EFFECTS OF HEAT TRANSFER ON WATER-STEAM FLOW THROUGH A POROUS MEDIUM

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1.Introduction

Numerous authors have reported theoretical studies of water-steam flow in a geothermal reservoir(for example, Toronyi et al.(1977), Thomas et al.(1978), Faust et al.(1979), Zyvoloski et al.(1980), Pruess et al.(1983) and Yusa et al.(1986).) However, it has not been clear experimentally and theoretically how heat transfer plays a role in water-steam flow through a porous medium. We have already reported comparisons of some experimental data with a simple model of water-steam flow through a porous medium(Niibori et al.(1987).) The calculations, however, disagreed with the experimental data in the region of steam ratio greater than 0.6. In this paper, these data are compared with calculations given by a new mathematical model,including a function between over-all heat transfer coefficient and water saturation in steady state. Also, effects of heat transfer on water-steam flow are explained in detail.

2.Mathematical Model

2-1.Assumptions and Fundamental Equations

Suppose a cylindrical porous medium as shown in Figure 1, and the following assumptions:

(a) The temperature of water injected into the bed is sufficiently near the boiling point, θ_f.
(b) The temperature of thermostat, θ_t is constant and higher than the boiling point.
(c) Fluid flow obeys Darcy's law.
(d) Capillary pressure has no effect on fluid flow.
(e) Phase change takes place instantaneously.
(f) The intrinsic permeability k and the porosity ε are constant.
(g) Since liquid water and steam coexist at the boiling point, heat diffusion is neglected.
(i) Distribution of saturation in radial direction is neglected.

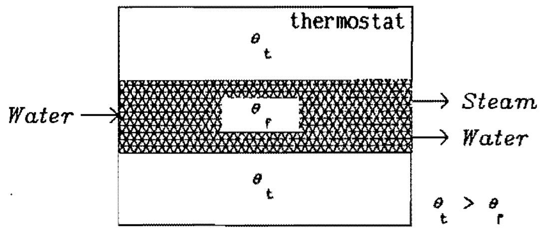

Fig.1 Illustration of the mathematical model.

The following equations are derived consequently based on the assumptions(Niibori et al.(1987)):

$$\frac{\partial}{\partial X}\{(k_{rw}+Mk_{rs})\frac{\partial P}{\partial X}\} = -G(\gamma-1), \qquad (1)$$

$$\frac{\partial S_w}{\partial T} = \frac{\partial}{\partial X}(k_{rw}\frac{\partial P}{\partial X}) - G, \qquad (2)$$

where S_w is the saturation of liquid water and k_{rw} and k_{rs} stand for the relative permeabilities of liquid and steam, respectively. And, other dimensionless variables, T,X,γ,M,G and P are defined as follows:

$$T = \frac{t}{t^*}, t^* = \frac{\varepsilon x_1}{u_w^*}, X = \frac{x}{x_1}, \gamma = \frac{\rho_w}{\rho_s}, M = \frac{\mu_w}{\mu_s}, G = \frac{aU(\theta_t-\theta_f)x_1}{u_w^* L_v \rho_w}, P = \frac{k(p-p_0)}{\mu_w u_w^* x_1}, \qquad (3)$$

where μ_i and ρ_i are the viscosity and the density of phase i, respectively, u_w^* the velocity which is estimated from the water intrinsic permeability k, x_1 the characteristic length, t time, a the specific area of the packed bed, p pressure, p_0 pressure at the outlet, and L_v the latent heat of vaporization of water. The quantity G, which is an unknown parameter of this model, is related to the local, instantaneous vaporization rate of water in the bed.

The boundary and initial conditions are described as follows:

$P=1, S_w=1$, at X=0, P=0, $\partial S_w/\partial X=0$, at X=1 and $S_w=1$, when T=0. (4)

Assume the relative permeability curves to be defined as follow:

$$k_{rw}=S_w^4, \qquad (5)$$

$$k_{rs} = \begin{cases} (1-\frac{S_w-C}{1-C})^2\{1-(\frac{S_w-C}{1-C})^2\}, & C<S_w<1, \\ 1, & 0<S_w<C, \end{cases} \qquad (6)$$

where C is a fitting parameter to experimental results on the relation between relative permeability of a non-wetting phase and saturation. That is,the parameter C means a critical value at which the interface between water and gas bubble starts to deform in order that gas bubbles flow through a dominative paths in a porous medium. In fitting of Eqs.(5) and (6) to the experimental results proposed by Wyckoff et al.(1936), these curves almost agree with the experimental results when C is equal to 0.12(Niibori et.al(1987)).

