

SALT PRECIPITATION IN GEOTHERMAL RESERVOIRS

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Summary We model the motion of the boiling front which develops when hot saline solution migrates towards a low pressure well from a geothermal reservoir which is initially saturated with hot saline solution. We derive a family of self-similar solutions which describe the motion of the liquid and vapour towards the well, as the boiling front migrates out into the reservoir. These solutions take into account the reduction in permeability and porosity due to salt precipitation at the boiling front. We find that for low reservoir pressure or small salt concentration there are two distinct branches of self-similar solutions. For each salt concentration, these branches coincide at a critical reservoir pressure. For larger reservoir pressure, the self-similar solutions cease to exist and we propose that in this regime, the pore space becomes fully clogged with salt precipitate.

PROBLEM FORMULATION

We consider the extraction of vapour from a low pressure well embedded in a hot porous rock saturated with aqueous saline solution. As the fluid evaporates, the salt concentration of the residual liquid increases leading to precipitation of salt in the porous space and hence a reduction of rock porosity and permeability [1-3]. The primary objective is to investigate this salt precipitation process; for the sake of simplicity we focus on the idealized isothermal problem in which the reservoir temperature is equal to the initial value $T = T_0$. This hypothesis implies that there is a cross-layer heat flux which maintains the temperature in the permeable layer from a neighbouring impermeable layer. Vaporization occurs within a geothermal reservoir if the pressure P_w in the well-bore is less than the saturation pressure $P_f(T_0)$ at the vaporization front. In the water and vapour zones, the pressure evolves according to Darcy's law combined with the local mass-conservation equations, leading to the governing equations for the liquid and vapour regions

$$\frac{\partial P}{\partial t} = \kappa_1 \Delta P, \quad \kappa_1 = \frac{k}{\phi \alpha \mu_w}; \quad (\text{grad } P)^2 + P \Delta P = 0; \quad (1)$$

where k is the permeability, ϕ the porosity, μ the viscosity and α the water compressibility coefficient. As the boiling front migrates away from the extracting well, the pressure distribution in the vapour zone is quasi-stationary owing to the low density of the vapour [4]. The solid salt precipitate occupies some part of the volume of porous space in the vapour zone. This part we denote as the unknown function S_{pr} . We assume that the vaporization front coincides with the precipitation front. The boundary condition for the mass of solution includes the reduction in the porosity and permeability of the vapour region due to the formation of salt deposit with density ρ_{salt} and has the form

$$\phi[\rho_w - S_{pr} \rho_{salt} - (1 - S_{pr}) \rho_v] V_n = -Q_{vn-} + Q_{wn+} \quad (2)$$

where V is the front velocity and the mass fluxes in the water and vapour regions are defined by the formulas

$$Q_w = -\rho_w \frac{k_0}{\mu_w} \text{grad } P, \quad Q_v = -\rho_v \frac{k_0 K(S_{pr})}{\mu_v} \text{grad } P \quad (3)$$

We assume that the advective transport of salt dominates the diffusive transport and conservation of salt across the front has the form

$$\phi(S_{pr} \rho_{salt} - c + \rho_w) V_n = -c + Q_{wn+} \quad (4)$$

where c is the salt concentration in the fluid ahead of the boiling front. The mass-conservation equation for the salt in the water region can be written as

$$\frac{\partial c}{\partial t} - \frac{k}{\phi \mu_w} \text{grad } P \text{ grad } c = 0 \quad (5)$$

We consider one-dimensional flow in an unbounded constant temperature reservoir, $x > 0$, and assume that at the extraction well, $x = 0$, the pressure has value P_w . Thus, the boundary and initial conditions have the form $t = 0$: $P = P_0$, $c = c_0$; $x = 0$: $P = P_w$. If the initial and boundary values are constants the problem admits a similarity solution $P = P(\xi)$, $c = c(\xi)$, $X = \beta \sqrt{t}$, $\xi = xt^{-1/2}$, $V = \dot{X}(t)$. The exact solutions for the water ($x > 0$) and vapour ($0 < x < X(t)$) regions are obtained from the equations (1) and (5) together with a law for the change in permeability associated with the precipitation. Here we use a parametric relation to describe the change in permeability as a function of the mass of precipitate, given by

$$k_- = k_0 \frac{1 - \exp[\mathcal{G} \phi (1 - S_{pr})]}{1 - \exp(\mathcal{G} \phi)} = k_0 K(S_{pr})$$

where $\mathcal{G}$ is a coefficient which accounts for different changes in the permeability as a result of precipitation.

