiency of any recharge program. In an important, recent contribution, Pruess *et al* (1987) analysed the injection of fluid from a line source, and presented a linearised similarity solution. We have built upon this study in several fundamental ways; we have (i) retained the full-nonlinear model; (ii) identified and explained the physical controls upon vapour production; (iii) carried out a systematic parameter study; (iv) calculated similarity solutions for point, line and planar source injection geometries and (v) analysed the full time-dependent process. Our suite of theoretical models identifies some of the most important controls upon vapour production.

A model of re-injection of water

Our model of the injection of water into a geothermal reservoir is based upon a number of simplifications and incorporates many of the features of the model of Pruess *et al.* (1987). Perhaps the most important simplification is the approximation that the reservoir is a permeable rock; on a sufficiently large scale, this assumption will capture many of the basic dynamical controls, even for a fracture dominated reservoir (Bodvarsson, 1972; Pruess *et al.* 1987). We also assume that the fluid supplied to the interface with the vapour has attained the interface temperature; this follows from the result that in the liquid saturated region, the isotherms lag behind the advancing and vaporising fluid front (Woods and Fitzger ald, 1992).

We also assume that the rate of diffusion of heat in the alongflow direction in the vapour region is much more rapid than the rate of migration of vapour; this implies that to leading order, the vapour-saturated region is isothermal.

Finally, we assume that gravity has a secondary role upon the motion of the injected water, and that it is primarily driven by pressure gradients; this approximation is valid if the pressure gradient across the vapour, ahead of the interface exceeds the gravitational force acting upon the fluid, as is the case for sufficiently rapid injection. The geometry of injection we model is shown in figure 1. Further details of the model, and a fuller discussion of the assumptions, are given in Woods and Fitzgerald (1992).

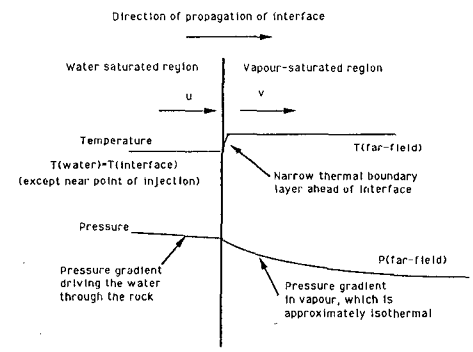

Figure 1 - Schematic of Interface

The motion of the vapour is governed by the conservation of mass

$$\frac{\partial \rho_v}{\partial t} + \nabla(u_v.\nabla \rho_v) = 0 \quad (1)$$

together with the momentum equation, modelled by Darcys Law (Rubin and Schweitzer, 1971, Dagan, 1989)

$$\mu u_v = -k\nabla P \quad (2)$$

and the equation of state (Young, 1988)

$$P = \rho_v R_g T Z \quad (3)$$

where ρ_v is the vapour density, u_v the vapour velocity, k is the permeability of the host rock, μ the dynamic viscosity of the vapour, R_g the gas constant, T the temperature and Z is the compressibility, which is approximately constant over the range of pressures and temperatures which arise in a geothermal reservoir.

These equations are coupled with the conservation equations across the water-vapour interface. The conservation of mass across the interface has the form

$$\rho_v u_v = (1-R)\rho_w u_w \quad (4)$$

where u_w is the fluid velocity, ρ_w the fluid density, and $1-R$ is the mass fraction vaporised. The conservation of energy has the form

$$\phi(1-R)\rho_w(h_{v\infty} - C_p T_i) = R(1-\phi)\rho_r C_{pr}(T_\infty - T_i) \quad (5)$$

where C_p is the specific heat at constant pressure, $h_{v\infty}$ is the enthalpy of the vapour ahead of the thermal boundary layer in the vapour-saturated region, and subscripts w, v denote the water and vapour. Finally, the interface temperature and pressure are related by the Clausius-Clapyron relation, as specified by the international steam tables. A simple empirical relationship which applies for $150 < T < 250^oC$ is

$$P = 6.7T^{0.23} \quad (6)$$

It may be shown that by combining the above equations, the rate of migration of pressure ahead of the interface satisfies the nonlinear diffusion equation

$$\frac{\partial P}{\partial t} = \frac{k}{\mu}\nabla.(P\nabla P) \quad (7)$$

This equation suggests that pressure perturbations diffuse ahead of the interface at a rate $(k\hat{P}/\mu)^{1/2}$, where $\hat{P}$ represents a typical value of the pressure.

