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DIFFERENCES BETWEEN STEAM-WATER AND AIR-WATER CAPILLARY PRESSURES

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ABSTRACT

Steam-water flow exists in most geothermal reservoirs where steam-water capillary pressure plays an important role in controlling fluid distribution, transfer of liquid between fracture and matrix, well productivity, and even the reserves. However, it is very difficult to measure steam-water capillary pressure due to the phase transformation and the significant mass transfer between the two phases as pressure changes. We would like to know if there are any differences between steam-water and air-water capillary pressures. If not, we could represent steam-water flow by air-water flow in which air-water capillary pressure can be measured easily. To address this question, we conducted spontaneous water imbibition into a vertically positioned ceramic sample saturated with steam and air respectively. The capillary force was equal to the gravity force once the water imbibition was completed. The imbibition steam-water and air-water capillary pressures in the same core sample were obtained correspondingly. The experimental results were compared, and it was found that there were significant differences between steam-water and air-water capillary pressures. The imbibition steam-water capillary pressure was less than the imbibition air-water capillary pressure. The experimental data demonstrated that we would not be able to substitute steam-water capillary pressure simply using air-water capillary pressure. Instead it is necessary to measure steam-water capillary pressure directly.

INTRODUCTION

There has been some argument regarding the differences between steam-water and air-water flow through porous media in recent years. Sanchez and Schechter (1990) reported that the differences between steam-water and nitrogen-water relative permeabilities were almost negligible in an unconsolidated core sample. Horne *et al.* (2000), however, found significant differences in Berea sandstone with a much lower permeability than that of the core sample used by Sanchez and Schechter (1990). Accordingly, there may also be significant differences between steam-water and nitrogen-water capillary pressures. Very few direct comparisons of steam-water and air-water capillary pressures are available due to the scarcity of methods available to measure both steam-water and air-water capillary pressures. Li and Horne (2000a) developed a technique based on the Kelvin equation to calculate steam-water capillary pressure using the data from steady-state steam-water flow experiments. This method is suitable for steam-water systems but not for air-water systems. Therefore, we developed another method that could measure both steam-water and air-water capillary pressures in order to identify the differences between the two. We conducted spontaneous water imbibition (cocurrent) into the same core sample saturated with steam and air respectively. The core sample was positioned vertically. The steam-water and air-water capillary pressures were calculated using the relationship between height and water saturation measured by an X-ray CT method. It was assumed that the capillary pressure was equal to the gravity force after the equilibrium between gravity and capillary pressure was reached.

METHOD

In this study, the basic theory behind the measurements of steam-water and air-water capillary pressures is the balance between gravity and capillary pressure as a function of height in a core sample positioned vertically. Steam-water or air-water capillary pressure is equal to the gravity force once the spontaneous water imbibition into the core sample has been completed. The equation is expressed as follows:

$$P_{ci} = \Delta r g h \quad (1)$$

where P_{ci} is steam-water or air-water capillary pressure; Dr is the density difference between water and steam or air; g is gravity constant and h the height.

The water saturation in the core at h was measured by using an X-ray CT method. Water saturation is calculated as follows:

$$S_w = \frac{CT_{\exp}(T) - CT_{dry}(T)}{CT_{wet}(T) - CT_{dry}(T)} \qquad (2)$$

where $CT_{wet}(T)$, $CT_{dry}(T)$ are CT numbers of the core sample when it is fully saturated by water and air respectively; $CT_{exp}(T)$ is the CT number of the rock when it is partially saturated by steam, all at the same temperature T.

Porosity measured by an X-ray CT method is usually computed using the following expression:

$$f = \frac{CT_{wet}(T) - CT_{dry}(T)}{CT_{water}(T) - CT_{air}(T)} \qquad (3)$$

where CT_{water} and CT_{air} are the CT numbers of water and air respectively. However, the ceramic core sample used in this study had a hollow center, as shown in Fig. 1. Hence we used a modified equation to calculate the porosity of the core sample with this particular shape once we know the CT values of the whole area with a radius of r_o.

