STEAM TRANSPORT IN POROUS MEDIA

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Numerous investigators have pursued development of large-scale two-phase digital simulation models of vapor-dominated geothermal systems. These represent significant advances in the capability to numerically simulate complex systems. However, the basic physical phenomena which are being modeled are still under investigation. The purpose of this discussion is to present the results of a numerical study in which some of the physical phenomena which may occur in vapor-dominated geothermal reservoirs are examined. These phenomena include: (1) superheating of discharging steam, (2) energy changes due to compressible work, (3) conductive heat transport, and (4) gravitational effects of the steam column. Further details pertaining to this study are available in a report by Moench (1976).

The numerical model used in this study draws upon the concepts of White and others (1971) for a vapor-dominated geothermal system, though of necessity some simplifications have been made. The physical system is idealized as a one-dimensional column of porous or highly fractured rock filled with a mixture of steam and liquid water under high pressure. This reservoir is overlaid by a "cap rock" that has low permeability. At the bottom of the reservoir there is a zone where liquid water saturates the pores. Heat is supplied by a magma chamber at depth and transferred upward through the liquid-saturated zone by conduction and convection. The primary mechanisms for heat transfer through the vapor-dominated zone are vaporization and condensation. Figure 1 illustrates the distributions of temperature and pressure to be expected in this idealized natural system.

The model is designed to determine the time-varying distributions of liquid-water saturation, pressure, and temperature within the vapor-dominated region. These distributions may be due to the withdrawal of steam at either constant pressure or constant discharge. Basic assumptions of the model include the following: (1) liquid water within the vapor zone is stationary, but subject to vaporization, (2) Darcy's law is valid for two fluids, (3) the rock matrix is rigid, (4) local thermal equilibrium occurs between the fluids and rock, (5) negligible viscous dissipation, (6) negligible thermal dispersion, and (7) negligible surface tension effects.

To simulate the vertical flow of steam through variably saturated porous media, two controlling equations are used (see Appendix): a fluid-flow equation and an energy equation. These equations contain parameters which are dependent upon pressure, temperature, and liquid-water saturation. The energy equation accounts for heat conduction, convection, vaporization, compressible work, and heat storage. These partial differential equations are coupled through the velocity terms, the vaporization terms, the liquid saturation, and the pressure- and temperature-dependent parameters. The equations are solved simultaneously at discrete time intervals by a finite-difference technique.

Results

Figure 2 shows the pressure, temperature, and liquid-water saturation after 10^9 sec (31.6 years) of steam production from the top of a one kilometer column of reservoir rock. This represents the effect of removing about 70% of the mass that was initially available. Steam is produced at a rate which declines with time due to withdrawal at constant pressure. All the liquid water in the top 300 m has been vaporized and steam in this region is superheated.

Temperature distributions "A" and "B" in Figure 2 show the influence of heat conduction and compressible work (as defined by the second term on the righthand side of the energy equation). Distribution "A" shows the temperature profile obtained using the complete energy equation. Distribution "B" shows the temperature profile obtained when the compressible work term is omitted from the calculations. It is clear that compressible work is significant only where superheated steam is present. Both profiles show the temperature increase at the top of the reservoir brought about by conduction from the base of the cap rock at a distance of approximately 50 m. Conduction from the cap rock or other nearby rocks not cooled by the vaporization process may be responsible for the temperature increase of produced steam observed in some wells (Sestini, 1970). The time variation in temperature at the top of the reservoir is shown in Figure 3 for curves "A" and "B". In the early part of the production history, the cooling effect of compressible work counteracts the heating due to conduction from the cap rock.

The effect of eliminating gravity from the calculations upon the pressure and temperature distributions is shown by the dashed lines in Figure 2. Apart from its possible influence upon the vertical distribution of liquid water (not included in this study) the effect of gravity can be safely neglected. The weight of the steam column has little, if any, effect upon reservoir production characteristics.

References

Moench, A.F., 1976, Simulation of steam transport in vapor-dominated geothermal reservoirs, U. S. Geol. Survey open-file report 76-607, 43 p.

Sestini, G., 1970, Superheating of geothermal steam, Geothermics Special Issue, v. 2, pt. 1, p. 622-648.

White, D.E., Muffler, L.J.P., and Truesdell, A.H., 1971, Vapor-dominated hydrothermal systems compared with hot-water systems, Econ. Geology, v. 66, p. 75-97.

APPENDIX

The basic equations used in this study are reproduced here for convenience. Additional details and constitutive relationships are given in the report by Moench (1976).

