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PRODUCTION AND REINJECTION BEHAVIOR OF FRACTURED TWO-PHASE RESERVOIRS

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ABSTRACT

Investigations on numerical treatments and physical processes of fractured two-phase reservoirs were done, based on simple hypothetical reservoir models. In order to maintain a constant power generation, production and reinjection design should be optimal, avoiding heat and fluid depletion. For this, numerical simulation is essential to understand the heat and fluid flow characteristics. For using the MINC approximation which treats fractured media as multiple interacting porous media representing fractures and rock matrices, classification of flow characteristics and hence the numerical treatments are done by using equilibrium times for pressure and temperature in the rock matrix. A zero-dimensional MINC model with no global flow was used to discuss the classification. Then a one-dimensional radial flow model was used to investigate reservoir behavior with global flow through fractures. When global flow exists, the difference of vapor saturation between the fracture and rock matrix brings about flow characteristics which are not expected by the zero-dimensional model. If the vapor saturation is different, total mobility of the fluid is different due to the change in relative permeabilities. Fluid and heat supply from rock matrices to the fractures influences the global flow characteristics. Next, in order to investigate the effect of reinjection, a one-dimensional rectangular reservoir model was used. Comparison of the changes in produced fluid enthalpies for fracture models with the same global permeability and fracture spacings but different matrix permeabilities was done. If the matrix permeability is small, vapor saturation in fractures and produced fluid enthalpy rapidly increase initially. Reinjection keeps the enthalpy steady after this early time. The production enthalpy jumps to a higher level when moving the reinjection well further from the producer. If the matrix permeability is large, the reservoir behaves similarly to a porous reservoir, and the enthalpy rise is gradual. This is due to the fluid supply from rock matrix to fractures, and it causes large mass reinjection which reduces the production enthalpy.

1. INTRODUCTION

For stable power generation from a geothermal reservoir, fluid depletion, pressure decrease and temperature lowering should be carefully avoided by appropriate design of production and reinjection wells. Reinjection can be used to maintain reservoir pressure, but it can also cause thermal breakthrough from the cold reinjection well to the production well. Especially in a fractured reservoir, cold fronts proceed faster through fractures than in a porous media. In most of the geothermal reservoirs under production, in-situ boiling prevails around production wells which leads to development of two-phase zones and even super-heated steam zones. Therefore, a need to understand of fluid behavior and find suitable exploitation and reinjection schemes for fractured two-phase reservoirs are very common among geothermal energy developers. However, fluid and heat transport in a two-phase zone is much more complicated than in a single-phase reservoir, because of the large difference of physical properties of liquid water and steam. Also, fractures add complications to the physical processes in the reservoir.

Numerical techniques in investigation of geothermal reservoirs have been applied on the aforementioned complicated physical processes. The MINC method (Pruess and Narasimhan, 1985) has been widely used in investigations of fractured reservoirs under exploitation. Yano and Ishido (1995) used the MINC method to characterize the behavior of fractured reservoirs under production which causes in-situ boiling.

In this paper, we first discuss the equilibrium times in the MINC approximation for the classification of numerical treatment of fractured reservoirs. Then, results of some numerical simulations of one-dimensional reservoir models are shown. All the numerical calculations were done using the STAR reservoir simulator (Pritchett, 1995).

2. EQUILIBRIUM TIMES IN MINC MODEL

In order to study the heat and fluid transport in a fractured reservoir which can be represented by a MINC model, understanding of pressure and temperature equilibrium times is essential. Pritchett and Garg (1990) used a spherical, zero-dimensional MINC model to classify appropriate numerical treatments for fractured reservoirs. The time required for temperature equilibrium to be reached due to heat conduction acting alone (τ_{hc}) and the time required for pressure equilibrium to be reached between the fracture zone and the rock matrix block (τ_{pe}) are the basic parameters for the classification.

Considering a sphere of rock matrix with a certain initial temperature and a high surface temperature as the boundary condition, τ_{hc} can be defined by the time scale of temperature change in the sphere. Figure 1 shows the change of temperature distribution in a sphere with time (Carslaw and Jaeger, 1959). Non-dimensional time $T = \kappa t/a^2$ is used, where t is time, κ is thermal diffusivity and a is the radius of the sphere. Initially, temperature changes are large, and heat conduction rapidly occurs from the surface into the sphere. As time goes on, temperature change becomes slower. At T = 0.4 in Fig. 1, temperature in the sphere is near the surface temperature. Assuming this state as the thermal equilibrium, τ_{hc} can be derived by transforming T = 0.4. As the fracture spacing $\lambda = 2a$, $\tau_{hc} = \lambda^2/10\kappa$. Since κ does not change widely ($1{\sim}2\times10^{-6}$ m^2/s), τ_{hc} depends mainly on λ.