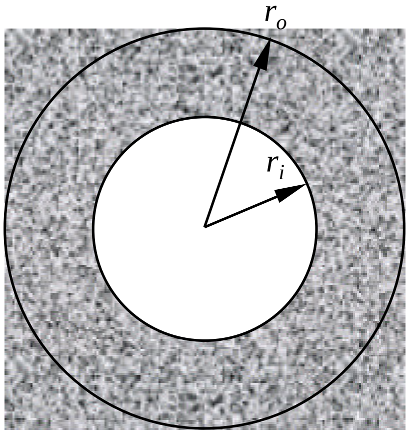

Fig. 1: Cross-section of a ceramic core sample.

The CT values, $CT_{wet}(T)$ and $CT_{dry}(T)$, of the whole area with a radius of r_o can be measured. The porosity calculated using Eq. 3 is the mean porosity f_m in that area, including the hole. The mean porosity is expressed as follows:

$$f^m = \frac{CT^m{}_{wet}(T) - CT^m{}_{dry}(T)}{CT_{water}(T) - CT_{air}(T)} \qquad (4)$$

where $CT^m{}_{wet}(T)$ and $CT^m_{dry}(T)$ are the average CT values of the whole area with a radius of r_o when the sample is saturated with water and air respectively. If we know the CT values of the rock part, then the porosity can be calculated using the following equation:

$$f = \frac{CT^o{}_{wet}(T) - CT^o{}_{dry}(T)}{CT_{water}(T) - CT_{air}(T)} \qquad (5)$$

where $CT^o{}_{wet}(T)$ and $CT^o_{dry}(T)$ are the average CT values of the annular area between r_o and r_i (see Fig. 1) when the sample is saturated with water and air respectively. We can measure $CT^m{}_{wet}(T)$ and $CT^m_{dry}(T)$ easily. Therefore, the question is how to calculate $CT^o{}_{wet}(T)$ and $CT^o_{dry}(T)$ from the measured values of $CT^m{}_{wet}(T)$ and $CT^m_{dry}(T)$. To this end, it is necessary to look into the fundamentals of the X-ray CT method. The linear absorption coefficient of X-ray through a uniform object is equal to:

$$m = m_m r \qquad (6)$$

where m and m_m are the linear absorption coefficient and mass absorption coefficient; r is the density of the object. For a nonuniform object composed of n components, the following equation applies:

$$m = \sum_{i=1}^{n} m_i V_i \qquad (7)$$

where m_i and V_i are the linear absorption coefficient and the volumetric fraction of component i.

CT value is defined as follows:

$$CT = 1000 \frac{m - m_w}{m_w} \qquad (8)$$

where m_w is the linear absorption coefficient of pure water. The CT value of water should be equal to zero according to Eq. 8 but the actual measurements may shift from zero due to the calibration error or other reasons. The absorption of X-ray in air is very small, so the CT value of air should be around –1000. The measured value of CT_{air} in this study was –1005.

According to Eqs. 7 and 8, the CT value of a nonuniform object can be calculated as follows:

$$CT = \sum_{i=1}^{n} CT_i V_i \qquad (9)$$

where CT_i is the CT value of component i.

The object shown in Fig. 1 can be considered as two parts: the hole and the annular solid. According to Eq. 9, the following expression applies:

$$CT_{wet}^{m} = CT_{wet}^{o}\frac{A_r}{A_m} + CT_{wet}^{h}\frac{A_h}{A_m} \qquad (10)$$

where $CT^{h}{}_{wet}$ is the CT value of the hollow part when the core sample is saturated with water. A_r, A_h and A_m are the areas of the annular solid rock part between r_o and r_i, the hollow part and the whole object respectively (see Fig. 1).

For the case in which the core is saturated by steam or air:

$$CT_{dry}^{m} = CT_{dry}^{o}\frac{A_r}{A_m} + CT_{dry}^{h}\frac{A_h}{A_m} \qquad (11)$$

here $CT^{h}{}_{dry}$ is the CT value of the hole when the core sample is saturated with air or steam. If no water exists in the hole when the core sample is saturated with water, $CT^{h}{}_{dry}$ is equal to $CT^{h}{}_{wet}$. Using Eqs. 10 and 11, we can obtain:

$$(CT_{wet}^{o} - CT_{dry}^{o}) = \frac{A_m}{A_r}(CT_{wet}^{m} - CT_{dry}^{m}) \qquad (12)$$

Substituting Eq. 12 into Eq. 5:

$$f = \frac{A_m}{A_r}\frac{CT_{wet}^{m} - CT_{dry}^{m}}{CT_{water} - CT_{air}} \qquad (13)$$

Substituting Eq. 4 into Eq. 13:

$$f = \frac{A_m}{A_r} f_m \qquad (14)$$

Eq. 14 can also be expressed as follows:

$$f = \frac{r_o^2}{r_o^2 - r_i^2} f_m \qquad (15)$$

The inner radius r_i and the outer radius r_o are known. Therefore, the porosity of the core sample can be calculated using Eq. 15 once the average porosity is measured.

