PROCEEDINGS, Twenty-Fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 2000
SGP-TR-165

STEAM-WATER CAPILLARY PRESSURE IN GEOTHERMAL SYSTEMS

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ABSTRACT

Steam-water capillary pressure has a significant effect on water injection into and production from geothermal reservoirs. The mass transfer between steam and water phases makes it very difficult to measure steam-water capillary pressure using routine methods such as the semipermeable porous plate method and centrifuge method. Due to the difficulties in measuring steam-water capillary pressure, very few steam-water capillary pressure data are available. We used a steady-state flow method to measure steam-water capillary pressures using an X-ray CT technique to monitor and measure the saturation and distribution of water in the core sample. The drainage steam-water capillary pressure was calculated using a formula derived from the Kelvin equation after measuring the pressures and temperatures of the water phase. The steam-water capillary pressure of the Berea sandstone sample was about 0.07 MPa (10.4 psi) at a water saturation of around 30% and a temperature of about 120^{o}C. The steam-water capillary pressure of the Berea sandstone sample was scaled up for a rock from The Geysers field using the experimental data of steady-state flow and the results obtained were consistent with those measured by Persoff and Hulen (1996) using an adsorption method. A mathematical model to calculate steam-water capillary pressure of geothermal rocks has been developed for application in geothermal reservoir engineering and numerical simulation.

INTRODUCTION

In recent years, much attention has been paid to the measurement of steam-water relative permeability (Sanchez and Schechter, 1990, Ambusso, 1996, Satik, 1998, Mahiya, 1999, Li and Horne, 1999, and Horne, et al., 2000). However, less attention has been paid to the experimental measurement of steam-water capillary pressure, even though capillary pressure is of equal significance to relative permeability and plays an important role in geothermal reservoirs. As an example, Tsypkin and Calore (1999) developed a mathematical model of steam-water phase transition with capillary forces included. They investigated the main characteristics of the vaporization process and found that capillary pressure can play a stabilizing role for the vaporization front, causing a sharp front to develop.

Urmeneta, et al. (1998) also studied the role of capillary forces in the natural state of fractured geothermal reservoirs and found that capillary pressure tended to keep the vapor phase in the fractures and the liquid phase in the matrix. The numerical results from Urmeneta, et al. (1998) showed that capillary forces control the transfer of fluids between fractures and matrix, the stability of the liquid-dominated two-phase zone, and the distribution of steam and water in geothermal reservoirs. Hence, the value of capillary pressure will influence the estimation of the energy reserves and production performance. Unfortunately, there are few experimental data of steam-water capillary pressure for steam-water flow in porous media.

Sta. Maria and Pingol (1996) inferred values of capillary pressure from the adsorption data of Horne, et al. (1995) for rock samples from The Geysers geothermal field and found the capillary pressure to range from 0 to 586 MPa (0 to 86000 psi). Persoff and Hulen (1996) also inferred the capillary pressure from adsorption data of The Geysers rock samples and found the capillary pressure ranging from 0 to about 190 MPa (0 to 28000 psi). Persoff and Hulen (1996) used different salt solutions to obtain a wide range of vapor pressures in the rock sample. These results show some inconsistency. Therefore, it is necessary to develop a reliable technique to measure and calculate the steam-water capillary pressure directly. We also need to develop a method to scale up the experimental data to reservoir conditions. This is of importance for geothermal reservoir engineering and numerical simulation.

The adsorption/desorption tests that have been used to infer capillary pressure are static processes in which there is no steam-water flow. In actual geothermal reservoirs, however, capillary pressure plays its important role while steam and water flow simultaneously through the rocks. Hence the process governing an adsorption test may not represent the mechanisms under actual fluid flow conditions in geothermal reservoirs. Consequently, the capillary pressures calculated using adsorption test data may or may not be the same as those measured using a dynamic method in which steam and water flow simultaneously through the porous medium. It is known that capillary pressure is influenced significantly by the contact angle. The contact angle in a static state (no fluid flow) is usually very different from the contact angle in a dynamic state (with fluid flow). Hence the capillary pressure is likely to be different under static and dynamic conditions. Finally, very strict sealing requirements have to be achieved for long periods of time during the adsorption tests, which is very difficult especially at high temperatures. These disadvantages of adsorption tests may be overcome by using a steady-state flow method for measuring steam-water capillary pressure.