Similar discussion can be made on τ_{pe}, because it is also controlled by a diffusion equation. Then, $\tau_{pe} = \lambda^2/10\eta = \phi_m \mu C_T \lambda^2/10k_m$, here η is the hydraulic diffusivity, ϕ_m, k_m are the permeability and porosity of the rock matrix, μ is the dynamic viscosity, and C_T the total compressibility. In contrast to τ_{hc} , τ_{pe} can change in several orders of magnitudes, because of the wide range of η which depends on the change of k_m.

3. MODELLING IN-SITU BOILING IN A FRACTURED RESERVOIR

In the in-situ boiling process in a fractured reservoir, transport of fluid mass between fracture and rock matrix plays an important role as does the transport of heat. Pritchett and Garg (1990) conducted numerical simulations of fluid production from a fracture in a MINC model. Since the initial condition is a saturated state, a two-phase zone occurs just after production starts. It is a zero-dimensional model with no global flow. Figure 2 classifies the behavior of a fractured reservoir, based on the zero-dimensional model. In case (a) in Fig. 2, permeability of the rock matrix is large, and τ_{pe} is much smaller than τ_{hc} . In case (b), τ_{pe} is larger than τ_{hc}. This latter case can exist widely in a two-phase reservoir because of the large compressibility. If k_m is smaller than $2\phi_m$ milli-darcy, τ_{pe} becomes larger than $0.1\tau_{hc}$ (Pritchett and Garg, 1990).

In case (a), if the time scale of the problem (production time or the representative time) is larger than τ_{pe}, the reservoir behavior can be treated by a porous model (region II in Fig. 2). Since temperature depends on pressure in the two-phase region, thermal equilibrium is attained when pressure equilibrium is attained, without regard to τ_{hc} in region II. In region IV where the representative time scale is shorter than τ_{pe}, fracture characteristics appear in the reservoir behavior. However, because of the relatively small effect of heat conduction, reservoirs with the same τ_{pe} behave in the same manner.

In case (b), if the representative time scale is longer than τ_{pe} (region III), a porous medium assumption is possible. However, in this case, vapor saturation in the fracture becomes larger than that in the equivalent porous medium, due to the heat conduction effect. The effect is larger, in case of smaller matrix permeability. In region V where the representative time scale is smaller than τ_{pe}, MINC solution is required. Due to the strong effect of heat conduction, models with the same τ_{pe} do not necessarily behave in the same manner.

Yano and Ishido (1995) investigated the behavior of fractured two-phase reservoirs by a radial flow model which has a global flow through fractures. It assumes production from a well. Nine fracture model cases by combination of three different matrix permeabilities and three different fracture spacings, and the equivalent porous model case were investigated. In Fig. 3, nine τ_{pe} s of the nine fractured models are plotted. It is shown by this plot that the high matrix permeability cases (H models) in Fig. 3 corresponds to region II in Fig. 2(a). M models (medium matrix permeability) and L models (low matrix permeability) are interpreted by Fig. 2(b), with M models in region III and L models in regions III and V.

The pressure transients of wellbore blocks of the ten cases including the porous case are plotted in Fig.4. Since H models correspond to region II in Fig. 2(a), the pressure transients of H models may be considered to be the same as the pressure transient of the porous model. In fact, they are a little higher than the latter. This is due to the difference of vapor saturation between fracture and matrix. The vapor saturation of a fracture is lower than that of the matrix, though temperature and pressure equilibrium exists between them. It is even lower than that of the equivalent porous model, and this leads to larger total fluid mobility and lower decrease in pressure. The smaller matrix permeabilities of M and L models lead to larger vapor saturation in the fractures, and greater pressure decreases, as expected for models in the regions III and V. All three M models show similar pressure transients, because they do not depend on λ. On the other hand, pressure transients of L models depend on λ. The perturbation of the pressure transients in Fig. 4 is due to numerical discretization, and has no physical meaning.

4. PRODUCTION-REINJECTION MODEL

In order to investigate the effect of reinjection in a fractured two-phase reservoir, a simple reservoir model shown in Fig. 5 was used. It is a one-dimensional numerical reservoir model, with one production well, and two optional reinjection wells. Production for a constant power generation (10MWe) continues for 6 years (if the production well cannot supply enough steam at wellhead pressure of 10 bars, power generation becomes less than 10 MWe), and reinjection well R1 is used for the first 3 years, and then R2 for the later 3 years. Produced fluid is separated at 5 bars, and all the produced liquid water and 30% of the condensate of produced steam are reinjected.

The length of the one-dimensional model is 2.5 km, with 500m low permeability porous zones (A) at both ends. Cross sectional area of the model is 90,000 m^2. Permeability of A zones is 0.5 md, and the permeability of the reservoir (B) is 5 md. Total porosities of A and B are 0.1. The reservoir B is a fractured medium, and MINC model is used.