Non-linear Similarity Solutions

If we specify that the water-vapour interface has position

$$r = 2\lambda t^{1/2} \quad (8)$$

then a similarity solution exists, in terms of a similarity variable $\eta = r/t^{1/2}$, in which a constant fraction, $1-R$, of the injected water vaporises per unit time. This is because the diffusion equation admits similarity solutions which propagate at a rate proportional to $t^{1/2}$. In these solutions, a constant fraction of the fluid injected vaporises, and the remainder invades the rock, thereby increasing the volume that is water-saturated. The fluid interface advances at a rate, proportional to $t^{1/2}$, and therefore depends upon the rate of injection in a simple manner; it is readily shown that (i) for planar injection, fluid must be injected at a rate proportional to $t^{-1/2}$; (ii) for line source injection, fluid must be injected at a constant rate; and (iii) for point source injection, fluid must be injected at a rate proportional to $t^{1/2}$. Pruess *et al.* analysed the injection from a line source, case (ii); in order to obtain an analytical solution, they linearised the non-linear diffusion coefficient in equation (6).

In contrast, we retain the full non-linear diffusion equation, in order to include effects resulting from variations in the pressure as the vapour migrates ahead of the interface. Further details of the derivation of our new solutions are given in Woods and Fitzgerald (1992).

Numerical solutions of the full non-linear similarity equation, together with the boundary conditions described above, allow simple determination of the effect of different reservoir properties and injection rates. In figure 2, we present four figures, modelling steady injection at a line source, which illustrate how the mass fraction vaporised changes with (i) the rate of injection of fluid; (ii) the reservoir pressure; (iii) the reservoir superheat; and (iv) the reservoir porosity.

In figure 2(i), we show the difference between the linearised and the full non-linear similarity solutions; the full solution predicts more vapour production at low injection rates and less vapour production at high injection rates. This results from the changing pressure, and hence effective diffusion coefficient, with distance from the interface, which is not included in the linearised model.

As the rate of injection of fluid increases, the total mass of vapour produced increases; this requires a greater pressure gradient to drive the vapour from the interface and so the interface pressure increases. As a result, the interface temperature increases, according to the Clapyron relation, and so less heat is available for vaporisation. This causes a decrease in the mass fraction vaporised and hence efficiency of injection.

As the reservoir pressure decreases, the difference in the maximum pressure at the interface and the far-field pressure increases; therefore, the maximum change in temeprature of the host rock, and associated heat release increases. Thus the fraction vaporised increases. Similarly, for larger reservoir temperatures, with other properties fixed, the mass fraction vaporised is greater.

If the effective porosity of the host rock increases, the heat released per unit volume of rock invaded by water decreases, and this heat released is distributed to a larger mass of water; therefore with other properties fixed, the mass fraction vaporising decreases.

Time-Dependent Numerical Solutions

The similarity solutions for injection from a point (planar) source require the mass injection rate to increase (decrease) with time, whereas the line source requires a constant injection rate (figure 3).

As mentioned above, these results suggest that for a constant injection rate, injection at a point source leads to an ever increasing mass fraction vaporised, whereas injection from a planar source implies an ever decreasing mass fraction vaporised.