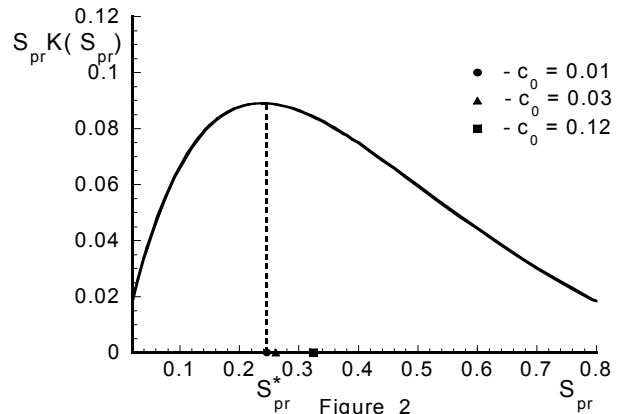
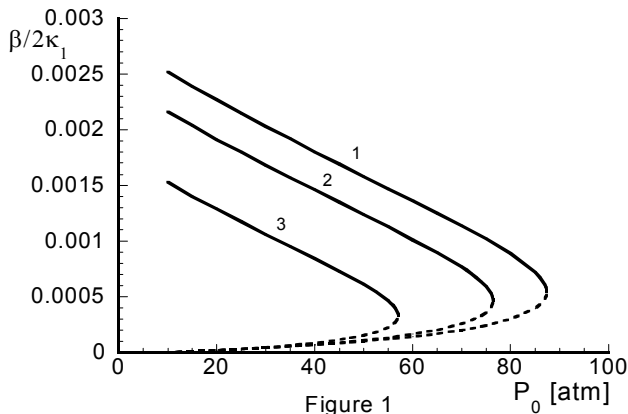
The unknown functions β and S_{pr} can be found if we substitute the similarity solutions into boundary conditions (2) and (4) at the vaporization front, leading to a system of transcendental equations.

EXISTENCE OF MULTIPLE SOLUTIONS

Numerical solutions of the transcendental system for the typical values of the main parameters, namely the far-field reservoir pressure and the salt concentration in solution are presented in figure 1 ($c_0=0.1$, $1-P_w = 4 \cdot 10^5 \text{ Pa}$, $2-P_w = 6 \cdot 10^5 \text{ Pa}$, $1-P_w = 8 \cdot 10^5 \text{ Pa}$). We have found that there are two solutions (solid and dashed lines) for small values of the far-field pressure and hence liquid flux, but that as the reservoir pressure increases, these two solutions eventually meet, and for large values of the pressure, there is no solution. Instead, we expect the pore space to be fully clogged with precipitate. It has been shown in [4] that in the limit of high reservoir pressure and hence large liquid flow from the far field, the motion of the boiling front is suppressed and $V \rightarrow 0$. From equation (2), we expect that in this limit, the approximate balance $Q_w = Q_v$ applies. If the front velocity V is sufficiently small then salt precipitate accumulates owing to the advective transport of fluid to the well-bore. For a self-similar flow, for which the boiling front advances at a rate $V_0 t^{1/2}$ and the fluxes decay at a rate $Q_0 t^{-1/2}$, then using equations (3) and (4) we find that

$$Q_{v0}^2 = \frac{\phi \rho_v \rho_{salt} k_0 \delta P}{c_0 \mu_v} S_{pr} K(S_{pr})$$

where δP is the fixed difference in pressure between the boiling front and the well and we have used the result that $S_{pr} \rho_{salt} \gg c_0 \rho_w$. Since the permeability decreases as the mass of salt precipitated increases, then quantity $S_{pr} K(S_{pr})$ may vary non-monotonically with S_{pr} . Indeed, it is likely to be very small for both small and large value of S_{pr} corresponding to the case of a very small mass of precipitate and a large mass of precipitate which nearly clogs the matrix. For intermediate values, the value of $S_{pr} K(S_{pr})$ is likely to be larger and there is some intermediate value S_{pr}^* at which it attains a local maximum. For $Q_{v0} < Q_{v0}(S_{pr}^*)$, we expect two solutions for S_{pr} and hence V_0 for the given value of Q_{v0} , with the other parameters fixed; this is consistent with the full numerical calculations (figure 1). In figure 2, the curve $S_{pr} K(S_{pr})$ is shown as a function of S_{pr} , and the critical value for S_{pr}^* is equal approximately 0.24. In this figure we also show the critical value as calculated from the complete similarity solution for three values of the salt concentration. It is seen that the exact value depends on the initial salt concentration. For small initial concentration, a large flow rate is needed to clog up the porous space, but for such flow rates the velocity of the boiling front is small and the effect of front motion is negligible. Therefore the water flux is equal approximately to the vapour flux and the exact numerically-computed critical value practically coincides with our simple asymptotic estimate.



CONCLUSIONS

Our analysis has established that if there is some salt precipitation associated with the boiling of the liquid, there are typically two possible self-similar solution branches. These two branches coincide for a critical value of the liquid flux, and above this value, the self-similar solution ceases to exist. Instead, the rock becomes clogged with salt.

We are grateful for funding from the BPI which supported GT as a senior visiting fellow.

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