Using a similar procedure, we were able to prove that the water saturation in the annular part, S_w, is equal to the average water saturation, S_{wm}, in the whole area. Therefore, we could calculate water saturation in the core sample using Eq. 2 with all the CT values from the whole object.

EXPERIMENTS

Rock and Fluids. Distilled water was used as the liquid phase in this study; the specific gravity and viscosity were 1.0 and 1.0 cp at 20°C. Steam and air were used as the gas phase; the surface tension of water/air at 20°C was 72.75 dynes/cm. The values of the surface tension at high temperatures were calculated from the steam property software bought from Techware Engineering Applications, Inc. It was assumed, as usual, that there were no differences between the surface tension of water/air and that of water/steam. The ceramic sample was provided by Refractron Technologies Corp. It had a porosity of 39.19%, a length of 25.0 cm, an inner diameter of 4.275 cm and an outer diameter of 6.287 cm. We did not measure the permeability of the core sample yet due to its special shape but the permeability was estimated to be over 10 darcy.

X-ray CT Scanner. Distribution of water saturation in the core sample was measured along the height using a Picker™ Synerview X-ray CT scanner (Model 1200 SX) with 1200 fixed detectors. The voxel dimension was 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 was about 3 seconds while the processing time was around 40 seconds.

Experimental Apparatus. A schematic of the apparatus used to measure both steam-water and air-water capillary pressures is shown in Fig. 2. The core system was assembled in an aluminum cylinder wrapped in a heating belt; the temperature in the cylinder was controlled using an Autotune Temperature Controller (manufactured by OMEGA, Model CN6071A) by turning the heating belt on and off automatically. The power of the heating belt was about 750 w. Temperatures at both the top (in steam or air) and the bottom (in water) of the core were measured during the experiment. A simulation test was conducted before the entire system was assembled in the CT scanner in order to obtain uniform temperature distribution along the core. We wanted to have the temperature at the top, T_1, equal to that at the bottom, T_2 (See Fig. 2). This was realized by adjusting the spacing between two strips of the heating belt wrapped outside the aluminum cylinder.

The vacuum pump (Welch Technology, Inc., Model 8915) was used to remove the air in the core sample and in the aluminum cylinder in order to generate the steam-water environments. The cold trap with dry ice was employed to protect the steam from entering the vacuum pump to extend its life and reduce the frequency of replacing the pump oil.

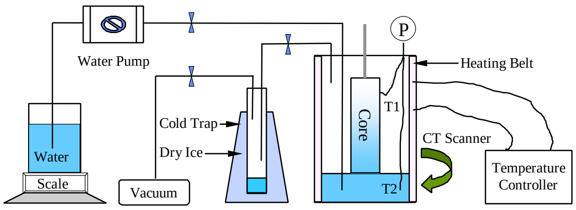

Fig. 2: Schematic of the apparatus of measuring steam- and air-water capillary pressure.

Water in the aluminum cylinder was delivered by the water pump (Dynamax, Model SD-200), manufactured by RAININ Instrument Co., and the amount was measured by the scale (Mettler, Model PE 1600) with an accuracy of 0.01g and a range from 0 to 1600g. Comparing the volume of the space under the bottom of the core, which was known, we could judge whether the water contacted the bottom of the core sample or not. This judgement was aided by the CT scanning near the bottom. We kept scanning from time to time and could know where the water level was by simply observing the CT image visually or checking the CT values in the annular space.

