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Heat Transfer Conference, Denver, CO,
August 4-7, 1985

A STUDY OF TWO-PHASE CONCURRENT FLOW OF STEAM AND WATER IN AN UNCONSOLIDATED POROUS MEDIUM

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April 1985

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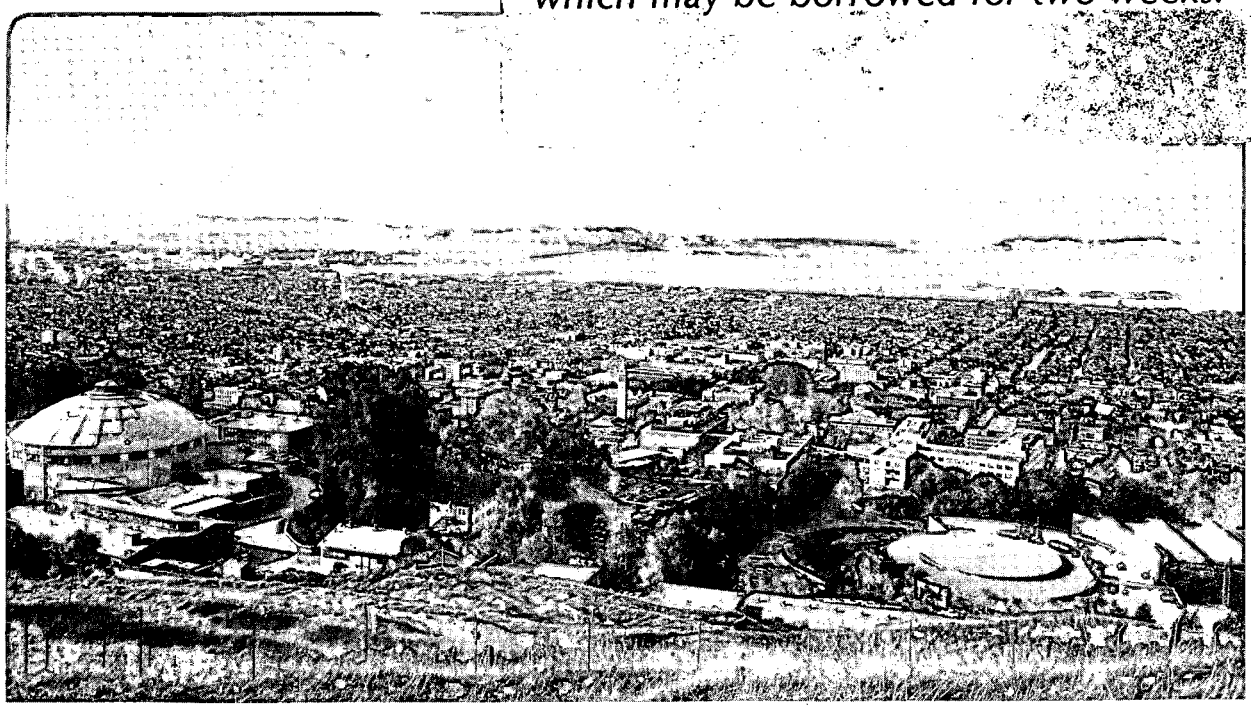

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Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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Submitted to the 23rd ASME/AIChE
National Heat Transfer Conference
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A STUDY OF TWO-PHASE CONCURRENT FLOW OF STEAM AND WATER IN AN UNCONSOLIDATED POROUS MEDIUM

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ABSTRACT

A combined experimental and numerical study of two-phase steam/water flow in porous media was carried out. An experiment consisting of steady state, two-phase concurrent flow of steam and water was conducted to obtain a set of relative permeability and capillary pressure curves. The experimental relative permeability and the capillary pressure curves were included in a numerical code, MULKOM, and the experiment was simulated. A good agreement between the numerical results and the experimental data was found, thus confirming the results. Upon comparing these results with gas/oil and oil/water relative permeabilities obtained by other investigators, it was found that while the wetting phase relative permeabilities in all cases are about the same, the vapor phase relative permeability is larger than the non-wetting phase relative permeabilities in gas/oil or oil/water flows. It is suggested that the phenomenon of enhanced vapor phase relative permeability is caused by channeling and/or phase transformation effects.