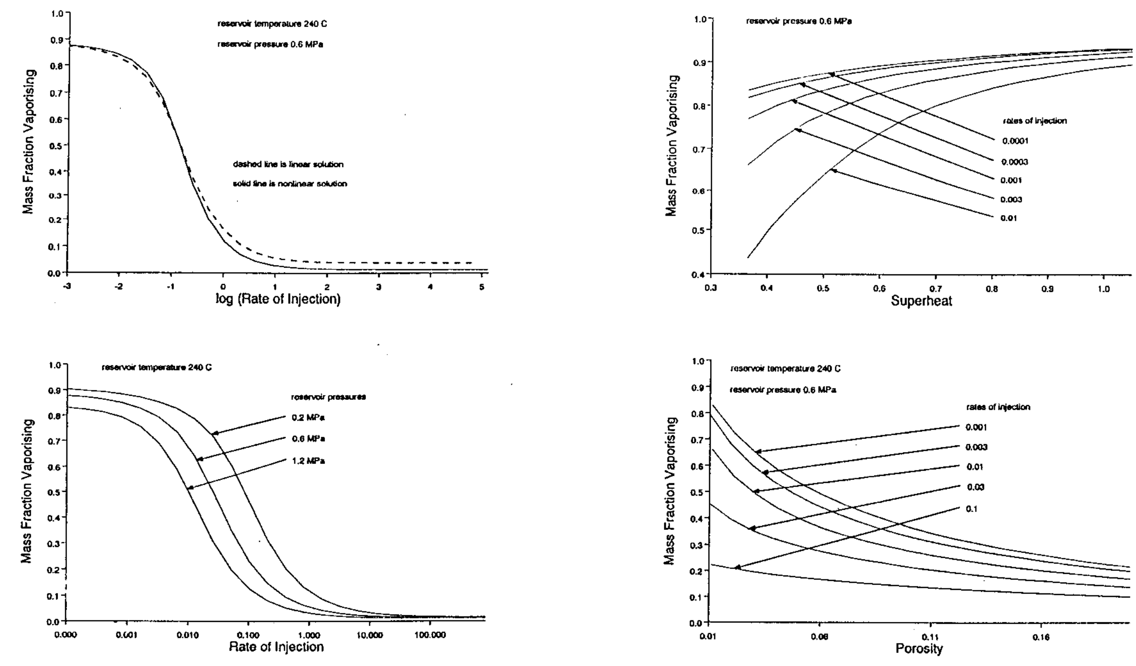

Figure 2: Parameter study of mass fraction vaporised

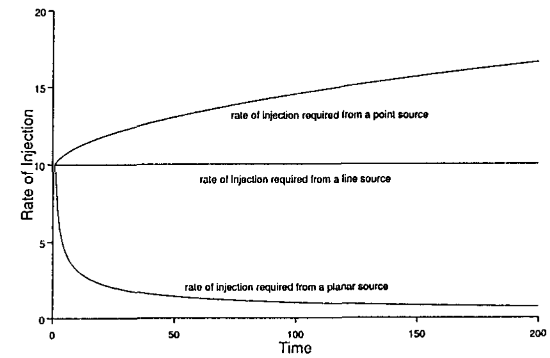

Figure 3: Mass flux injected for similarity solution

In order to test this hypothesis, we have solved numerically the time-dependent equations, given above, for injection from a point, line and planar source, with a constant rate of injection. Details of our numerical scheme are given in Woods and Fitzgerald (1992).

In figure 4(i), we present the results of our calculations. It may be seen that, as expected, the mass fraction vaporised from one dimensional injection progressively decreases, whereas, after an initial transient, the mass fraction vaporised from a point source injection, progressively increases. In figure 4(ii), we present calculation of the total mass of vapour produced as a function of time; for the case of point source injection, the total mass of vapour produced is the greatest, whereas the planar source produces the least. Essentially, this occurs because the vapour diffuses from the interface and so if the fluid front advances at a rate faster (slower) than $t^{1/2}$ then with time, less (more) vapour is able to migrate ahead of the interface, and the fraction vaporising decreases (increases).

