



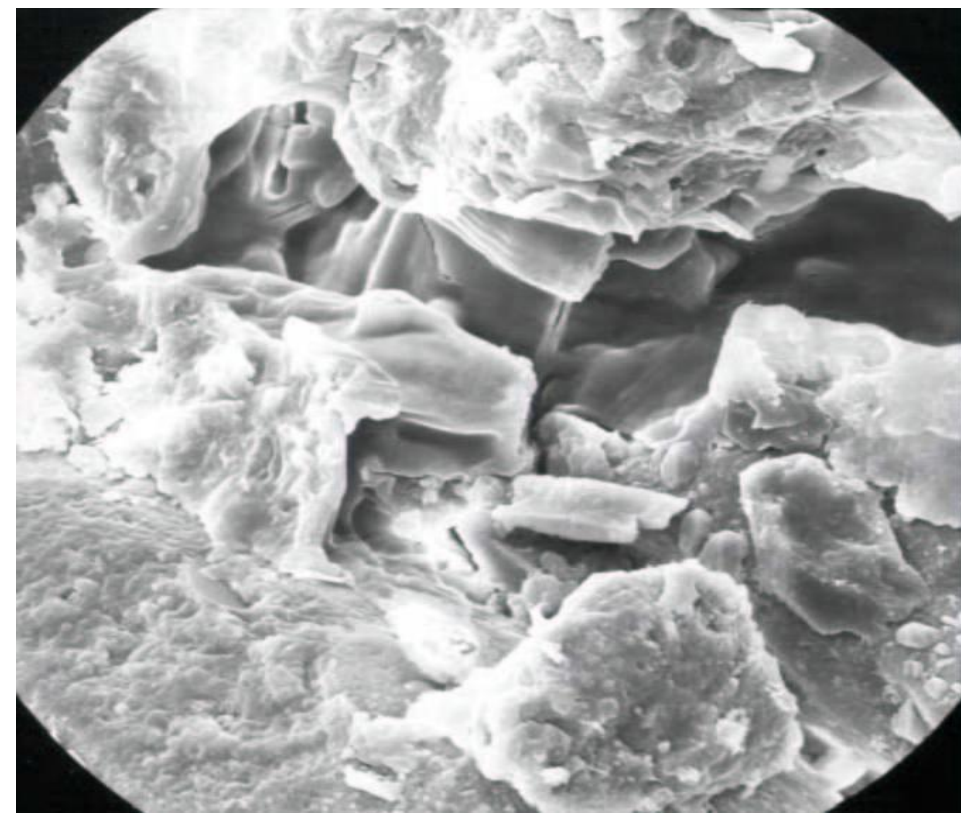
Phase transitions and precipitate formation in geothermal reservoirs

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Introduction

Processes in porous permeable rock in which solid material is deposited from solution or is removed due to dissolution are very important for different applications, such as exploitation of geothermal reservoirs, oil and gas fields, storage of gas in aquifer or depleted reservoir, in agriculture etc [1,2,3].



Scanning electron micrograph of salt precipitate in the rock around gas producing wells[2].