NOMENCLATURE

A	core cross-sectional area
A_t	cross-sectional area of the core holder wall
D	molecular diffusivity of vapor
f	dynamic quality $(m_v/(m_v + m_w))$
g	acceleration of gravity
h	specific enthalpy
h_{wv}	$= h_v - h_w$
I_d	γ-ray beam intensity through dry sample
I_s	γ-ray beam intensity through fully saturated sample
k	intrinsic permeability of the sample
k_r	relative permeability
m	mass flow rate
N	number of counts from γ-ray densitometer
P	pressure
Pe	modified Peclet number $(m_v/m_{v,d})$
Q	total energy input to boiler
q	heat flux due to conduction
R	gas constant for vapor
r_{eq}	equivalent radius of curvature $r_{eq} = 2\gamma/P_c$
S	in-place saturation
S_r	immobile water saturation
S_m	water saturation at which the water phase is fully mobile
T	temperature
v	specific volume
x	linear distance
z	vertical distance along the core holder
λ	thermal conductivity
μ	absolute viscosity
γ	Gibb's free energy per unit area of interface
ρ	density of fluid
ν	liquid island enhancement factor
ϕ	porosity
α	tortuosity factor

SUBSCRIPTS

c	capillary
d	diffusive component
o	condition at the inlet of the test sample
v	vapor phase
w	water phase
∞	infinite radius of curvature

INTRODUCTION

Two-phase flow of steam and water in porous media is encountered in many energy-related problems involving, for example, geothermal reservoirs, heat pipes, chemical distillation, and nuclear waste disposal. Simulation studies of these problems require knowledge of the relative permeability and capillary pressure functions for the porous matrix. Much information is available on relative permeabilities for water-oil and oil-gas systems, but steam-water relative permeabilities are poorly known, in spite of considerable theoretical and experimental

efforts during the last decade. Since no conclusive results exist, many investigators have used ad hoc parametrizations, or have adopted results obtained from flow of gas and oil (Corey, 1954). It has been shown by Reda and Eaton (1980) that this can lead to serious deficiencies. Effects of the relative permeability curves on predicted mass flow rate and flowing enthalpy into geothermal wells have been studied by many investigators (e.g., Bodvarsson et al., 1980; Reda and Eaton, 1980; and Sun and Ershaghi, 1979). It can be concluded from these studies that the behavior of two-phase steam/ water flow depends greatly on the relative permeability curves used. Hence, there exists a need for obtaining reliable relative permeability functions.

Most of the past efforts towards determining the relative permeability functions have been directed towards flow of two-component, two-phase fluids, such as oil-water or immiscible gas-fluid in porous media. It was found that the relative permeabilites depend primarily on phase saturations, but also on many other factors, such as: (i) viscosity ratio of the fluids (e.g., Downie and Crane, 1961; Odeh, 1959; Schneider and Owens, 1980; and LeFebvre du Prey, 1973); (ii) wetting characteristics of the two phases (e.g. Coley et al., 1956; Donaldson et al., 1966; Owens and Archer, 1978; McCaffery and Bennion, 1974; Heiba et al., 1983); (iii) interfacial tension, or more generally, the capillary number (e.g. Bordon and Longeron, 1980; Fulcher et al., 1983; Laverett, 1939; and Taber, 1969); (iv) saturation history (e.g., Johnson et al., 1959; and Naar et al., 1962).

While rationales have been advanced for some of these factors, a satisfactory theory of relative permeability has not yet been developed (Heiba et al., 1982). However, extensive experimental investigations have produced some reliable relative permeability curves for two-phase-two-component fluid flow through some typical porous media (e.g., Corey, 1954; Brooks and Corey, 1964; Osoba et al., 1951; Hauzenberg and Zaslavsky, 1963). Applicability of these curves to a single-component two-phase flow, such as steam-water, is questionable because of the possibility of phase transformation in the flow channels. Phase change provides an additional degree of freedom in a single-component, two-phase system, which may be expected to have a significant effect on the nature of the relative permeability curves.

The present paper reports on a combined experimental and numerical study of two-phase steam-water flow through porous media which yielded information on relative permeability functions and capillary pressure curves at elevated temperatures. A numerical study was initially made using the three-dimensional, two-phase steam-water flow code, MULKOM, to arrive at the best experimental design and parameters (Verma et al., 1983). The numerical method used in MULKOM involves simultaneous solution of a highly nonlinear system of discretized equations describing two-phase mass and heat flow including phase transitions, taking all coupling terms into account. Newton-Raphson iteration is performed to handle the nonlinearities arising from phase transformation and from nonlinear material properties (Pruess, 1983).

The numerical results indicated that the capillary discontinuities at the ends of the flow column could cause a very large saturation gradient near the ends which would make it difficult to interpret data in this regime for the purpose of obtaining relative permeability and capillary pressure functions. End effects were minimized in the experiment by using a rather long (100 cm) insulated column packed with beads of 100 micron grain size (Fig. 1.) Double-deionized, degassed water was pumped into the column at a controlled rate. Upon entering the column, a fraction of the water was flashed into steam by means of electrical resistance heaters causing two-phase concurrent flow in the column. Temperature, vapor pressure, and liquid pressure were measured at regular intervals along the column. Saturation readings were obtained with the aid of a γ-ray densitometer. From the experimental data we obtained relative permeability and capillary pressure as a function of saturation for the porous medium. These functions were subsequently used in the numerical model to simulate temperature, pressure, and saturation along the entire column. Good agreement with the experimental results was found, thus confirming the relative permeability functions and capillary pressure curves obtained.