2-2.Over-all heat transfer coefficient U in steady state

In order to decide the value of U, consider an across section of the cylindrical porous medium as shown in Figure 2. r_1 and r_2 are the inner and outer radii, respectively. The region of $0<r<r_1$ indicates porous medium. Assuming two heat transfer coefficients for the inside and outside, h_0 and h_i, respectively, U is described as follows:

$$U=\frac{\frac{1}{r_1}}{\frac{1}{h_0 r_2}+\frac{1}{\lambda}\ln\frac{r_2}{r_1}+\frac{1}{h_i r_1}}, \qquad (7)$$

where λ is the thermal conductivity in the region of $r_1<r<r_2$. In Eq.(7) h_i is defined as follows:

$$h_i=\frac{\bar{\lambda}_{ws}}{\delta}, \qquad (8)$$

where δ indicates the thickness of gas-film on heat transfer, which is assumed to be

$$\delta=a S_w^n+b\ . \qquad (9)$$

On the other hand, $\bar{\lambda}_{ws}$ is an apparent thermal conductivity, assumed to be a function of saturation as follows(Kimura(1959)):

$$\bar{\lambda}_{ws}=(\lambda_{ew}-\varepsilon\lambda_w)(1-\psi)+\lambda_{eg}\psi+\varepsilon S_w\lambda_w, \qquad (10)$$

$$\psi=\frac{1-S_w}{1+10.4S_w}, \qquad (11)$$

where λ_w is the thermal conductivity of liquid water and λ_{ew} and λ_{eg} are the effective thermal conductivities of water and steam in a porous medium. These values are estimated by the following equations(Kunii et al.(1960)):

$$\lambda_{ew}=\lambda_w\left(\varepsilon+\frac{1-\varepsilon}{\phi_1+(2/3)(\lambda_w/\lambda_s)}\right), \qquad (12)$$

$$\lambda_{eg}=\lambda_g\left(\varepsilon+\frac{1-\varepsilon}{\phi_2+(2/3)(\lambda_g/\lambda_s)}\right), \qquad (13)$$

where λ_g and λ_s are the thermal conductivities of steam and solid. ϕ_1 and ϕ_2 depend on combination of solid and liquid in a porous medium, and are set at 1/3 and 0.1, respectively in this paper. Figure 3 shows the relation between water saturation and $\bar{\lambda}_{ws}$. It is recognized that the value of $\bar{\lambda}_{ws}$ decreases quickly in the region of water saturation less than 0.2.

Pressure and saturation are obtained by solving Eqs.(1),(2)and (4) numerically. In this paper, these equations are analyzed by using the finite difference method (FDM). We also apply the upstream weighting (Faust et al.(1979)) to the terms of relative permeability included in Eqs.(5) and (6).

Figure 4 shows the typical examples of saturation distribution of the liquid water in the case of the parameter G of 10^{-2}. It is clear

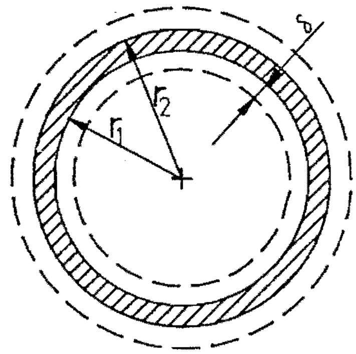

Fig.2 Across section of porous medium

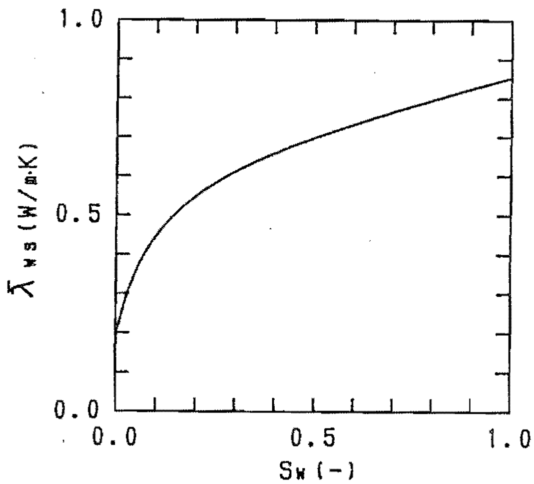

Fig.3 Relation between $\bar{\lambda}_{ws}$ and S_w.