Procedure. The core sample was dried by heating to a temperature of 105°C until the weight did not vary during 8 hours or more. We conducted the spontaneous water imbibition into the air-saturated and upward-positioned core sample using the procedure of Li and Horne (2000b) at room temperature. An X-ray CT scan was made at each centimeter along the sample before and after the water imbibition. Then the core was dried again and saturated with water. Another X-ray CT scan was made after the saturation to obtain the values of CT_{wet}. We calculated the air-water capillary pressure in the core sample using these measurements.

The core sample was dried one more time and was assembled in the aluminum cylinder (see Fig. 2). The X-ray CT machine was set in the vertical mode. After that, the whole core system was installed into the X-ray CT machine. A series of X-ray CT scans from the bottom to the top of the core sample were made to obtain the values of CT_{dry} since these may be affected by the presence of the aluminum cylinder. After that, the temperature of the core system was increased to about 98°C. We scanned the core to obtain the values of CT_{dry} at 98°C about 10 hours later after the core was kept at this temperature. The main purpose of waiting 10 hours was to obtain a uniform temperature distribution. The core was evacuated to around 30 minitorr for about 4 hours to remove the air in the core after the hot scan. A certain amount of water was then introduced into the bottom of the aluminum cylinder using the water pump. The core then became saturated with steam. Water started to imbibe into the steam-saturated core once the bottom of the sample was brought into contact with the water surface that was raised by injection using the water pump. In order to monitor the distribution of water saturation in the core sample, we scanned the core from time to time until the spontaneous water imbibition was completed. Finally, the sample was dried again and the last X-ray CT scan was made after completely resaturating with water. The CT values measured under different states were used to calculate the porosity by Eqs. 4 and 15. Also calculated was the distribution of the water saturation as a function of height which was correlated to the capillary pressure using Eq. 1. We obtained the steam-water capillary pressure from these data.

RESULTS

A series of spontaneous water imbibition experiments were conducted respectively in steam- and air-saturated core sample to measure steam-water and air-water capillary pressures. Then the experimental results were compared in order to identify whether there were any differences between the two.

Fig. 3 shows the distribution of the CT values of the whole area with a radius of r_o (see Fig. 1) when the core sample was dry and saturated with water respectively. As shown in Fig. 3, the CT values of both the dry and wet core did not vary much along the height.

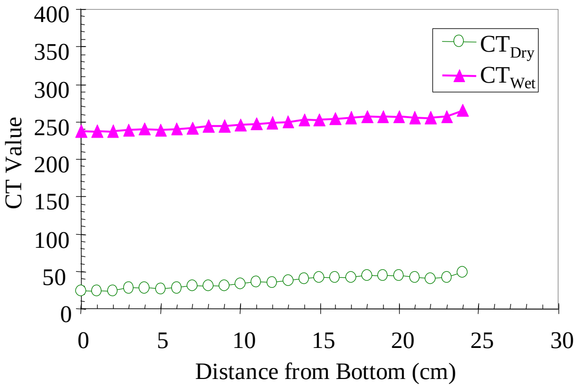

Fig. 3: Distribution of CT value in the core sample along height.

The porosity of the core sample was calculated using Eqs. 4 and 15, as shown in Fig. 4. The porosity distribution along the height of this ceramic core sample was homogeneous although we could observe some local heterogeneity in the CT images. The average porosity from Fig. 3 was 39.61%. The porosity measured by weighing the core sample before and after saturating with water was 39.19%, which was in good agreement. The average porosity of the core sample (including the hole) calculated using Eq. 3 is also shown in Fig. 4; as expected, it is much smaller than those values of the actual porosity.

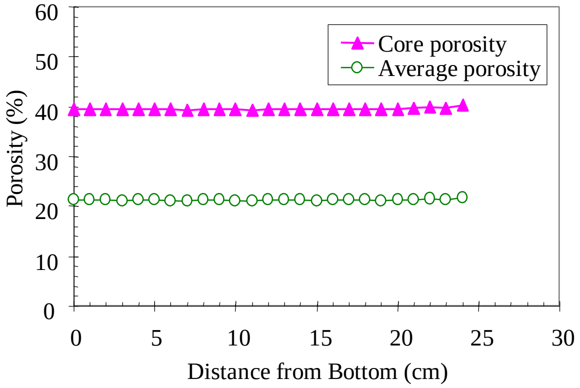

Fig. 4: Porosity distribution of the core sample by the X-ray CT method.