Upon comparing these results to the curves obtained by other investigators (Corey, 1954; Osoba et al., 1951; and Johnson et al., 1959) for gas and oil flow through porous media we find that while the liquid phase (also the wetting phase) relative permeabilities are nearly the same, the measured steam relative permeabilities are considerably higher than the gas relative permeabilities obtained in two-component flow experiments. Also, the sum of the relative permeabiities ($k_{rv} + k_{rw}$) for steam and water is higher than the same for gas and oil. Some of the phenomena that could cause these effects are discussed in this paper, but further studies are needed before any conclusive results can be drawn.

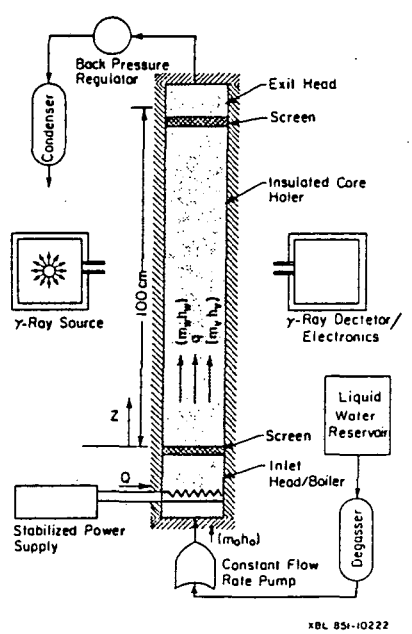

Fig. 1. Schematic of the experimental setup.

THEORETICAL CONSIDERATIONS

The theoretical considerations involved in analyzing the experimental data have been presented by Reda and Eaton (1981), so that they need not be discussed in detail here. The only major departure from their method is that while they neglect the capillary pressure and associate the measured pressure with both the liquid and the vapor phases, we measure the pressures in the two phases separately and obtain capillary pressures at different cross-sections.

We consider a steady-state, one dimensional, vertical forced convection of steam and water through an insulated cylindrical test sample (Fig. 1). Conservation of mass and energy is considered in order to interpret the experimental data for the steam/water relative permeabilities of the porous medium. The equation for flowing steam quality, f, and water and vapor relative permeabilities k_{rw} and k_{rv} are, respectively, (see Apendix A)

$$f = \frac{m_o(h_o - h_w) + Q - q}{m_o(h_v - h_w)} \qquad (1)$$

$$k_{rw} = \frac{(f-1)\, m_o\, \mu_w\, v_w}{k\, A\, \frac{d}{dz}\,(P_w + \rho_w\, gz)} \qquad (2)$$

$$k_{rv} = -\frac{f\, m_o\, \mu_v v_v}{k\, A\, \frac{dP_v}{dz}} \qquad (3)$$

and

$$P_c = P_v - P_w \qquad (4)$$

Here q represents the conductive heat flow along the flow direction given by

$$q = -\frac{dT}{dz}\,\{\lambda_t A_t + (1-\phi)\,\lambda_m A + \phi\,[S_w \lambda_w + (1-S_w)\,\lambda_v]\,A\} \qquad (5)$$

where λ_t, λ_m, λ_w and λ_v represent the thermal conductivities of the core holder, the matrix, water, and steam respectively. A_t is the cross-sectional area of the core-holder wall. Other notations have their usual meaning.

The right hand side of Equations 1-4 consist of quantities which are either known or can be measured from the experiment. Hence, Equations 2-4 can be used to obtain the relative permeabilities and the capillary pressure.

Effect of Vapor Diffusion

Vapor flux, a quantity needed to calculate the vapor phase relative permeability, is not a directly measurable quantity but it is derived from conservation of mass and energy. The quantity thus derived, the total vapor flux (m_v), represents the sum of advective vapor flux and diffusive vapor flux. Therefore, use of total vapor flux in Equation 3 will overestimate the vapor relative permeability.

The effect of self diffusion on vapor flux can be represented in terms of a modified Peclet number ($Pe \equiv m_v/m_{v,d}$), which for the present case is given by (Appendix-B)

$$Pe = \frac{k\, k_{rv}\, P_v\, h_{wv}}{\phi\, S_v\, \alpha\, \nu\, D\, (h_{wv} - RT)} \qquad (6)$$

where R denotes the gas constant; D is the molecular diffusivity of the vapor phase; α is the empirical tortuosity factor allowing for extra path length, ν is the liquid island enhancement factor (Walker et al., 1981); ϕ denotes porosity and other notations have the usual meanings defined previously.