In this paper, a method to calculate steam-water capillary pressure has been developed using the data from steady-state steam-water flow experiments by Mahiya (1999). An X-ray CT technique was used to monitor and measure the water saturation and its distribution in the core sample. The pressures and temperatures of water phase in a Berea sandstone sample were measured at different axial positions. Water saturation was varied by changing the flow rates of steam and water at the inlet of the core sample. Experiments were conducted under near-adiabatic conditions controlled automatically by a computer. As will be described in the following sections, steam-water capillary pressures in the Berea sandstone sample can be calculated using a formula derived from the Kelvin equation together with the measured values of the pressure and temperature of the water phase. Following that, the steam-water capillary pressure of a rock sample from The Geysers field can be computed on the basis of the results from the Berea sandstone sample using the concept of a *J*-function. The values estimated here by this approach were compared to the vapor-water capillary pressures measured by Persoff and Hulen (1996) using an adsorption method.

METHOD

Using the Kelvin equation, steam-water capillary pressure can be calculated from the experimental data of liquid phase pressure, temperature, and related parameters. The procedure is described in this section.

The *relative pressure* (p_v/p_0), the ratio of vapor pressure, p_v, on a curved surface to the vapor pressure, p_0, on a flat surface, is used to characterize the capillary condensation on curved surfaces. Kelvin established the relationship between the relative pressure and the curvature of the interface along with other properties of the fluid and the substrate. In a circular capillary tube with a radius of r, the relative pressure can be calculated using the Kelvin equation as follows:

$$\ln(\frac{p_v}{p_0}) = -\frac{2\sigma M_w \cos\theta}{r\rho_w RT} \tag{1}$$

where p_0 is the vapor pressure when the vapor-liquid interface is flat; p_v is the vapor pressure in a capillary tube of radius r when the vapor-liquid interface is curved; σ is the interfacial tension and θ is the contact angle measured through the liquid phase; R is the gas constant, T the absolute temperature, M_w the molecular weight of liquid, and ρ_w the density of liquid.

The Kelvin equation assumes that: (1) all adsorption is due only to capillary condensation; (2) adsorbate density is equal to bulk liquid density; and (3) the validity, including the constancy of σ and the system pressure p, is unimpaired at low values of r.

The capillary pressure, P_c, in a circular capillary tube is also determined by the interface curvature, fluid and substrate properties, and can be calculated as:

$$P_c = \frac{2\sigma\cos\theta}{r} \tag{2}$$

Combining Equation 1 and 2:

$$P_c = \frac{\rho_w RT}{M_w}\ln(\frac{p_0}{p_v}) \tag{3}$$

Capillary pressure is defined as the pressure difference between vapor and liquid phases:

$$P_c = p_v - p_w \tag{4}$$

where p_w is the pressure of liquid phase.

Substituting Equation 4 into 3:

$$p_v - p_w = \frac{\rho_w RT}{M_w}\ln(\frac{p_0}{p_v}) \tag{5}$$

The units used in Equation 5 are as follows: p_v, p_w, p_0 kPa (absolute), ρ_w (g/ml), R = 8310 (kPa.ml)/(°K.mole), T °K, and M_w g/mole.

In our steam-water flow experiments, we can measure p_w and T at the same time and the same location, while p_0 can be calculated according to the measured saturation temperature. Therefore, p_v, as the only unknown parameter in Equation 5, can be obtained by Newton iteration. The capillary pressure is then computed using Equation 4 once p_v is known. The solver function of Microsoft® Excel 97 was used to solve Equation 5 in this work.

Note that Equation 2 is only correct in a capillary tube with a circular shape. On the other hand, the adsorption process in porous media is governed not only by capillary pressure but also Van der Waals attractive forces, including the dispersion forces. In addition, the electrostatic forces may play an important role. In order to apply Equation 5 in porous media, we need to assume also that differences of pore shape from circular can be ignored. It may be necessary to make some correction to apply Equation 5 in porous media, in order to meet this assumption as well as all the assumptions inherent in the Kelvin equation itself. In this work, we calculated the vapor pressure in porous media using Equation 5 and then calculated steam-water capillary pressure using Equation 4. The appropriateness of using Equation 5 in this way was evaluated by comparing to actual capillary measurements by earlier authors.