Using the image manipulation tools provided in the X-ray CT machine, we could measure the CT value of a local area of any size in the CT image. We measured the CT values of four small circular areas (top, bottom, left, and right sides) in the annular solid rock part of the core sample between r_o and r_i at different states. The diameter of the circular area was a little less than r_o - r_i. Then we calculated the mean values of the CT numbers from the four different areas for each state (dry, wet, and after water imbibition). The calculated results of the core sample before and after the spontaneous water imbibition, including those when the core was saturated completely with water, are shown in Fig. 5.

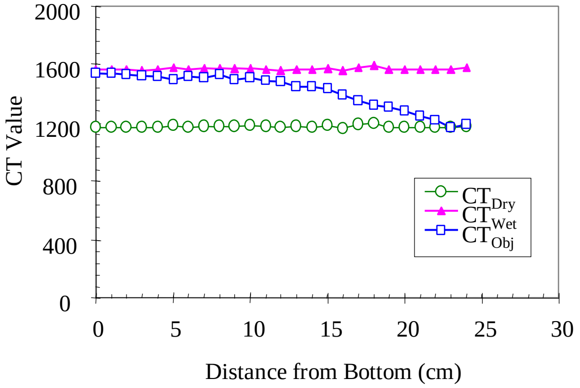

Fig. 5: CT distribution before and after water imbibition in the air-saturated core (including those for complete saturation with water).

Obviously, the values of CT_{dry} and CT_{wet} shown in Fig. 5 are different from those in Fig. 3. This is because the calculated CT numbers using this method are the real CT values of the rock part instead of those (in Fig. 3) including the hollow part in the center. With the CT values shown in Fig. 5, we also calculated the porosity of the core sample by using Eq. 3 directly instead of Eq. 15. The average porosity calculated using the data shown in Fig. 5 is also 39.61%, the same as that in Fig. 4. This confirms the validity of calculating porosity using Eq. 15. The method of measuring average CT values as shown in Fig. 5 is much more time-consuming than measuring those shown in Fig. 3. Therefore, for all the rest of calculation, we only measured the CT values for the whole area with a radius of r_o (see Fig. 1) to compute porosity and saturation in the core sample.

Using the data presented in Fig. 5, the air-water capillary pressure of the core sample at a temperature of 21°C was calculated and is plotted in Fig. 6. The unit of the capillary pressure in this paper is centimeter water column.

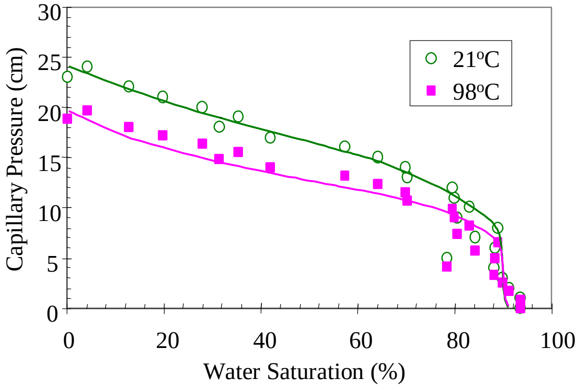

Fig. 6: Air-water capillary pressure curves.

Steam-water capillary pressure was measured at a temperature of 98°C and a pressure lower than atmospheric. Therefore we needed to scale the air-water capillary pressure data at 21°C to 98°C in order to compare steam-water and air-water capillary pressure curves at the same temperature. Assuming that there is no effect of temperature on the wettability or contact angle of the air-water-rock system, the air-water capillary pressure at a temperature of T_2 can be calculated from that at a temperature of T_1 using the following equation (Li and Horne, 2000c):

$$P_c^{T_2}(S_w)=\frac{\sigma_{T_2}}{\sigma_{T_1}}P_c^{T_1}(S_w) \tag{16}$$

where $P_c^{T_1}(S_w)$ and $P_c^{T_2}(S_w)$ are the air-water capillary pressures at the same water saturation S_w but at different temperatures T_1 and T_2 while σ_{T_1} and σ_{T_2} are the surface tensions at temperatures T_1 and T_2 respectively. The air-water capillary pressures at a temperature of 98°C calculated using Eq. 16 are shown in Fig. 6 and were used to compare to the steam-water capillary pressures.