Figure 6 shows simulation results by the production-reinjection model. It shows changes of average produced fluid enthalpy. Two cases of fracture models with different matrix permeabilities are shown. The fracture spacing in both models is 30m. In case of larger k_m(0.2md), the behavior of the reservoir can be approximated by a porous model. The case corresponds to the region II in Fig. 2(a). In contrast, the smaller k_m (0.002md) model presents fracture characteristics, and it corresponds to the region V-III.

In the small k_m case, vapor saturation of fractures rapidly increases within a short period of time, and leads to the rapid increase of produced fluid enthalpy. After three quarters of a year no further increase in maximum vapor saturation, and gradual decrease in temperature/pressure due to the injection, lead to gradual enthalpy decrease. At three years, the reinjection is moved from R1 to R2 which is far from the production well. Because of the abrupt decrease in reinjection effect, the produced fluid enthalpy rises abruptly at three years.

In the large k_m case on the other hand, because of the fluid supply from rock matrix to the fractures, vapor saturation of the fracture does not show the abrupt rise as in the small k_m case. This causes production of larger amounts of liquid water, and thus a large recharge inflow into the reservoir. Therefore, the reinjection effect is large during the early stages of production. The rise in the produced fluid enthalpy is gradual for the first three years. At three years, vapor saturation in the fracture reaches near maximum. Due to the gradual decrease in temperature and pressure, produced fluid enthalpy shows a little decrease after three years, without regard to the shifting of the reinjection well to a farther location.

5. CONCLUSIONS

For sustainable production from a fractured, two-phase reservoir, an understanding of physical processes occurring in the reservoir and knowledge of reservoir behavior are important. Numerical reservoir simulation is essential for this purpose. Numerical treatment of fractured reservoirs can be classified based on pressure and temperature equilibrium times. Observation of vapor saturation and fluid mobility is needed to understand reservoir behavior, because of their influence on global flow through fractures. Effects of reinjection can be different for different reservoir parameters and production/reinjection configurations. For instance, even if the global permeabilities and fracture spacings are the same, different matrix permeabilities bring about different transient patterns of produced fluid enthalpy.

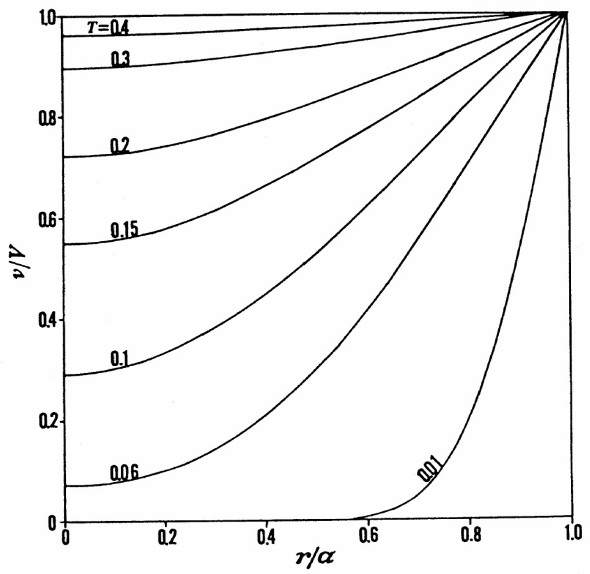

Figure 1. Temperature distribution at various non-dimensional times (T) in a sphere of radius a, with zero initial temperature and surface temperature V (Carslaw and Jaeger, 1959), where r is the distance from the center of the sphere, and v is temperature.

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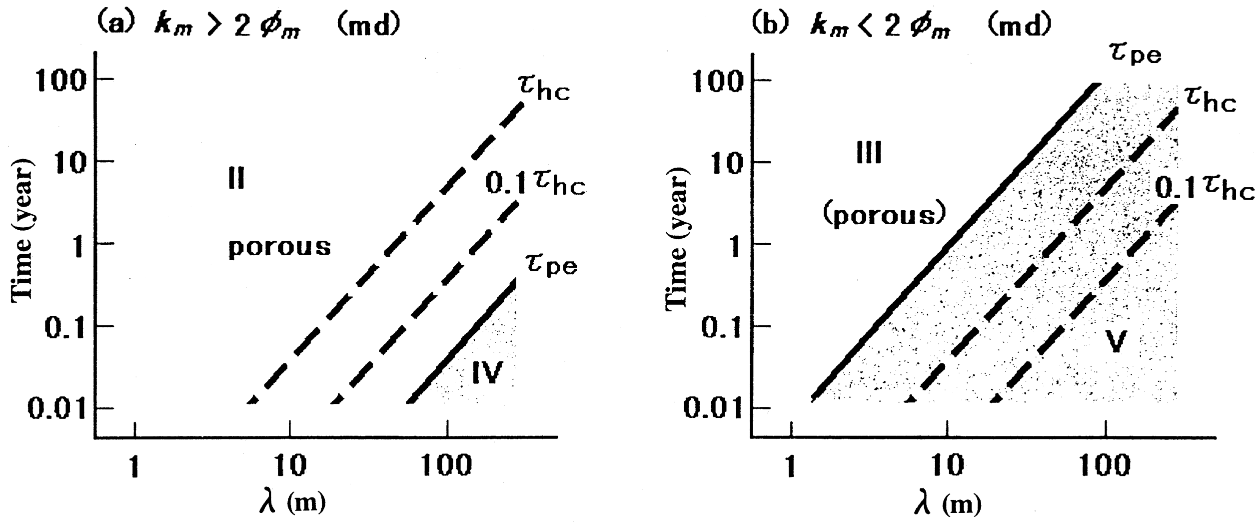