Once the steam-water capillary pressure in the Berea sandstone sample was available, we were able to infer the steam-water capillary pressure in geothermal rocks. The procedure is described here. Capillary pressures in rocks with different porosity and permeability may be correlated using the *J*-function suggested by Leverett (1941) as follows:

$$P_c = \frac{\sigma \cos\theta}{\sqrt{\frac{k}{\phi}}} J(S_w) \qquad (6)$$

where k, ϕ, S_w, and $J(S_w)$ are permeability, porosity, water saturation, and *J*-function, respectively. Assuming that the *J*-function in both Berea and geothermal rock samples are the same, we can calculate the steam-water capillary pressure in geothermal rocks using the following equation:

$$P_c^G(S_w) = \frac{\sigma_G \cos\theta_G}{\sigma_B \cos\theta_B} \frac{\sqrt{\frac{k_B}{\phi_B}}}{\sqrt{\frac{k_G}{\phi_G}}} P_c^B(S_w) \qquad (7)$$

here $P_c^G(S_w)$ and $P_c^B(S_w)$ are the steam-water capillary pressures at a water saturation of S_w in a geothermal rock sample with a permeability of k_G and a porosity of ϕ_G and in a Berea sandstone sample with a permeability of k_B and a porosity of ϕ_B, respectively. Considering that the temperatures may be different in the two systems, σ_B, the surface tension in the steam-water-Berea system, and σ_G, the surface tension in the steam-water-geothermal rock system, are introduced in Equation 7. Similarly, θ_G and θ_B are the contact angles in steam-water-Berea and steam-water-geothermal rock systems, respectively. Equation 7 was derived by applying Equation 6 to each type of rock – Berea and geothermal. Since the contact angle in steam-water-geothermal rock systems is not available, we assumed in this study that the contact angles in both Berea and geothermal rock samples are the same. Furthermore, if we scale the experimental data to the same temperature, the surface tension will be the same. Therefore, Equation 7 would be reduced to:

$$P_c^G(S_w) = \frac{\sqrt{\frac{k_B}{\phi_B}}}{\sqrt{\frac{k_G}{\phi_G}}} P_c^B(S_w) \qquad (8)$$

Based on Equation 8, the steam-water capillary pressure in geothermal rocks can be computed once the steam-water capillary pressure in the Berea sandstone sample, and the permeability and porosity in both Berea and geothermal rocks are known. We compared the steam-water capillary pressure calculated using Equation 8 for a rock from The Geysers geothermal field with the steam-water capillary pressure measured in the same rock by Persoff and Hulen (1996) using an adsorption method. Because the adsorption tests by Persoff and Hulen (1996) were conducted at a temperature of 28.5°C and the steady-state flow tests were conducted at a temperature of 120°C, it is necessary to scale up the capillary pressure measured by Persoff and Hulen (1996) to the same temperature, 120°C. This was achieved using the following equation:

$$P_c^{G,T_2}(S_w) = \frac{\sigma_{T_2}}{\sigma_{T_1}} P_c^{G,T_1}(S_w) \qquad (9)$$

where $P_c^{G,T_1}(S_w)$ and $P_c^{G,T_2}(S_w)$ are the capillary pressure for the same rock at the same water saturation of S_w but at different temperatures of T_1 and T_2, respectively. σ_{T_1} and σ_{T_2} are the surface tensions at temperatures T_1 and T_2.

Usually, the *J*-function is consistent for rocks with similar depositional environment. That is, the *J*-function may be the same for rocks in similar depositional environments but with different porosity and permeability. The *J*-function for geothermal rocks may or may not be different to that of Berea sandstone since the deposition conditions are not the same. Therefore, the steam-water capillary pressure calculated using Equation 8 for the rock from The Geysers geothermal field may not be consistent to that measured in the same rock by Persoff and Hulen (1996) using an adsorption method.

EXPERIMENTS

The experimental details regarding the collection of the data used this study have been described in Mahiya (1999). For convenience, a brief description of the fluid flow tests is repeated here. Distilled water was used as the liquid phase and to generate steam; the specific gravity and viscosity were 1.0 and 1.0 cp at 20^{o}C. The steam properties at high temperatures were calculated using a steam table, based on the measured values of pressure and temperature . The surface tension of steam/water at 20^{o}C is 72.75 dynes/cm. The core sample was a Berea sandstone fired at high temperature; its permeability and porosity were 1400 md and 24.0%; the length and diameter were 43.2 cm and 5.04 cm, respectively.