SYSTEM DESIGN AND OPERATING CONDITIONS

The optimum design parameters and operating conditions were obtained with the aid of numerical modeling. It was speculated that the effects of capillary pressure, and the end effects resulting from it, could be very significant. To study these effects various capillary pressure curves were incorporated into a geothermal reservoir simulation code, MULKOM (Pruess, 1983), and test runs were simulated for a 100 cm long column. A typical result of the simulation with the end effects is shown in Figure 2, and for the purpose of comparison, a typical result without the end effects is shown in Figure 3. From these figures we can see that, while the four parameters of interest, P_v, P_c, T, and S_v, vary monotonically with more or less constant gradient in Figure 3, the end effects cause a very sharp gradient at the exit end (Fig. 2). We found that in a moderately permeable medium ($k = 6.41 \times 10^{-13}$ m^2) the end effects can extend up to 20 cm even at moderate flow rates ($.32 \times 10^{-2}$ g/cm^2 sec). Readings taken in this region would be difficult to interpret to yield the relative permeabilities.

We also considered the effects of matrix properties, and boundary conditions on the experiment. Results of the numerical studies showed that for the test samples under consideration it is possible to obtain a region of almost constant saturation over an extended length in a 100 cm long column. Readings taken in this region can be analyzed directly to yield relative permeabilities.

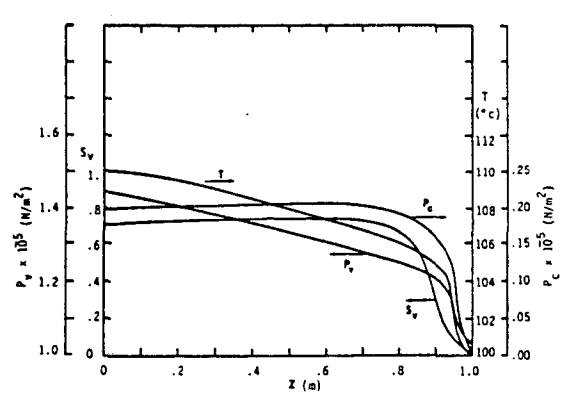

Fig. 2. Design simulation with the end effects.

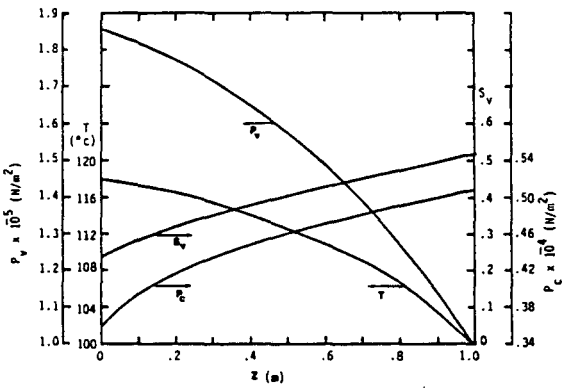

Fig. 3. Design simulations without the end effects.

The inside diameter of the test column was chosen such that the maximum attenuation of the γ-ray beam due to water was approximately 20 percent (i.e., $(I_d - I_s)/I_d \sim .2$). For most materials under consideration an I.D. of 7.5 cm (3 in.) was found to be optimum.

The flow rates were chosen such that, while the flow remains Darcian, it produces a measurable pressure drop over a 20 cm segment of the test column. In the present case the flow rate was held constant at .2944 g/sec.

INSTRUMENT CALIBRATION AND PERFORMANCE

All the measuring instruments were calibrated prior to and again immediately after the experiment to ensure the reliability of the readings obtained. The thermocouples were calibrated against a master platinum resistance thermometer and all the readings were within ±0.3°C in the range of 80° to 120°C. All the probes worked satisfactorily and no failure was detected during the experiment.

The absolute pressure transducers and the differential pressure transducers were calibrated over the entire range of working temperatures (80° - 120°C). They were checked for drift, hysteresis, repeatability and linearity. Since the differential pressure transducers showed some fluctuations during the experiment, all the pressure readings were taken with the aid of the absolute pressure transducers. These transducers were found to be accurate within ±0.003 bars in the entire range of interest (1-3 bars absolute). Therefore, both the pressure drop and the capillary pressure readings are believed to be accurate within ±0.006 bars.