Flow Equation

$$\frac{\partial}{\partial z}\left[\rho_v \frac{k\,k_r}{\mu_v}\left(\frac{\partial P}{\partial z} - \rho_v g\right)\right] + q + q' = \phi(1-S)\rho_v\,\kappa\,\frac{\partial P}{\partial t}$$

$$-\phi(1-S)\rho_v\,\beta\frac{\partial T}{\partial t} - \phi\rho_v\,\frac{\partial S}{\partial t}$$

where

- ρ_v density of the water vapor
- μ_v dynamic viscosity of the water vapor
- k intrinsic permeability
- k_r relative permeability to water vapor
- g acceleration of gravity
- ϕ porosity
- S liquid-water saturation
- P pressure
- q source or sink of steam through wells (positive if source of steam)
- q' source or sink of steam by vaporization or condensation (positive if source of steam)
- z vertical coordinate (positive downward)
- t time
- κ compressibility of water, $\frac{1}{\rho_v}\left(\frac{\partial \rho_v}{\partial P}\right)_T$
- β thermal expansivity of water vapor, $-\frac{1}{\rho_v}\left(\frac{\partial \rho_v}{\partial T}\right)_P$
- T temperature

Energy Equation

$$\frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right)-c_1 v\frac{\partial T}{\partial z}-Lq'+Q=[c_1+c_2+c_3]\frac{\partial T}{\partial t}$$

$$-\ \phi(1-S)\ T\ \beta\ \frac{DP}{Dt}$$

where

K	effective thermal conductivity
v	average interstitial velocity
c_1	heat capacity of vapor, $\phi(1-S)\rho_v c_{pv}$
c_2	heat capacity of liquid, $\phi S\rho_\ell c_{p\ell}$
c_3	heat capacity of solid, $(1-\phi)\rho_s c_{ps}$
ρ_ℓ	density of liquid water,
ρ_s	density of solid rock particles
c_{pv}	specific heat at constant pressure of vapor
$c_{p\ell}$	specific heat at constant pessure of liquid
c_{ps}	specific heat at constant pressure of solid
L	latent heat of vaporization
Q	energy source or sink by means other than condensation or vaporization (positive if source of heat)
$\frac{D}{Dt}$	substantial derivative, $\frac{\partial}{\partial t}+v\frac{\partial}{\partial z}$