Salt precipitation in soils

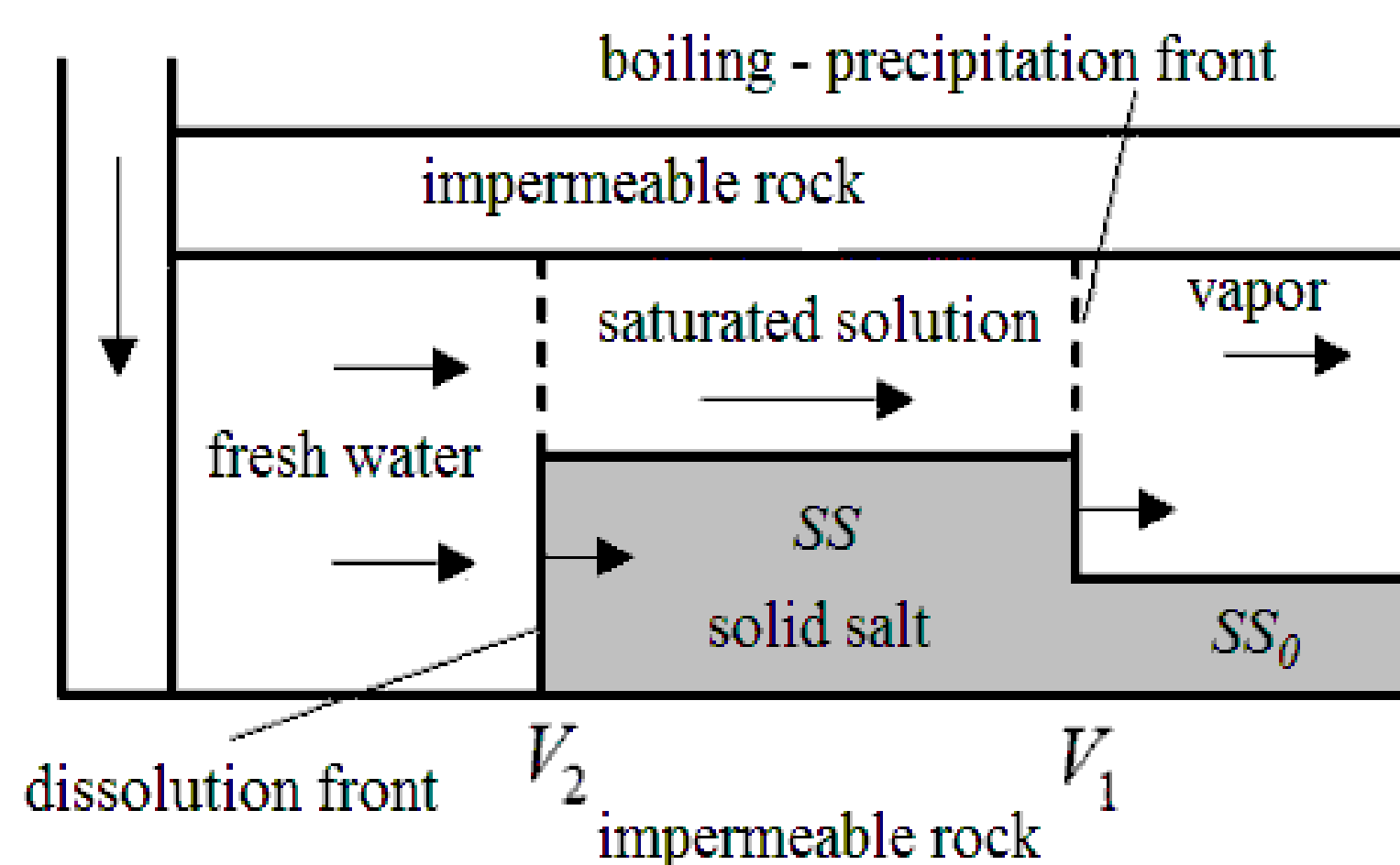
Motion and evaporation of salty water in high-temperature permeable rock may occur both during the operation of geothermal systems and in natural processes. The injection of cold water into a depleted hot geothermal reservoir is accompanied by heating of the liquid injected and may lead to the boiling. In natural processes a liquid with the same temperature as the surrounding rocks may flow from a high- to a low-pressure region saturated with superheated vapor. If the thermodynamic conditions at the salty water – vapor interface reach boiling point, the water evaporates and the salt concentration in the liquid phase increases. With increase in the evaporation rate the salt concentration reaches the solubility value and then the excess salt is precipitated and solid salt changes the porosity and permeability of the rock. In [1] TOUGH2 software package was used for studying the effect of a decrease in permeability due to salt precipitation during evaporation in low-permeability blocks. In [4], the vapor extraction from a geothermal reservoir saturated with salty water was investigated analytically. A family of self-similar solutions describing the salt precipitation and the decrease in porosity and permeability was obtained. It was shown that this family of solutions is two-valued. With variation of one of the parameters (initial or well pressure, temperature, etc.) these solutions converge, and eventually coincide. Beyond this critical point, there is no similarity solution. It was assumed that the regime in which there is no solution corresponds to the complete sealing of the pore space by precipitated salt and the blocking of the flow. In [5] the authors used the TOUGH2-EWASG code to verify this hypothesis and investigate precipitate formation near the critical point, where asymptotic solution ceases to exist. They found that the numerical solution describes sealing process, when solid salt saturation tends to 1 and mass flux through the porous rock vanishes. The aim of this work is to investigate pure water injection into hot rock where superheated steam coexists with solid salt. A mathematical model of the process is formulated. This model describes formation of two unknown moving boundaries of phase transitions, which separate three regions. We investigate similarity solution of the problem and find regimes when the solution ceases to exist [6].