The γ-ray densitometer was checked and calibrated for possible errors due to change in detector temperature, electronic drift and statistical error in evaluating γ-ray beam intensity (details in Verma, 1985). The overall accuracy was checked by evaluating the adsorption coefficients of aluminum and brass (70% Cu, 30% Zn) and comparing them to those reported elsewhere. In both cases agreement was within 4%. A second test was conducted to determine if it was possible to accurately measure 10% water saturation change within ± 2%. A set of 1.59 mm (1/16") lucite plates in series with a 5 cm thick aluminum plate were used to simulate γ-ray attenuation by water. Nine plates were used in series, so that a removal of one plate would simulate 89% saturation, two plates removed would simulate 78% saturation etc. Additional tests were conducted to determine if the arrangement of the lucite plates would make a measurable difference, i.e., if the first plate was removed near the source or near the detector. The results of this study are plotted in Figure 4. The error of each measurement, $1/\sqrt{N}$, is included on the graph. The results indicate that it was possible to measure these small changes accurately. A second run was made where the plates were removed in the opposite order and the results were found to be within the error bars of the first experiments.

In the case of the present experiment the errors at the lower saturation (S_w = 0.4) are within ± 3% and those for the higher saturation readings (S_w = 0.8) are within ± 5%.

EXPERIMENTAL APPROACH

The schematic of the experimental setup is presented in Figure 1. The test cell consists of a high temperature epoxy tube (7.62 cm I.D. x 100 cm length) packed with 100 μm pyrex glass beads. The beads are held in place by an inlet-head and an exit-head mounted at opposite ends of the tube. The inlet head also serves as a boiling chamber where a controlled fraction of the incoming water was flashed by electric resistance heaters to achieve a desired flow quality in the test section. The outer surface of the test-cell was made adiabatic with the aid of guard heaters wrapped around it at regular intervals.

At regular intervals there are instrument ports for temperature, liquid pressure, and vapor pressure probes. Pressures at the ports and pressure drop between the two neighboring ports are measured with the aid of absolute pressure transducers and differential pressure transducers, respectively. Vapor pressure and liquid pressures at each cross section were measured in separate ports (Fig. 5). Internal surfaces of all the tubes connecting the vapor

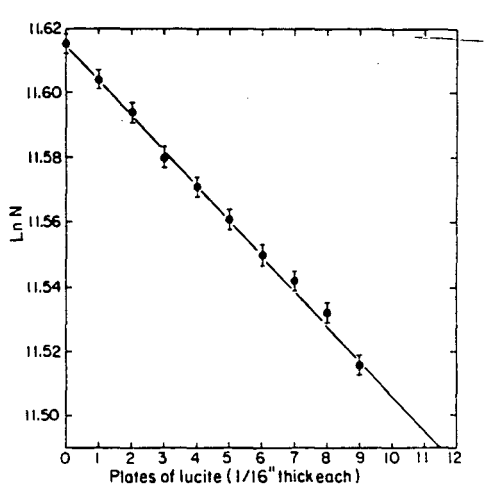

Fig. 4. Attenuation of γ-rays through lucite plates.

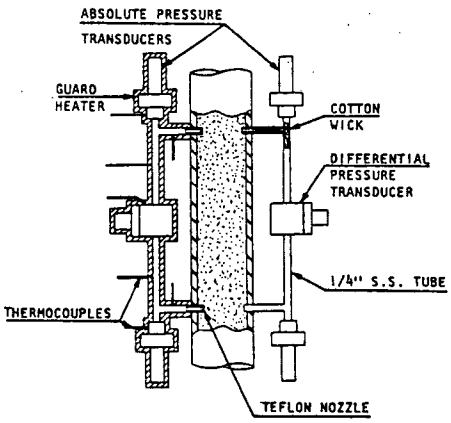

Fig. 5. Schematic of pressure measurement system.

pressure transducers to the ports were coated with Teflon and both the tubes and the pressure transducers were maintained at a temperature of 1-2°C above the local vapor temperatures with the aid of guard heaters. These precautions were taken to eliminate errors in vapor pressure measurements due to liquid condensation in the tubes and the pressure transducers. (The error in vapor pressure readings due to intentional increase in temperature is expected to be negligible.) On the other hand, all tubes connecting liquid pressure transducers to the test sample were filled with cotton wicks in contact with the porous matrix. The tubes and the transducers were kept cooler than the saturation temperature to prevent evaporation in the liquid pressure measurement unit. The temperature readings were taken with the aid of copper-constantan thermocouples sheathed inside 1/16 in. stainless steel tubes.

The test cell was mounted vertically, to avoid flow stratification, on an indexing table capable of accurate vertical movement. Double-deionized, degassed water was pumped into the inlet head with the aid of a dual-cylinder, constant flow-rate pump (accurate within ±.3%). Upon entering the chamber, a fraction of the water was flashed into steam by means of electric resistance heaters, causing two-phase concurrent flow in the test column. Temperature, vapor pressure, and liquid pressure were measured at regular intervals along the column. Saturation readings at different cross-sections were taken with the aid of a γ-ray densitometer by moving the indexing table while the γ-ray source and the detector remained fixed to a rigid frame.