Figure 2. Classification of flow characteristics of fractured two-phase reservoirs.

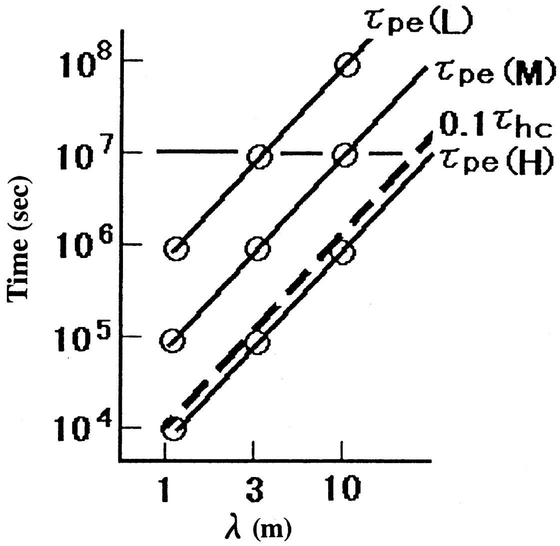

Figure 3. Distribution of τ_{pe}s of the nine fractured reservoir models and the common τ_{hc} for them.

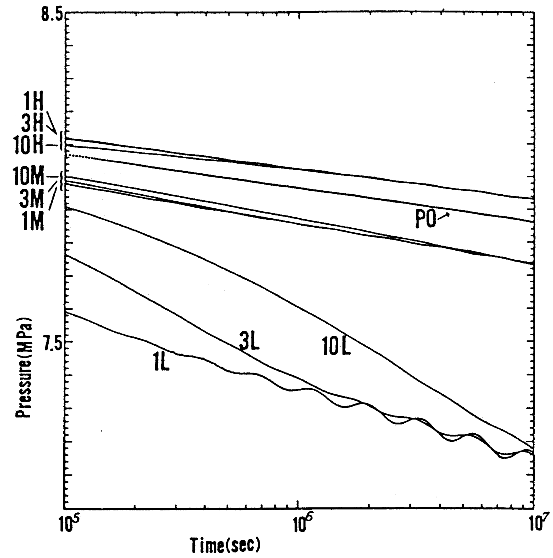

Figure 4. Pressure transients of the well block in production tests with in-situ boiling for nine fractured models and a porous model (Yano and Ishido, 1995).

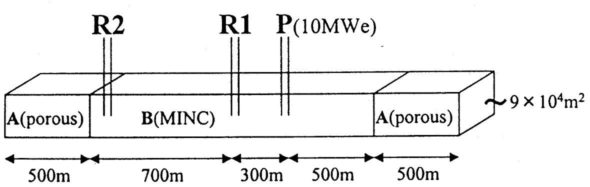

Figure 5. One-dimensional production-reinjection model.

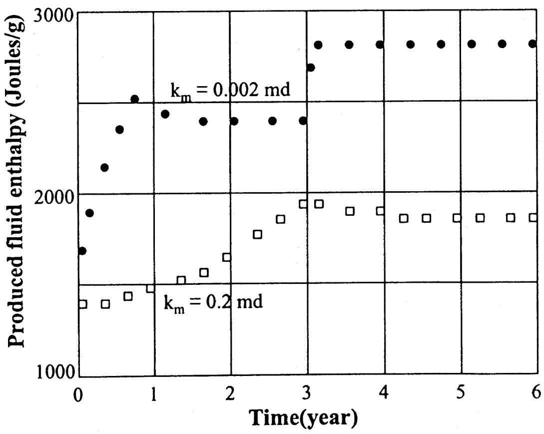

Figure 6. Average produced fluid enthalpies for production-reinjection models with different matrix permeabilities.