Problem formulation

Consider one-dimensional flow in an unbounded constant-temperature porous permeable rock, located in the half-space $x > 0$, saturated with solid salt and superheated vapor. As it has been shown in [5] the isothermal approach gives correct description of the main features of the boiling process.

We assume that at the injection well, $x = 0$, the pressure has value P^0 . Salt in a solid state occupies some part of the volume of the porous space, which we denote as SS .

There are three regions separated by two unknown moving boundaries. The boiling and precipitation front separates region 1 saturated with superheated vapor from region 2 containing a saturated solution coexisting with solid-phase salt. The dissolution front, moving at a lower velocity, separates region 2 from region 3 adjacent to the well and saturated with fresh water. We consider the isothermal problem of flow, in which heat supplied from neighbouring impermeable rock maintains an approximately constant temperature of the permeable rock.



Sketch of the problem

Thus, the boundary and initial conditions have the form $x = 0 : P = P^0 ; t = 0 : P = P_0, SS = SS_0$.

We will describe the liquid and vapor flow through permeable rocks using Darcy's law, the mass conservation laws, and the equations of state for water and vapor. We assume also that matrix of porous rock and solid salt are immobile. In the vapour region the system of basic equations has the form

$$\frac{\partial}{\partial t} (1 - SS_0) \phi \rho_v + \text{div}(\rho_v \bar{v}_v) = 0,$$

$$\bar{v}_v = - \frac{k K(SS_0)}{\mu_v} \text{grad} P, \quad P = \rho_v R T$$

In the liquid regions we have

$$\frac{\partial}{\partial t} \phi (1 - SS) \rho_l + \text{div}(\rho_l \bar{v}_l) = 0, \quad \bar{v}_l = - \frac{k K(SS)}{\mu_l} \text{grad} P,$$

$$\rho_l = \rho_{l0} [1 + \alpha_l (P - P_0) + \alpha_c c], \quad \frac{\partial SS}{\partial t} = 0$$

ϕ – porosity, ρ – density, k – permeability, K – relative permeability, μ – viscosity, α_l – compressibility of liquid, P – pressure, v – filter velocity, SS – solid salt saturation c – salt concentration, The subscripts: m – mixture, l – liquid, v – vapour.

We assume that the salt precipitates across a narrow front that coincides with the vaporization front. The boundary conditions across this front can be found using the conservation of mass for the H_2O and the salt, including the reduction in the porosity and permeability of the vapor region due to the formation of a salt deposit with density ρ_{salt} . Conditions through the leading front of boiling – precipitation

$$\left[(1 - SS_0) \frac{\rho_{v*}}{\rho_{w2}} - (1 - SS_*) \right] V_{1n} = \frac{k_0 K(SS_*)}{\phi \mu_2} \text{grad} P_{n-} - \frac{\rho_{v*}}{\rho_{w2}} \rho_v \frac{k_0 K(S_*)}{\phi \mu_v} \text{grad} P_{n+},$$