Upon leaving the exit head, steam was condensed in a heat exchanger and condensate was discharged through a constant head tank to maintain constant exit pressure.

RESULTS AND DISCUSSION

The experiment resulted in a set of relative permeability and capillary pressure curves shown in Figures 6a and b. The readings presented cover only a limited range of saturation ($.38 < S_w < .8$) because (i) the readings taken at saturations above 0.8 are not accurate because of the difficulties in-

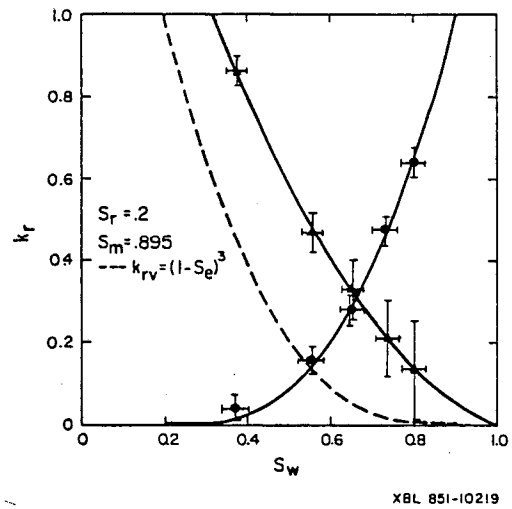

Fig. 6a. Experimental relative permeability curves.

volved in evaluating the flow quality (Verma, 1985); and (ii) the lower limit (S_w = .38) represents very nearly the irreducible water saturation. An attempt to reduce this saturation further was abandoned because the system temperature rose beyond the operating temperature of the differential pressure transducers.

Figure 6a shows that the measured values of the relative permeabilities can be represented by:

$$k_{rw} = S_e^3 \quad \text{, and} \tag{7}$$

$$k_{rv} = 1.2984 - 1.9832\, S_e + .7432\, S_e^2 \tag{8}$$

where

$$S_e = \frac{S_w - S_r}{S_m - S_r} \tag{9}$$

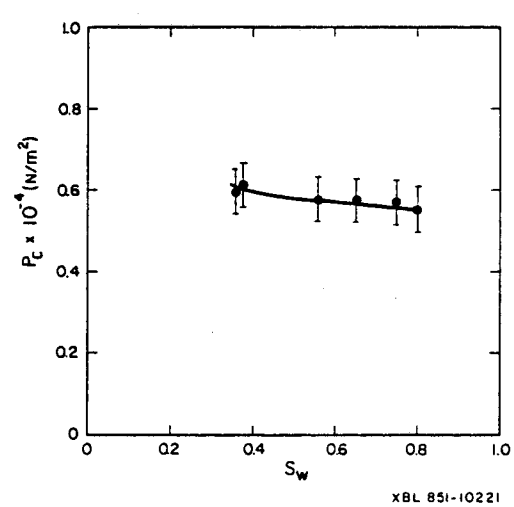

Fig. 6b. Experimental capillary pressure curve.

Since the limits S_r and S_m of the mobile saturation range for the liquid phase are not measured in the present experiment, but obtained by curve fitting (S_r = .2, S_m = .895), they should be considered approximate. Since the irreducible steam saturation could not be measured accurately it was assumed that there is no irreducible steam saturation for the present experimental configuration where the liquid water flows towards lower thermodynamic pressure and temperature (Verma, et al., 1983). This assumption was invoked in curve fitting to obtain equation 8.

A typical set of simulated results along the entire column using the experimental relative permeability and capillary pressure curves is presented in Figure 7. These are compared against the experimental data and a good agreement is found, thus confirming our analysis of experimental data. The flow quality along the flow path for this test-run is presented in Figure 8. It indicates that the flow quality in the region of interest is very nearly constant.

It is interesting to note that Equation 7 for wetting phase relative permeability has been suggested independently by many investigators, including: (i) Irmay (1954), semi-empirical study of flow in unsaturated soils; (ii) Hauzenberg and Zaslavsky (1963), experimental study on well sorted sand; (iii) Brooks and Corey (1964), semi-empirical study.