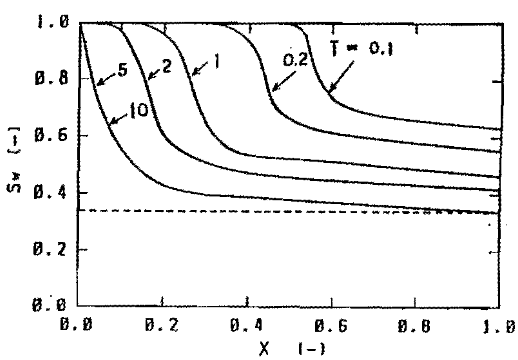

Fig.4 Distributions of S_w for each time T(-)(G=.01,C=0.12)

Table 1 Experimental Conditions

	Experiment I[1]	Experiment II
Length of tube	0.29m	0.145m
Temperature of thermostat	371.1,373.5,374.3,375.7,376.5 377.4,379.6,381.7,385.6(K)	375.8,375.9,375.9,376.0 378.1,378.3,379.4,379.4(K)
Intrinsic Permeability	$7.8\times10^{-11}m^2$	$7.0\times10^{-11}m^2$
Differece in hydrostatic head	$0.2mH_2O$	$0.05mH_2O$

1)Niibori et.al(1987)

from this figure that the location of vaporization is closer to the inlet momentarily, and that $S_w(X)$ is assumed to be $S_w(1)$ in steady state shown by the dotted line in Fig.4. Under this assumption, the value of U is conformed to the water saturation at the outlet.

3.Comparison of Mathematical Model with Some Experimental Data

3-1. Experimental apparatus and Procedures

Figure 5 shows a schematic diagram of the experimental apparatus. Hydrostatic heads at the inlet and the outlet are fixed by the overflow, respectively. In this paper a glass beads bed with the radius of 9.5mm is used as a porous medium. Temperature in the bed are measured by thermo-couples, and flow rates of water and steam at the outlet with a separater, a cooler and two electric balances. These data are stored to a magnetic disc through a personal computer every 15 seconds. The experimental procedures are as follows;

(a) The bed full with water is kept at a pre-determined temperature in a thermostat.

(b) Water of room temperature(about 293K) is injected into the packed bed until both the temperature and flows rates of water and steam attain to be steady.

Table 1 indicates the experimental conditions.

3-2. Comparisons with Experiment Results

Figure 6 shows the temperature distribution in the bed at each temperature of thermostat in steady state. Can be seen from this figure that the temperature of water increases quickly up to the boiling point near the inlet. The higher the temperature is, the more noticeable the tendency is. So that, it is possible to be assumed that the temperature in the bed is almost at the boiling point in an analytical point of view.

Figure 7 shows the comparison of the experimental results with calculations in the steam ratio R, which is defined as follows:

$$R = Q_S/(Q_S+Q_W), \quad (14)$$

where Q is flow rate, the subscripts s and w mean steam and liquid water respectively. The curve A indicates the fittest to experimental results, which is different from the dashed line D in the case of a constant value of U. From the

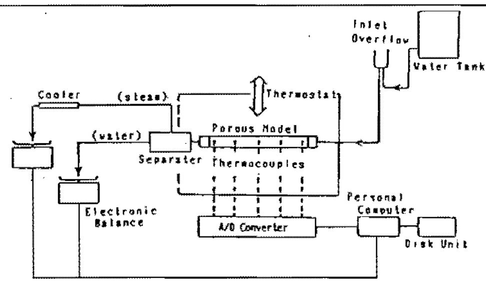

Fig.5 Experimental apparatus.

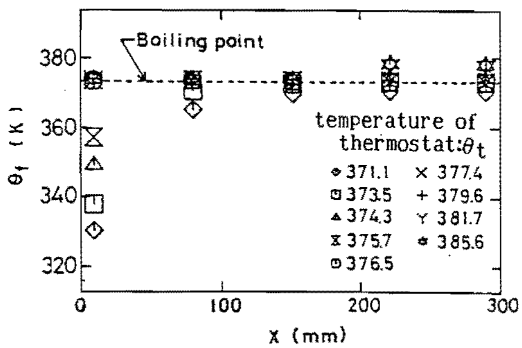

Fig.6 Temperature Distribution in the bed for each θ_t(Niibori et. al(1987).)

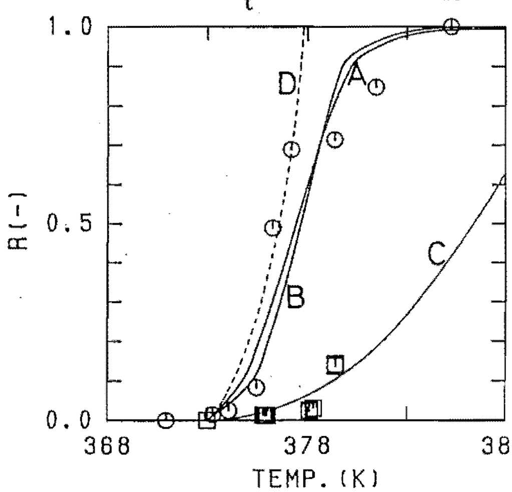

Fig.7 Comparisons between experimental data and calculations (o;Ex.I,□;Ex.II,dashed line D ;the case of fixed U (Niibori et.al(1987).)

curve A, the three unknown parameter a, b and n in Eq.(11) are estimated to be -11mm,13mm and 1, respectively.