A schematic of the apparatus for the steady-state flow tests is shown in Figure 1. One of the challenges in this steady-state flow test was to maintain an adiabatic condition. To this end, a technique using flexible guard heaters wrapped around the coreholder was developed by Mahiya (1999). The exact amount of heat that was lost from the core-fluid system was supplied back to the system using the heaters, so that the overall heat loss would be negligible. Automation and data acquisition were realized by using the software LabView 4.1 and corresponding hardware (National Instrument Co.). Steam and water saturations were measured using a Picker^{TM} Synerview X-ray CT scanner (Model 1200 SX) with 1200 fixed detectors. The voxel dimension is 0.5 mm by 0.5 mm by 5 mm, the tube current used was 50 mA, and the energy level of the radiation was 140 keV. The acquisition time of one image is about 3 seconds while the processing time is around 40 seconds.

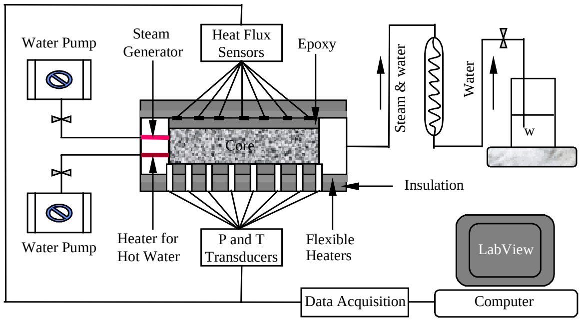

Figure 1: Schematic of the apparatus for steady-state flow tests.

Pressure and temperature were measured through ports at eight positions along the core spaced about 5 cm apart. The experiments used differential pressure transducers manufactured by CES Co. (Model 238) with a linearity of 0.25% full scale and a range of differential pressure from 0 to 10 psi. All the pressure transducers were calibrated before and after the experiments using a pressure gauge with an accuracy of 0.05 psi.

The core sample was dried by evacuation at about 30 millitorr while heating. Once dried, the core sample was saturated with distilled water. In order to achieve two-phase flow conditions in the core sample, dry steam and hot liquid water were injected separately from two streams at the inlet. Each stream of fluid came from deionized water pumped from a common reservoir to a boiler and then to a condensing loop. This process eliminated the dissolved air that would introduce errors in the saturation measurements. The deaerated water was then delivered to the heating head where each of the two streams was heated to either steam or hot water (see Figure 1). Steam and water then became partially mixed at the interface between the core and the head, and further mixed as they entered the porous medium. Steam and water were produced from the outlet end of the core and the volumetric flow rate was computed using a balance (with an accuracy of 0.01g) and timer, and compared with the injection rates specified at the pumps. Temperatures, pressures, and saturations in the core were measured once the flow reached steady-state , and these values were used to calculate steam-water capillary pressure with Equations 4 and 5. After each set of steady-state measurements, the water saturation in the core sample was changed by adjusting the ratio of steam flow rate to water flow rate by varying the power supplied to the steam heater.

RESULTS

The steam-water capillary pressures calculated using Equations 4 and 5 with the experimental results of steady-state flow of steam and water in the Berea sandstone sample are shown in Figure 2. The solid line is a fitting curve using an exponential function. During the experimental process, the water saturation in the Berea sandstone sample was decreased from 100 percent to the remaining water saturation, about 28 percent. Therefore, Figure 2 shows a drainage capillary pressure curve. The entry capillary pressure of steam is very small for this sandstone sample. The steam-water capillary pressure in the Berea sandstone sample at a water saturation of about 30% is around 0.07 MPa (10.4 psi), as shown in Figure 2. The water saturation remained in the core sample after the drainage by steam flooding is about 28 %. The actual residual water saturation may be less than this value because of practical experimental limitations such as limited steam flooding time. However, the real residual water saturation in the core sample may be estimated using a regression analysis for the relationship between steam-water capillary pressures and water saturations.