After completing the air-water capillary pressure measurements, we conducted the spontaneous water imbibition into the steam-saturated core sample at a temperature of about 98°C. We measured the distribution of the water saturation along the height from time to time after starting the spontaneous water imbibition. The relationships between the height and the water saturation at different time of water imbibition are shown in Fig. 7. It can be seen that the water imbibition stopped by about 24 hours. This implies that the capillary and gravity forces were in equilibrium by that time. The steam-water capillary pressures were calculated according to the force balance (considering the height as the capillary pressure).

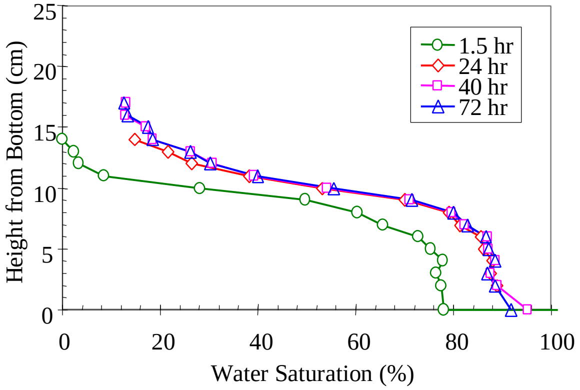

Fig. 7: Distribution of water saturation in the core at different time at a temperature of 98°C.

The calculated steam-water capillary pressure at 98°C is plotted in Fig. 8. Air-water capillary pressure previously scaled to the same temperature is also shown in Fig. 8 for comparison. The results demonstrate that steam-water capillary pressure in the ceramic core is about 3 cm water column less than the air-water capillary pressure at the same water saturation in the range from 20 to 85 percent.

Horne *et al.* (2000) found that both steam and water relative permeabilities of steam-water flow were greater than gas (nitrogen) and water relative permeabilities of gas-water flow in a Berea sandstone sample. In this study, it was found that steam-water capillary pressure was less than air-water capillary pressure. In summarizing this, we could probably conclude that the greater the capillary pressure, the smaller the gas and liquid relative permeabilities. Is this true? This is a complicated question to be answered. Li and Firoozabadi (2000a) reported that the effects of surface tension and wettability on gas-condensate relative permeabilities using a network modeling technique. They found that the greater the surface tension, the smaller both the gas and condensate relative permeabilities; the greater the contact angle through liquid phase in a range from zero to 90 degree, the greater the gas and condensate relative permeabilities. The later result was observed experimentally to some extent by Li and Firoozabadi (2000b). Although steam-water and air-water systems are much different from gas-condensate systems, the effect of capillary pressure on relative permeability might be general.

Considering capillary pressure as a function of surface tension and wettability ($P_c = 2\sigma\cos\theta/r$ in a circular capillary tube), we could conclude from the study of Li and Firoozabadi (2000a) that the greater the capillary pressure, the smaller the gas and condensate relative permeabilities. This conclusion would be consistent with the experimental results in this study and the study by Horne *et al.* (2000) regarding the differences between steam-water and air-water capillary pressures as well between steam-water and air-water (or nitrogen-water) relative permeabilities. Obviously, further research will be required on this issue.

The differences between the steam-water and air-water capillary pressures are significant considering the high permeability of the core sample used in this study. According to the experimental results shown in Fig. 8, we would not be able to substitute steam-water capillary pressures simply using air-water capillary pressure measurements.

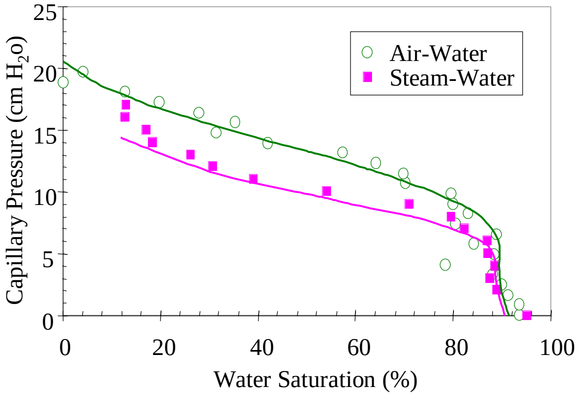

Fig. 8: Comparison of steam-water and air-water capillary pressures at a temperature of 98°C.