Liquid-Water Saturation Equation

$$\frac{\partial S}{\partial t}=-\frac{q'}{\phi\rho_\ell}$$

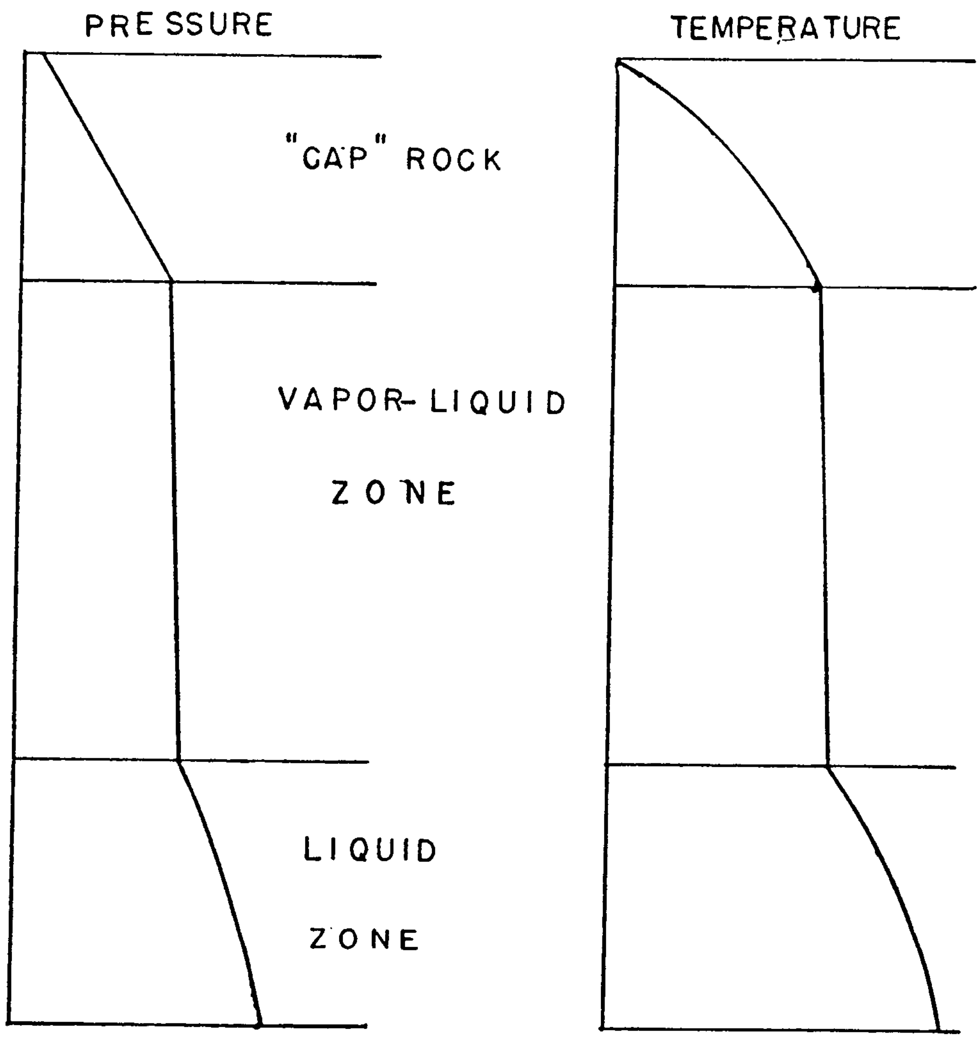
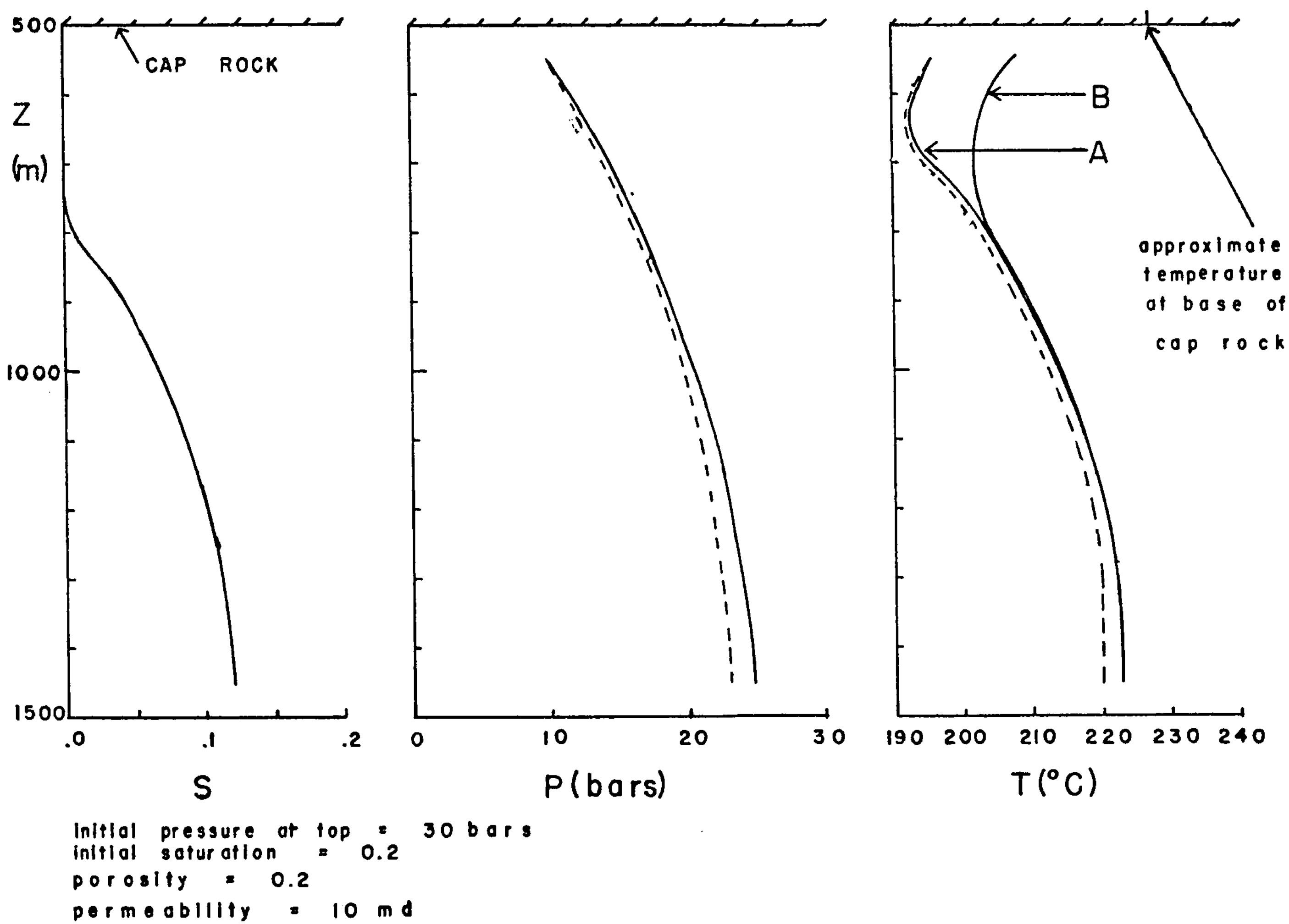


Figure 1. Vertical temperature and pressure distributions in an idealized natural vapor-dominated system.