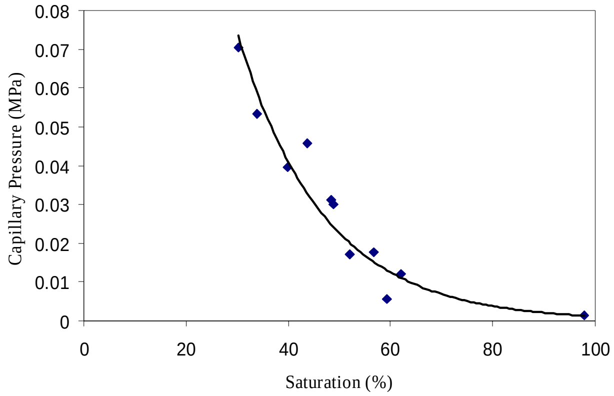

Figure 2: Steam-water capillary pressure curve (drainage) calculated from the data of steady-state flow of steam and water in a Berea sandstone sample.

As mentioned before, we can use Equation 8 to calculate the steam-water capillary pressure in geothermal rocks once the steam-water capillary pressure in a Berea sandstone sample is available. The purpose is to compare the results with those measured by Persoff and Hulen (1996) and hence evaluate the appropriateness of the assumptions of Equation 8. First of all, we need to know the porosity and permeability of the geothermal rocks. Persoff and Hulen (1996) measured the porosity and permeability of four rocks from The Geysers geothermal field, the porosity ranging from 0.2% to 0.5% and the permeability ranging from 1.3 to 26 nd (10^{-6} md). The steam-water capillary pressure data were computed using Equation 8 for the two rock samples with the low and high limit values of porosity and permeability. Figure 3 shows the calculated capillary pressure curves.

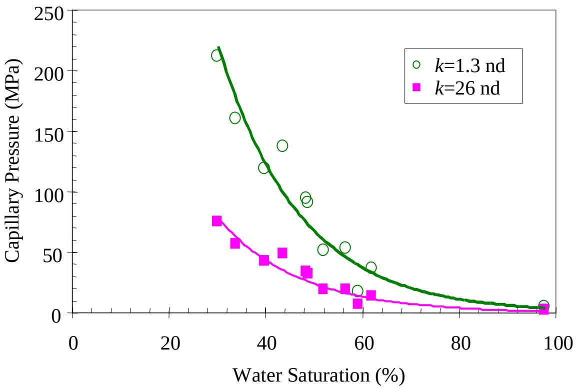

Figure 3: Steam-water capillary pressure curves calculated using a scaling method for two rocks from The Geysers field.

The effect of permeability on steam-water capillary pressure is significant for the geothermal rocks over the range of low water saturation, as shown in Figure 3. However, the effect of permeability on the entry capillary pressure of steam is small (see Figure 3). Note that this analysis is based only on the results calculated using a scaling method instead of experimental data of steam-water capillary pressure measured directly in the geothermal rock samples. Hence the results need to be confirmed by direct measurement. However, the results shown in Figure 3 give us an understanding of the magnitude of the effect of the permeability on steam-water capillary pressure in geothermal rocks.

Figure 4 shows the comparison of the steam-water capillary pressure curve calculated using Equation 8 with that measured by Persoff and Hulen (1996) using an adsorption method at a temperature of 28.5°C. The porosity and permeability of the rock sample from The Geysers geothermal field that was used for the numbers in Figure 4 were 0.2% and 1.3 nd; the low range values measured by Persoff and Hulen (1996).

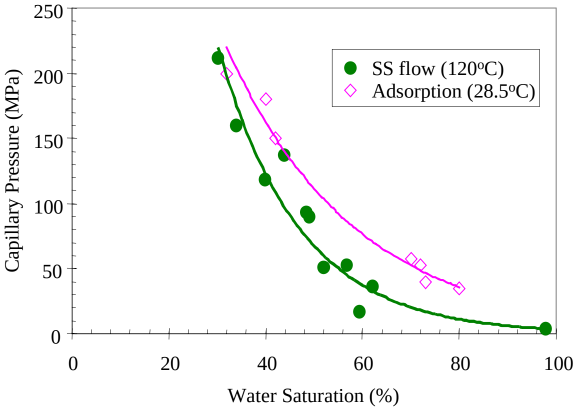

Figure 4: Steam-water capillary pressure curves by steady-state (SS) flow and adsorption methods for a rock sample from The Geysers field.