Brooks and Corey (1964) also suggested that for a well sorted sand, the relative permeability to the non-wetting phase could be represented by

$$k_{r,nw} = (1 - S_e)^3 \qquad (10)$$

However, upon comparing the experimental vapor phase relative permeability to Equation 10 (Fig. 6a), we find that the measured values are much larger than the ones given by Equation 10. Similar differences are found upon comparing the present results to those of other investigators (e.g. Osoba et al., 1951; and Johnson et al., 1959). These comparisons are plotted in Figure 9. Johnson et al. conducted their studies on flow of oil and water through a packed column (permeability = 11.5 Darcies) of glass beads, and Osoba et al.'s studies were conducted on oil and gas through consolidated rock core of permeability = 4.18 Darcy. Figure 9 also shows that over the

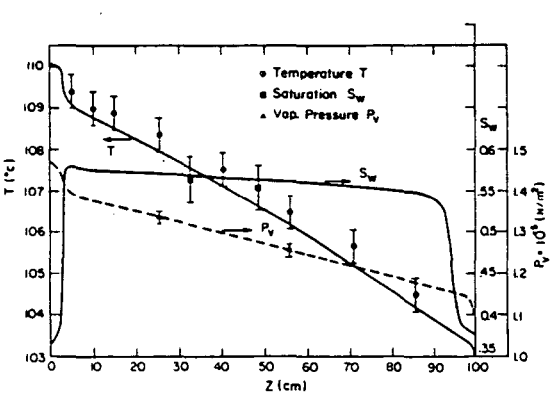

Fig. 7. Comparison of experimental data with numerical simulation for Run-4 (S_w = 0.557).

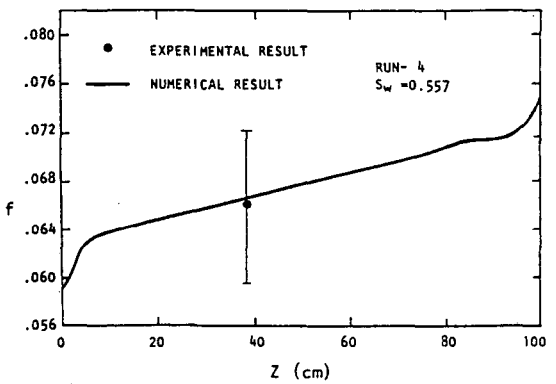

Fig. 8. Plot of flow quality (f) for Run-4.

entire two-phase zone ($0 < S_w < 1$), the sum of the relative permeabilities ($k_{rw} + k_{rnw}$) are larger in case of steam and water flow, suggesting a more efficient advection of the two phases. The enhancement of vapor phase relative permeability cannot be attributed to self-diffusion of vapor in the flow channels, because the Peclet numbers in our experiment are very large ($P_e > 10^3$, Cf Appendix B). A possible cause for enhanced vapor permeability is channeling of vapor phase where vapor forms preferential channels causing a reduction in pressure gradient compared to homogeneous two-phase flow. These channels could be formed either along the contact surfaces between the glass beads and the confining tube and/or within the porous medium itself (Udell, 1985). The possibility of preferential channeling within the porous medium in our experiment is very small, however, because our saturation readings at three different locations along the flow direction change consistently with changing flow quality. In presence of preferential channeling this could happen only if the channel formed within the porous medium was intersected by the γ-ray beam.

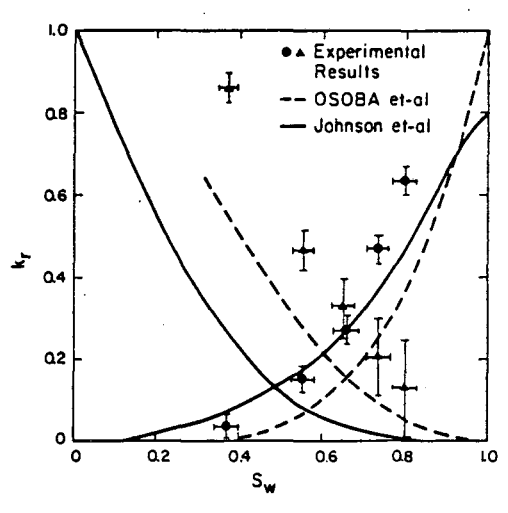

Fig. 9. Measured steam/water relative permeabilities compared with results for oil/gas and oil/water flow.

Since the γ-ray beam covers only about 5% of the cross-sectional area of the porous medium, the probability of the beam encountering the same channel(s) at three different locations, where saturation readings are taken, is very low.

The effects of channeling along the boundary could not be quantified at this stage. This is under investigation and shall be reported later by Verma (1985). We believe that the observed permeability enhancement for vapor is caused by phase transformation effects specific to single-component, two-phase systems. Enhancements of vapor mobility have been observed in unsaturated soils, where they have been attributed to condensation-vaporization effects with flux "short-circuiting" at liquid islands (Walker et al., 1981). It is likely that the enhancement of steam relative permeability observed in our experiment is caused by similar mechanisms. A quantitative evaluation of this effect is currently underway.