$$\left[\frac{SS_0 \rho_{salt}}{\rho_{sol} c_{sat}} - \frac{SS_* \rho_{salt}}{\rho_{sol} c_{sat}} - (1 - SS_*) \right] V_{1n} = \frac{k_0 K(SS_*)}{\phi \mu_2} \text{grad} P_{n-}$$

$$P_f = P_f(T_0);$$

The subscript * denotes value at the moving front

Boundary conditions at the second front have the form

$$\left[(1 - SS_*) \frac{\rho_{w2}}{\rho_{w3}} - 1 \right] V_{2n} = \frac{k_0}{\phi \mu_3} \text{grad} P_{n-} - \frac{\rho_{w2}}{\rho_{w3}} \frac{k_0 K(S_*)}{\phi \mu_2} \text{grad} P_{n+},$$

$$\left[\frac{SS_* \rho_{salt}}{\rho_{sol} c_{sat}} + 1 - SS_* \right] V_{2n} = - \frac{k_0 K(SS_*)}{\phi \mu_2} \text{grad} P_{n+}$$

Boiling pressure for the isothermal approach can be found from the Clausius – Clapeyron equation directly:

$$P_1^* = G(T, c) = G(T_0, c_{sat}(T_0)) = G(T_0)$$

Density at the boiling surface we obtain from the equation of state $\rho_{v*} = P_1^* / RT_0$

Similarity solution and calculation results

From the basic systems of equation, excluding density and velocity, we obtain equations for the pressure. In the vapour region (1) and in regions (2), (3) saturated with the salty and fresh water the equations have the form

$$\frac{\partial P}{\partial t} = \kappa_1 \left[(\text{grad} P)^2 + P \Delta P \right] \quad \kappa_1 = \frac{k_0 P_0 K(SS_0)}{\phi \mu_v (1 - SS_0)}, \quad \frac{\partial P}{\partial t} = \kappa_{2,3} \Delta P, \quad \kappa_{2,3} = \frac{k_{2,3}}{\phi \mu_l \alpha_l}$$

Within the linear approach we derive similarity solution of the above equations in the form

$$P = P(\xi), \quad T = T(\xi), \quad SS = SS(\xi), \quad X_{1,2}(t) = 2\gamma_{1,2} \sqrt{\kappa_2 t}, \quad \xi = \frac{x}{2\sqrt{\kappa_2 t}}$$

By combining the solutions with the boundary conditions through the fronts we obtain four transcendental equations for the quantities $\gamma_1, \gamma_2, SS_*, P_2^* / P^0$. As an example we give equation of H_2O conservation at the first boundary.

$$\left((1 - SS_0) \frac{\rho_{v*}}{\rho_{w2}} - 1 + SS_* \right) \gamma_1 = \frac{P^0}{P_0} \sqrt{\frac{\kappa_1}{\pi \kappa_2}} \frac{\rho_{v*}}{\rho_{w2}} (1 - SS_0) \left(\frac{P_1^*}{P^0} - \frac{P_0}{P^0} \right) \exp(-\gamma_1 \kappa_2 / \kappa_1) + \frac{K(SS_*)}{2(\gamma_2 - \gamma_1)} \left(\frac{P_2^*}{P^0} - \frac{P_1^*}{P^0} \right)$$

From boundary condition for the mass of salt at the first front we get SS_* as a function of γ_1 . The above equation gives the speed of the second front as a function of SS_* and γ_1 . From the mass of H_2O conservation equation at the second front the pressure at this front can be expressed in terms of the parameters SS_*, γ_1 and γ_2 . As a result, substituting these functions to the mass of salt conservation at the second boundary, we reduce the system to a single transcendental equation $F = F(\gamma_1)$. This method makes it possible to investigate fully the behavior of the roots of the transcendental system. The resulting equation was solved numerically for typical values of the parameters.