It is to be expected that the steam-water capillary pressure for a geothermal rock sample at the higher temperature of about 120°C is smaller than that at the lower temperature of 28.5°C, as shown in Figure 4. We scaled the experimental values of steam-water capillary pressure from Persoff and Hulen (1996) to the temperature of 120°C using Equation 9. The surface tension of steam/water at 120°C is 54.96 dynes/cm. The comparison of the steam-water capillary pressure for the Geysers rock by steady-state flow and adsorption methods is shown in Figure 5, based on the same temperature. The two sets of steam-water capillary pressure values are remarkably consistent after the temperature calibration.

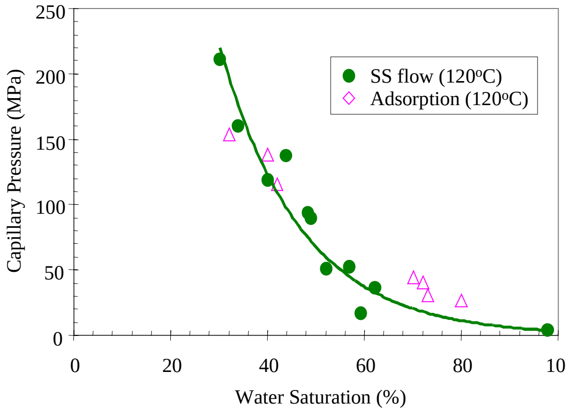

Figure 5: Comparison of steam-water capillary pressure curves by steady-state (SS) flow and adsorption methods for a rock from The Geysers field.

The consistency of the steam-water capillary pressure values shown in Figure 5 gives us confidence in applying these steam-water capillary pressure data in geothermal reservoir engineering, by the application of Equation 6. The purpose in using Equation 6 is that the reservoir rocks in geothermal fields have different porosity and permeability and it is impossible to measure the steam-water capillary pressure for every rock sample. Therefore, we need to use Equation 6 to establish a correlation between the steam-water capillary pressure of rocks with different porosities and permeabilities.

It would be useful for geothermal reservoir engineers to have a technique to estimate the values of steam-water capillary pressure for geothermal rocks. This technique would be based on the experimental data and would be able to calculate steam-water capillary pressure for geothermal rocks with any porosity and permeability at any reservoir temperature. Until now, geothermal reservoir engineers have usually hypothesized the form of the steam-water capillary pressure curve used for numerical simulation, or ignored it entirely. In order to constitute such a steam-water capillary pressure model for geothermal rocks, we plotted all the steam-water capillary pressure data shown in Figure 5, including those measured by Persoff and Hulen (1996), vs. the normalized water saturation. The results are shown in Figure 6. The normalized water saturation is calculated using the following equation:

$$S_w^* = \frac{S_w - S_{wr}}{1 - S_{wr}} \tag{10}$$

where S_{wr} and S_w^* are the residual water saturation and normalized water saturation. The Brooks-Corey (1964) capillary pressure function is often used to model the capillary pressure curve; it is given by:

$$P_c = p_e (S_w^*)^{-1/\lambda} \tag{11}$$

where p_e is the entry capillary pressure and λ is the pore size distribution index. We used the Brooks-Corey capillary pressure function to fit the data. Figure 6 shows a match to all the data from this study and that of Persoff and Hulen (1996). The values of the best-fit parameters are S_{wr} = 0.20, p_e = 13.96 MPa and λ =0.669. Note that these values are only valid when the normalized water saturation is expressed as a fraction rather than as a percentage.

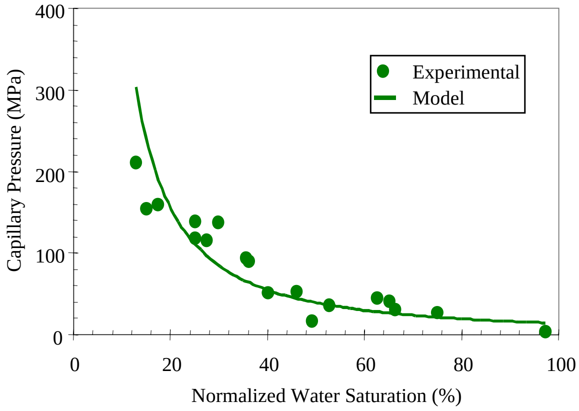

Figure 6: Normalized steam-water capillary pressure for a rock from The Geysers field.