FIGURE 2. Pressure, temperature and liquid-water saturation distributions in a one-kilometer column of reservoir rock which has been producing steam at a pressure of 10 bars for 10^9 sec. 500 m of cap rock overlie the reservoir. Dashed lines indicate effect of eliminating gravity.



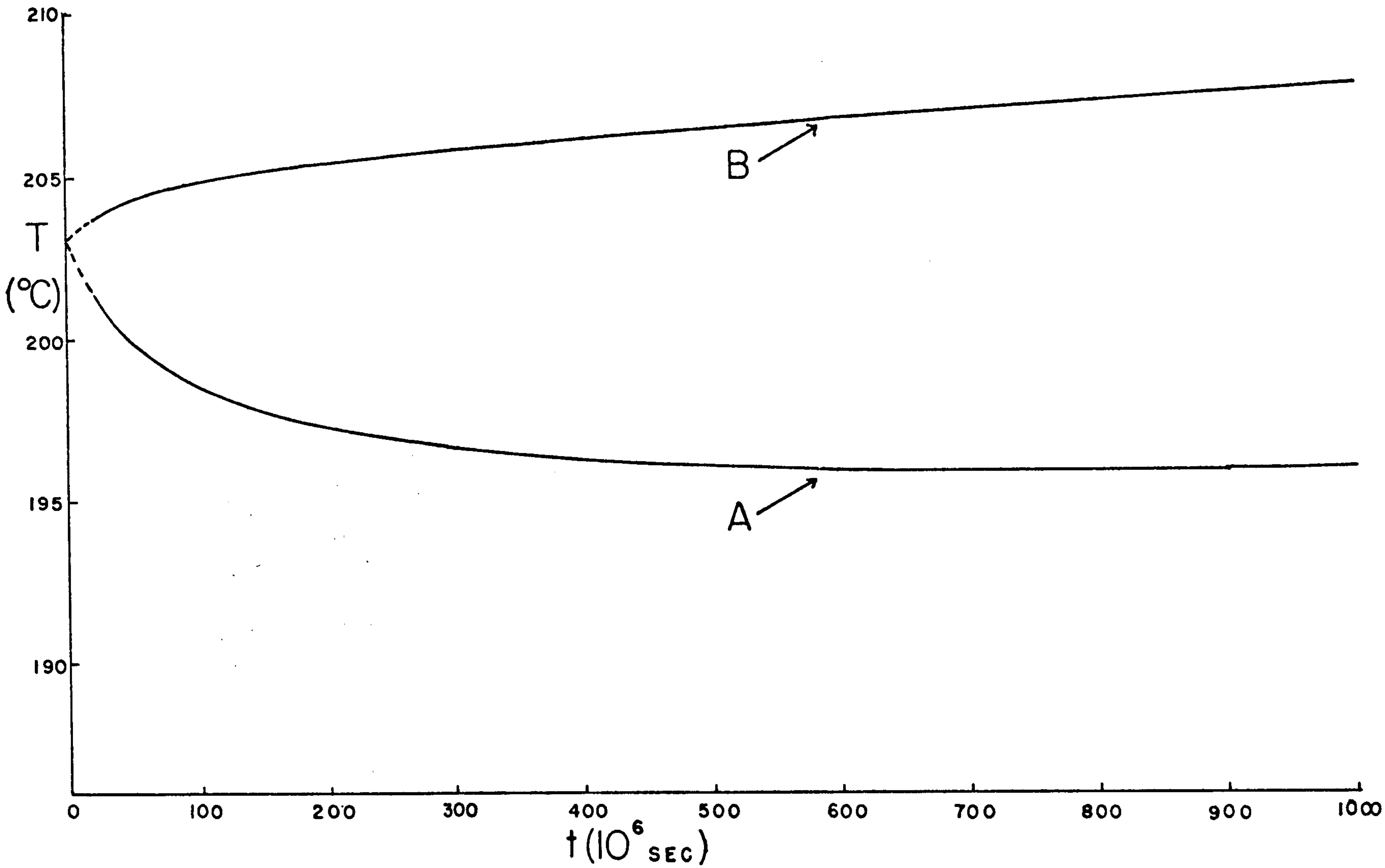


Figure 3. Temperature versus time at top of reservoir for conditions shown in Figure 2.