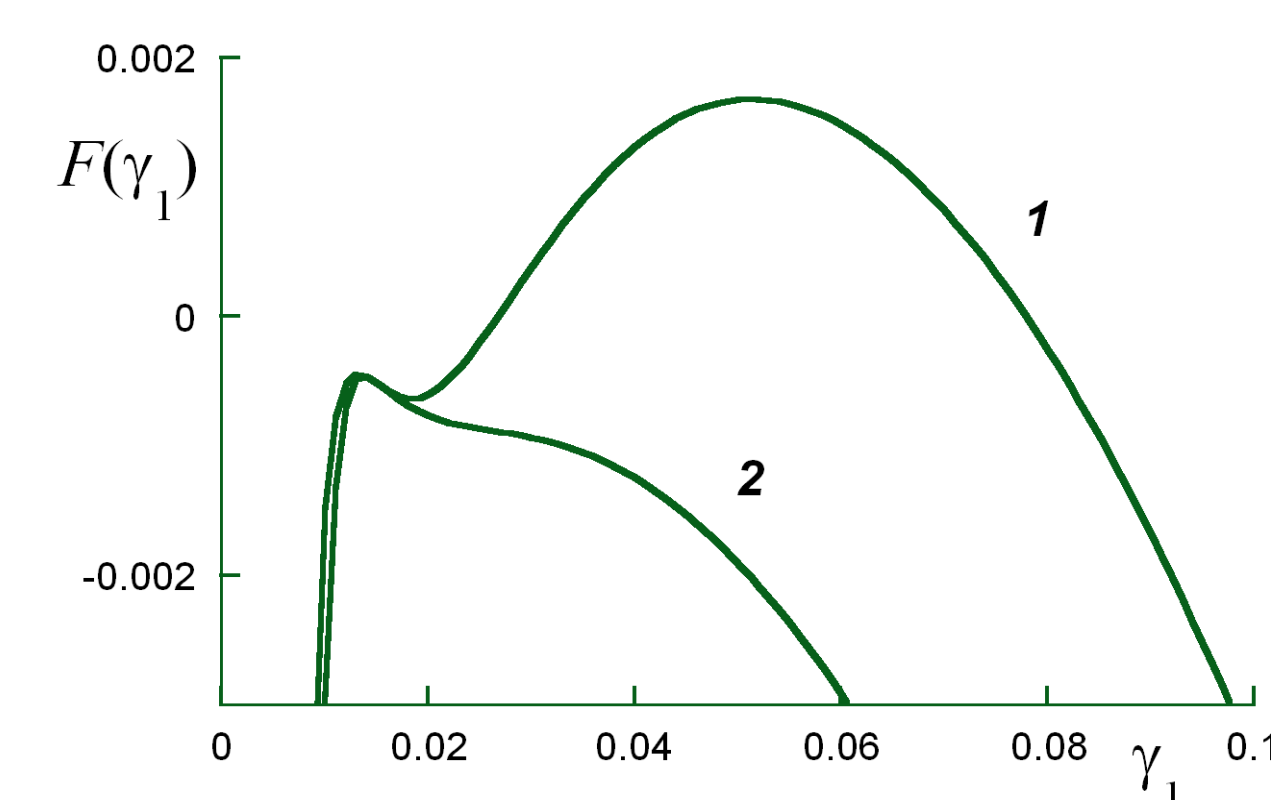


Figure 1

Figure 1 shows an example of calculations when the solution ceases to exist, and demonstrates the shift of the transcendental curve $F(\gamma_1)$ which occurs due a change in injection pressure. The equation $F(\gamma_1) = 0$ has two solutions in curve 1, corresponding here to an injection pressure $P^0 = 5.9$ MPa. By reducing the injection pressure to 5.7 MPa, the curve moves downwards, and no longer passes through zero. Thus, we obtain two similarity solutions for a large injection pressure. When the pressure decreases these two solutions eventually meet and for small value of the injection pressure there is no solution.