Since the steam-water capillary pressure data shown in Figure 6 were obtained from a rock sample with a permeability of about 1.3 nd and a porosity of 0.2% at a temperature of 120°C, we would need to scale the data for rocks with different porosity and permeability or for different temperatures. This can be done using Equation 6. Using this approach, we have created a mathematical model of steam-water capillary pressure based on the experimental data from this study and from Persoff and Hulen (1996) for geothermal rocks as follows:

$$P_c = 6.475 \frac{\sigma}{\sqrt{\frac{k}{\phi}}} (S_w^*)^{-1.495} \tag{12}$$

where the units of P_c, σ and k are MPa, dynes/cm and nd respectively; ϕ and S_w^* are expressed as fractions. The porosity and permeability of reservoir rocks would need to be measured. The surface tension can be calculated once the reservoir temperature is known. Therefore, the steam-water capillary pressure curve for geothermal reservoir rocks may be obtained using Equation 12. It is assumed that the contact angle does not change with permeability and temperature.

DISCUSSION

The results of steam-water capillary pressure calculated by applying the Kelvin equation to the data from steady-state steam and water flow experiments are very preliminary, although Figure 5 shows remarkable consistency between the capillary pressure values obtained by steady-state flow and adsorption methods. The main uncertainties are the *J*-function and the contact angle in steam-water-Berea and steam-water-geothermal rock systems. If the difference of the *J*-function and the contact angle between the steam-water-Berea and steam-water-geothermal rock systems could be identified, then we could calculate the steam-water capillary pressure of geothermal rocks more accurately. It takes much less time and effort to measure the steam-water capillary pressure in highly permeable rocks than in low permeability rocks. Unfortunately, few data for the *J*-function and the contact angle in geothermal rocks are available. Hence, the application of the steam-water capillary pressure model (Equation 12) to geothermal reservoir engineering also depends on this further research on these parameters.

Another important question also remains: is there any difference between steam-water capillary pressure and air-water or nitrogen-water capillary pressure? If there is no difference, we could measure air-water capillary pressure as a substitute of the steam-water capillary pressure. The air-water measurements are very much easier to conduct. We have embarked on a project to measure the steam-water and air-water capillary pressures using the same rock sample.

CONCLUSIONS

Based on the present work, the following conclusions may be drawn:

1. It is possible to calculate steam-water capillary pressure by applying the Kelvin equation to the experimental data from the steady-state flow of steam and water in porous media.

2. The steam-water capillary pressure measured in the Berea sandstone sample with high permeability can be scaled to infer the steam-water capillary pressure in geothermal rocks with much lower porosity and permeability.

3. The steam-water capillary pressure scaled for a rock from The Geysers field using the data from steady-state flow experiments is consistent with that measured by Persoff and Hulen (1996) using an adsorption method. This implies that the *J*-functions of The Geysers rocks (matrix) may be similar to those of Berea sandstone.

4. A preliminary mathematical model has been developed for the steam-water capillary pressure in geothermal rocks based on the properties of a rock sample from The Geysers geothermal field.

ACKNOWLEDGEMENT

This research was conducted with financial support to the Stanford Geothermal Program from the US Department of Energy under grants DE-FG07-95ID13370 and DE-FG07-99ID13763.

NOMENCLATURE

$J(S_w)$ = *J*-function
k = permeability
k_B = permeability in a Berea core sample
k_G = permeability in a geothermal rock sample
M_w = molecular weight of liquid
p_0 = vapor pressure on flat vapor-liquid interface
p_c = capillary pressure
p_c^{G,T_1} = capillary pressure of a geothermal rock sample at a temperature of T_1
p_c^{G,T_2} = capillary pressure of a geothermal rock sample at a temperature of T_2
p_e = entry capillary pressure
p_v = vapor pressure on curved vapor-liquid interface
p_w = pressure of liquid phase
r = radius of a capillary tube
R = gas constant
S_w = water saturation
S_w^* = normalized water saturation
S_{wr} = residual water saturation
T = temperature
ϕ = porosity
ϕ_G = porosity in a geothermal rock sample
ϕ_B = porosity in a Berea sandstone sample
θ = contact angle measured through the liquid phase
θ_B = contact angle in a steam-water-Berea system
θ_G = contact angle in a steam-water-geothermal rock system
ρ_w = density of liquid water
σ = surface tension
σ_B = surface tension in a steam-water-Berea system
σ_G = surface tension in a steam-water-geothermal system
σ_{T_1} = surface tension at a temperature of T_1
σ_{T_2} = surface tension at a temperature of T_2
λ = pore size distribution index

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