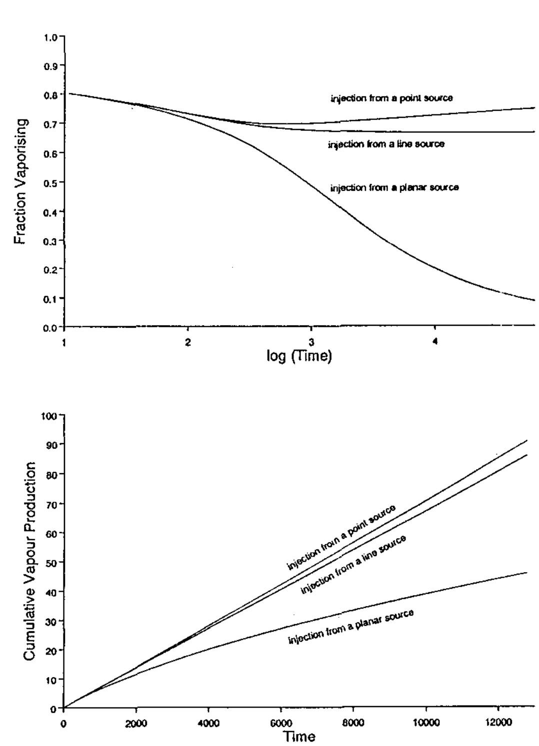

Figure 4: Steady injection in different geometries

Discussion

We note that other considerations such as the work exerted in injection, the maximum pressure which an injection pump can generate and the time available for injection need consideration.

We define the cumulative pump work, W, to be the time integral of the mass flow rate of water, Q, into the reservoir times the pressure, P, which must be applied at the well-bore to drive this flow rate

$$W = \int PQdt \tag{9}$$

In figure 5(i), we show that for three dimensional steady injection, the total pump work, per unit mass of vapour produced, is much less than that associated with steady one dimensional injection; this is because the interface pressure builds up in one-dimensional injection, and therefore requires an ever increasing well-bore pressure to continue the steady injection process,

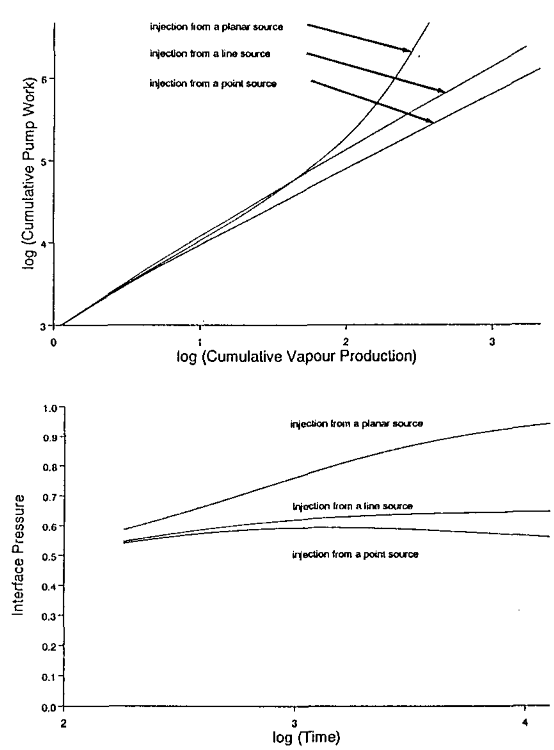

Figure 5: Pump work and interfacial pressure

figure 5(ii). In three dimensional injection, the interface pressure decreases, and therefore the wellbore pressure necessary to continue the injection decreases with time; as a result, less work is required per unit of fluid vaporised.

This is a crucial result which must be accommodated into any vapour regeneration strategy; injection from a point source ulitimately produces a greater mass of vapour per unit mass of fluid injected, and also requires much less pump work in order to produce that vapour.

However, we note that the optimal conditions in the reservoir for extraction of power through turbines may be incompatable with the optimal conditions for vapour generation through injection; this leads to a more complex problem of operating efficiency. In addition, the initial cost of installing drill holes to cause point and line sources of fluid needs consideration. We plan to address some of these issues through further development of our model.

Conclusions

Our results have important implications for the optimal strategy one should adopt in any scheme for vapour regeneration. From our study, it is clear that (i) the larger the volume of rock into which the injection occurs, the greater the mass fraction that will be vaporised - injection from a point source is the most efficient injection technique, requiring the minimum pump work and resulting in the maximum mass of vapour per unit mass of water input to the reservoir; (ii) the more rapidly the fluid is injected, the less efficient the vapour production, since the interface pressure increases, and so less thermal energy can be extracted from the rock for vaporisation; and (iii) the lower the reservoir pressure on injection, the greater the efficiency of injection, since, with optimal three-dimensional injection, the host rock can cool to the saturation temperature associated with the reservoir pressure (except at very long times, when thermal diffusion becomes important, Woods and Fitzgerald, 1992).

We are developing our model to include other effects, for example, a geothermal temperature gradient, inhomogeneities in the reservoir structure, and gravity.

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