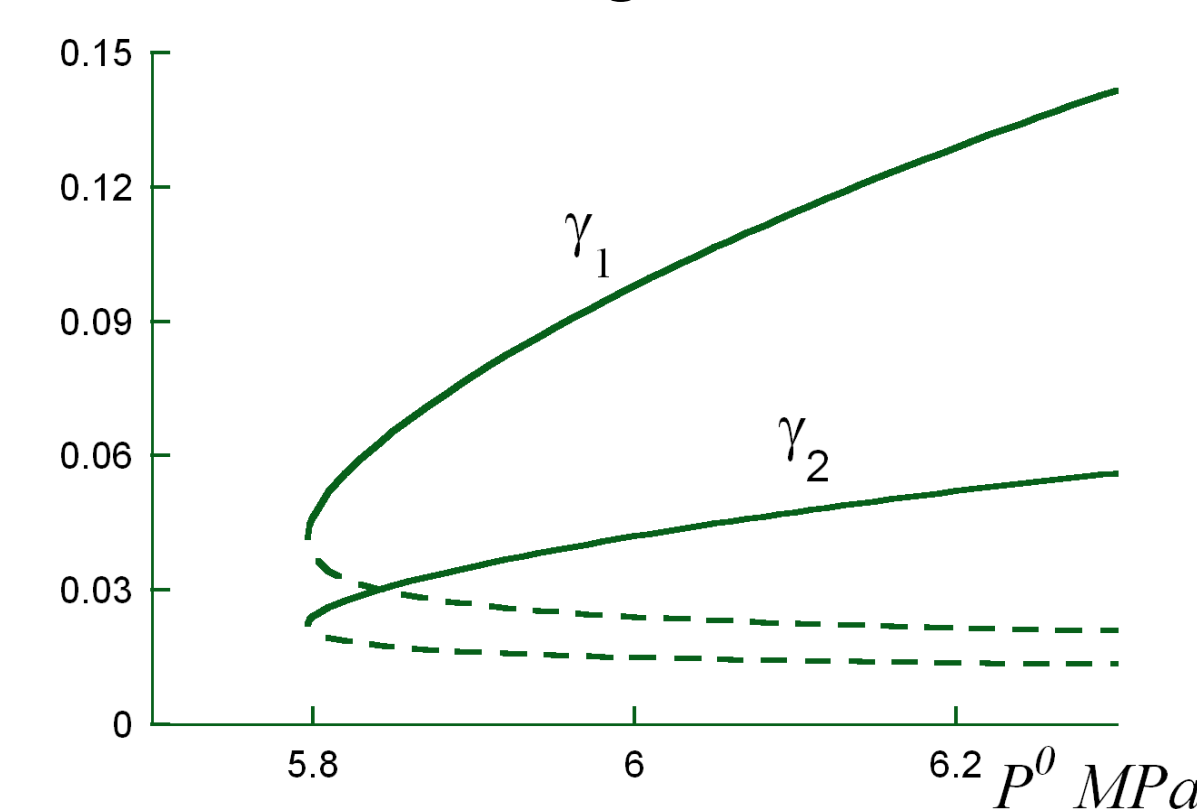


Figure 2

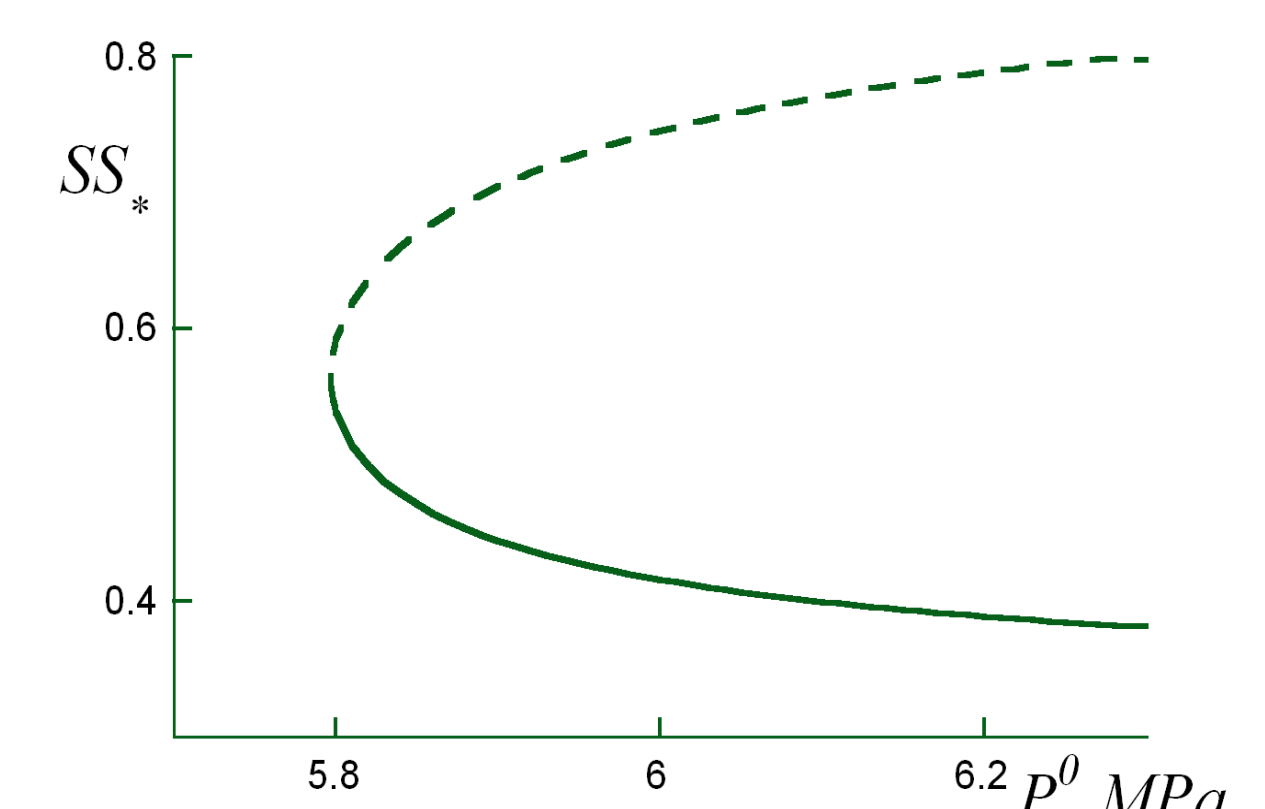


Figure 3

Figure 2 demonstrates dimensionless velocities of the vaporization-precipitation and dissolution fronts as functions of the injection pressure. The solid line corresponds to the fast solution and dashed line gives the slow solution.

Figure 3 gives variation of solid salt saturation as a function of the injection pressure. The solid line corresponds to the fast solution and dashed line gives the slow solution.

Calculations show that the lower injection pressure causes sufficiently more intensive vaporization process therefore more salt precipitates. In contrast, the high injection pressure suppresses boiling in the reservoir that leads to the decreasing of precipitate formation.

Discussion

We have investigated the problem of injection of fresh water in a geothermal reservoir saturated with solid salt and superheated vapor. Our analysis has established that there are two possible branches for the self-similar solution. Further, these two branches coincide at a critical value of the liquid flux, and for some value of the flux the self-similar solutions cease to exist. Instead, the rock becomes clogged with salt. This result is in sharp contrast to the case with no precipitation, in which there is a unique flow solution, and the self-similar flow regime can develop for arbitrarily small liquid fluxes from the injection well-bore.

Multi-valued solutions appear in many branches of mathematical physics and we need some additional constraints to determine which solution will arise in practice. In the limit of zero initial salt saturation, the fast flow solution tends to the simpler problem of pure water injection. For the case of the injection of pure water, the speed of boiling front increases with the injection pressure. The same behavior demonstrates the fast solution for the problem of salt precipitation. In contrast, with the slow solution, the front velocity decreases when the injection pressure increases. Furthermore, for the fast solution, the mass of precipitate (solid salt saturation SS) increases with initial salt saturation whereas it is predicted to decrease in the slow solution. These properties suggest that the fast solution is stable while the slow solution is unstable, and so we expect the fast solution arises in practice.

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