For simplicity, we assume further a=0 and n=0. In a result, the curve B is obtained. Then, the parameter b(that is, the thickness δ) is constant to 9.7mm. This value is almost coincided with the radius of tube r_1(=9.5mm). Since the curve B almost agrees the A, it is valid that is assumed equal to r_1. This fact indicates that the heat transfer is just determined by the apparent thermal conductivity λ_{ws}.

The curve C is the fitting to Experiment II. In the experiment, the characteristic length, x_1 is estimated at one third of the whole length of the tube(as shown in Table 1), considering the temperature distribution in the bed.

Figure 8 shows the relations between U and R for the curve B and D. In regard to the B, U decreases quickly in 0<R<0.1 and 0.9<R<1.0. The reasons are due to the facts that when R increases slightly from zero, S_w decreases quickly from unity as shown in Figure 9, and that when S_w decreases in the region smaller than 0.2, λ_{ws} decreases quickly as shown in Fig.3.

Figure 10 shows the relation between G and total flow of water and steam. When G increase just from zero, both the experimental data and the calculation fairthfully describe the sudden decrease of Q_t, caused by obstruct effects of steam phase on flow of water.

4.Conclusions

The conclusions are as follows;

(1) The proposed mathematical model, containing a function between saturation and over-all heat transfer coefficient, describes approximately water-steam flow through a porous medium.

(2) The apparent thermal conductivity, which is a non-linear function of saturation, is an important factor to estimate the heat transfer in water-steam flow through a porous medium.

(3) Effects of steam phase on the apparent thermal conductivity is remarkable in the region of water saturation smaller than 0.2.

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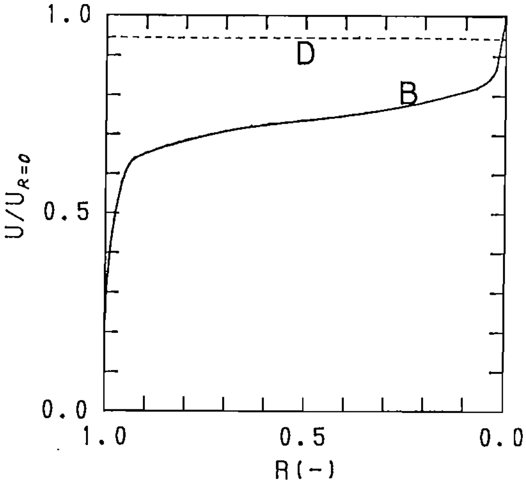

Fig.8 Relation between steam ratio and $U/U_{R=0}$, under conditions of the curves B and D in Fig.7

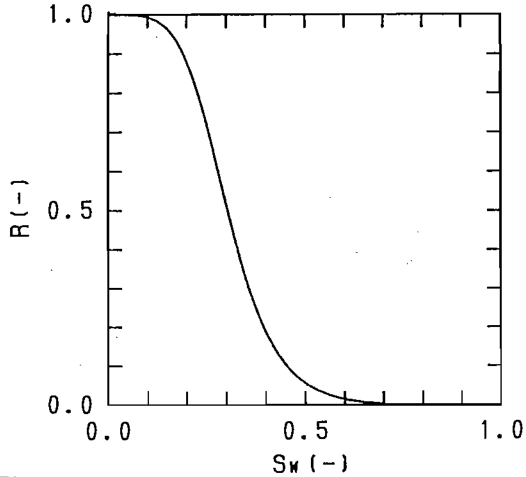

Fig.9 Relation between water saturation and steam ratio.

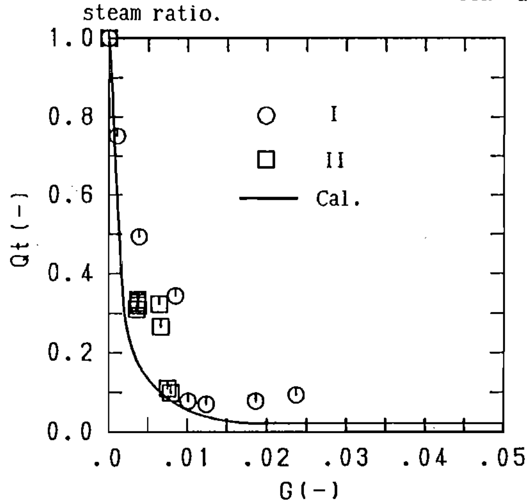

Fig.10 Relation between G and total flow rate.