SUMMARY

An experimental facility to measure steam-water relative permeability was constructed and a set of results was obtained. These results are compared against numerical simulation, and good agreement was found, thus confirming the experimental results. Upon comparing our results with oil-water and gas-oil relative permeabilities reported in the literature, we find an approximate agreement for the wetting phase relative permeabilities. However, steam relative permeability is substantially larger than the non-wetting phase relative permeabilities of gas-oil and oil-water flows. We suggest that this enhancement of non-wetting phase permeability is caused by phase transformation in water/steam flow. However, more studies are needed before quantitative, conclusive results can be drawn.

ACKNOWLEDGEMENT

This work was supported through U.S. Department of Energy Contract NO. DE-AC03-76SF00098 by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technology Division of Geothermal and Hydropower Technologies.

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APPENDIX A

Analysis of the Relative Permeability Experiment

We consider a one-dimensional, steady-state, adiabatic flow of steam and water in a porous medium (Fig. 1). The conservation of mass is expressed by,

$$m_o = m_v + m_w \tag{A.1}$$

where m_o is the known input mass flow rate, and m_v and m_w are the mass flow rates of steam and liquid water,respectively.

The potential energy and kinetic energy effects are negligible for the conditions of the experiment, so that the energy equation is

$$m_o h_o + Q = m_v h_v + m_w h_w + q \tag{A.2}$$

where Q is the energy input to the boiling chamber and q is the conductive heat flux at any cross section (cf Eq. 5). Other notations have their usual meaning.

Assuming Darcy's Law, the momentum equations for the liquid and the vapor phases are given by

$$m_w = -\frac{k\, k_{rw}\, A\, \rho_w}{\mu_w} \frac{d}{dz} (P_w + \rho_w g z) \tag{A.3}$$

and

$$m_v = -\frac{k\, k_{rv}\, A\, \rho_v}{\mu_v} \frac{dP_v}{dz} \tag{A.4}$$

The flowing steam quality is defined as

$$f \equiv \frac{m_v}{m_v + m_w} \tag{A.5}$$

combining Equations A.1 and A.5

$$1-f = \frac{m_w}{m_o} \tag{A.6}$$

Substituting Equations A.5 and A.6 into the energy equation A.2, and solving for f yields

$$f = \frac{m_o(h_o - h_w) + Q - q}{m_o(h_v - h_w)} \tag{A.7}$$

Equations for k_{rw} and k_{rv} are obtained by substituting for m_v from Equation A.5 into Equation A.4 and for m_w from Equation A.6 into Equation A.3. Solving for k_{rw} and k_{rv} we obtain (Reda and Eaton, 1981).

$$k_{rw} = \frac{(f-1)\, m_o \mu_w v_w}{kA \frac{d}{dz} (P_w + \rho_w g z)} \tag{A.8}$$

and

$$k_{rv} = \frac{-f\, m_o \mu_v v_v}{kA \frac{d}{dz} P_v} \tag{A.9}$$

APPENDIX B

Self-diffusion of vapor in flow channels

The diffusive mass flux in flow channels is given by (Walker et al., 1981)

$$m_{v,d} = -\phi S_v\, D\alpha v \nabla \rho_v \tag{B.1}$$

Assuming

(i) local thermodynamic equlibrium,
(ii) vapor behaves as perfect gas,
(iii) effect of capillary pressure on vapor pressure reduction is negligible,
(iv) P_v and T are correlated according to Clausius-Clapeyron equation

$$\frac{dP_v}{dT} = \frac{h_{wv}}{T(v_v - v_w)} \tag{B.2}$$

(v) $v_v >> v_w$, and,
(vi) one dimensional flow,

the vapor density gradient can be expressed as

$$\frac{d\rho_v}{dx} = \frac{P_v}{RT^2} \left\{ \frac{h_{wv}}{RT} - 1 \right\} \frac{dT}{dx} \tag{B.3}$$

From Equation (B.1) and (B.3) we have for divvusive mass flux

$$m_{v,d} = -\phi S_v\, D\alpha \frac{P_v}{RT^2} \left\{ \frac{h_{wv}}{RT} - 1 \right\} \frac{dT}{dx} \tag{B.4}$$

the advective component of vapor flux is given by

$$m_v = \frac{-k\, k_{rv}\, \rho_v}{\mu_v} \frac{dP_v}{dx} \tag{B.5}$$

From Equations (B.5) and (B.2)

$$m_v = \frac{-k\ k_{rv}}{\mu_v} \frac{\rho_v\ h_{wv}\ P_v}{RT^2} \frac{dT}{dx} \qquad (B.6)$$

Defining a modified Peclet number $Pe \equiv \frac{m_v}{m_{v,d}}$

$$Pe = \frac{k\ k_{rv}\ P_v\ h_{wv}}{\phi S_v\ \alpha\nu\ D\ \mu_v\ (h_{wv} - RT)} \qquad (B.7)$$

For the present calculations we take both ν and $\alpha = 1$ because our test sample is well-sorted and value of ν is unknown.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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