Another phenomenon shown in Fig. 8 is that there are almost no differences between the residual steam saturation and the residual air saturation. Horne *et al.* (2000) observed that the residual steam saturation was less than the residual nitrogen saturation in Berea sandstone with a permeability of about 1400 md, which was much lower than the permeability of the ceramic core in this study. We may also need more research on this issue.

DISCUSSION

Few reports could be found regarding the direct comparison between steam-water and air-water capillary pressures, which may be because of the lack of a method that could be used to measure both in the same core sample. This was one of the primary objectives of this study: to develop such a technique.

However, the experimental results presented in this paper are preliminary due to some experimental limitation. For example, the air-water capillary pressures used to compare to the steam-water capillary pressures were measured at room temperature instead of the temperature of 98^oC at which steam-water capillary pressures were measured.

In order to confirm the phenomenon we observed in Fig. 8, we are planning to conduct water drainage tests in the same core at the same temperature but under different conditions (steam- and air-saturated respectively). In doing this we will obtain drainage steam-water and air-water capillary pressures. Then we will be able to compare the two after removing the assumption that there is no effect of temperature on the wettability of the air-water-rock systems. Through the comparison, we will see if the drainage steam-water capillary pressures would be less than the drainage air-water capillary pressures as expected from the experimental results presented here.

We are also planning to change the way of scanning the core sample from the vertical mode to the horizontal mode. The core sample will be still positioned vertically but the X-ray CT scanner will be positioned horizontally. By doing so, we will be able to obtain the whole water saturation profile (the relationship between the water saturation and the height) through just one scanning. Therefore, we will be able to monitor the process of the spontaneous water imbibition into the core sample in a better way. Scanning a rectangular object in this way may be subject to image artifacts.

On the other hand, it would be helpful to conduct theoretical analysis of the differences between steam-water and air-water capillary pressures. For example, why is the steam-water capillary pressure different from the air-water capillary pressure in porous media from the point of view of thermodynamics? The answer to this question would provide guidance to the design of the future experimental study.

CONCLUSIONS

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

1. A direct method available to measure both steam-water and air-water capillary pressures in porous media has been developed based on an X-ray CT technique.
2. Imbibition steam-water capillary pressure in the ceramic core sample studied is less than the imbibition air-water capillary pressure at the same water saturation. The differences between the two are significant.
3. The experimental results in this study show that we would not be able to infer steam-water flow measurements simply using air-water experiments.

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NOMENCLATURE

A_h = cross section area of the hollow part in the core sample
A_m = entire cross section area of the core sample
A_r = cross section area of the annular part between r_o and r_i
CT_{air} = CT number of air or steam
CT_{dry} = CT number of a core sample when it is fully saturated with air or steam
CT_{water} = CT number of water
CT_{wet} = CT number of a core sample when it is fully saturated with water
CT^m_{dry} = average CT value of the whole area with a radius of r_o when the sample is saturated with air
CT^o_{dry} = average CT value of the annular area between r_o and r_i when the sample is saturated with air
CT^h_{wet} = CT value of the hole when the core sample is saturated with water
CT^m_{wet} = average CT value of the whole area with a radius of r_o when the sample is saturated with water
CT^o_{wet} = average CT value of the annular area between r_o and r_i when the sample is saturated with water

CT_{exp} = CT number of a core sample when it is saturated with both water and air or steam
CT_i = CT value of component i
g = gravity constant
h = height
n = number of component
P_c = capillary pressure in a circular capillary tube
P_{ci} = steam-water or air-water capillary pressure
P_c^{T1} = air-water capillary pressure at T_1
P_c^{T2} = air-water capillary pressure at T_2
r = radius of a circular capillary tube
r_i = inner radius of the core sample
r_o = out radius of the core sample
S_w = water saturation
T = temperature
V_i = volumetric fraction of component i.
f = porosity
f^m = mean porosity
r = density
Dr = density difference between water and steam or air
m = linear absorption coefficient
m_i = linear absorption coefficient of component i
m_m = mass absorption coefficient
m_w = linear absorption coefficient of pure water
σ = surface tension
s_{T_1} = surface tension at a temperature of T_1
s_{T_2} = surface tension at a temperature of T_2

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