PROCEEDINGS, Twenty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 28-30, 2002
SGP-TR-171

WETTABILITY DETERMINATION OF GEOTHERMAL SYSTEMS

Kewen Li and Roland N. Horne

Stanford Geothermal Program, Stanford University
Stanford, CA 94305-2220
e-mail: kewenli@stanford.edu horne@stanford.edu

ABSTRACT

A method has been developed to infer the wettability of steam-water-rock systems based on the relationship between permeability and capillary pressure by Purcell. The Purcell model was extended to two-phase flow to verify whether the wettability is a function of water saturation. The results calculated using the experimental data showed that the wettability index in the drainage process was greater than that in the imbibition. The corresponding contact angle in drainage was smaller than that in imbibition, which is realistic and consistent with the existing experimental results in capillary tubes. Both the receding (drainage) and advancing (imbibition) contact angles in steam-water-rock systems were reasonably independent of water saturation ranging from about 25 to 85%. It was also found that the wettability model could be reduced to the model reported by Slobod and Blum (1952) in specific cases. The method developed in this study to estimate wettability of steam-water-rock systems could be applied directly to other gas-liquid-rock and liquid-liquid-rock systems.

INTRODUCTION

Gas-liquid-rock systems are usually considered to be strongly liquid-wet, which is true in most natural fluid-rock systems. It is also often assumed that the contact angle through the liquid phase is zero in gas-liquid-rock systems (Slobod and Blum, 1952), which may not be true. Li and Firoozabadi (2000) discussed the phenomena of nonzero contact angle in more detail. The wettability in different gas-liquid-rock (or other porous media) systems may not be the same. For example, the intrinsic contact angle of water against air on smooth PTFE (Teflon) measured by Morrow and McCaffery (1978) was 108^o while the contact angles in most natural gas-liquid-rock systems are much smaller, as is already known. Al-Siyabi *et al.* (1997) measured the gas-oil contact angles of four binary mixtures (C_1/nC_4, C_1/nC_8, C_1/nC_{10}, and C_1/nC_{14},) at reservoir conditions. Their results showed that the gas-oil contact angles were about 20^o.

Li and Horne (2001a) found significant differences between steam-water and air-water capillary pressures, and Horne *et al.* (2000) found significant differences between steam-water and air-water relative permeabilities. We therefore speculated that there might be differences of wettability in different gas-liquid-rock systems such as steam-water-rock and air-water-rock systems.

Slobod and Blum (1952) developed a method to evaluate the wettability of reservoir rocks from the threshold capillary pressures measured in oil-water-rock and air-oil-rock systems respectively. However the semiquantitative method was based on the assumption that the contact angle through the liquid phase in gas-liquid-rock systems is zero. Hence this method would not be suitable for the wettability determination in many gas-liquid-rock systems.

Purcell (1949) developed a model to correlate the rock permeability and the pore size distribution that could be inferred from capillary pressure curves measured by the technique of mercury injection. According to this relationship, we developed a quantitative method to calculate the wettability index or apparent contact angle in steam-water-rock systems from the data of steam-water capillary pressure. This method was also extended to two-phase flow to verify whether the wettability is a function of fluid saturation. In this case, both capillary pressure and relative permeability data are required to calculate the wettability index at different values of water saturation.

Using the experimental data of capillary pressure and relative permeability measured simultaneously in the same rock at the same temperature of about 120^oC, the values of the wettability index in both the drainage and the imbibition processes in steam-water-Berea systems were calculated and compared. Some other published experimental data of oil-water flow were also used to conduct the calculation and the comparison in order to further confirm the phenomena observed in steam-water systems.

METHOD

The method to determine the wettability of gas-water rock systems is derived in this section. Using Poiseuille's equation and Darcy's Law, Purcell (1949) derived a relationship between the rock permeability and the capillary pressure curve as follows:

$$k = F\phi(\sigma\cos\theta)^2\int_0^1 \frac{dS_w}{P_c^2} \qquad (1)$$

where k and ϕ are the absolute permeability and porosity of the rock; F is the so-called lithology factor. σ and θ are the interfacial tension between the two fluids and the contact angle through the liquid phase; P_c and S_w are the capillary pressure and the saturation of the wetting phase.

To calculate the rock permeability using Eq. 1, it is convenient to have a mathematical representation for the capillary pressure curve. Brooks and Corey (1966) suggested a function to represent capillary pressure curves in porous media as follows:

$$P_c = p_e(S_w^*)^{-1/\lambda} \qquad (2)$$

where p_e is the entry capillary pressure and λ is the pore size distribution index; S_w^* is the normalized wetting phase saturation. For the drainage process, it is expressed as follows:

$$S_w^* = \frac{S_w - S_{wr}}{1 - S_{wr}} \qquad (3)$$

where S_{wr} is the residual saturation of the wetting phase, representing the residual water saturation in this study.

Although the capillary pressure function (see Eq. 2) suggested by Brooks and Corey (1966) was originally for the drainage cases instead of imbibition cases, in this study it was used to calculate the wettability index in the imbibition by defining the normalized wetting phase saturation as follows:

$$S_w^* = \frac{S_w - S_{wr}}{1 - S_{wr} - S_{nwr}} \qquad (4)$$

where S_{nwr} is the residual saturation of the nonwetting phase, representing the residual steam saturation in this study.

Substituting Eq. 2 into Eq. 1 to obtain the rock permeability by using the capillary pressure data:

$$k = F\phi(\frac{\sigma\cos\theta}{P_e})^2\frac{\lambda}{\lambda+2} \qquad (5)$$

The wettability index W_i was defined as $\cos\theta$ and from Eq. 5, it can be calculated as follows:

$$W_i = \cos\theta = \sqrt{(\frac{\lambda+2}{\lambda})(\frac{k}{F\phi})}\,\frac{P_e}{\sigma} \qquad (6)$$

The only unknown parameter in Eq. 6 is the lithology factor, F, once the capillary pressure curve is available. Purcell (1949) measured the values of the lithology factor for numerous rock samples by means of comparing the air permeability to the permeability calculated using Eq. 1. The capillary pressure curves were measured by the technique of mercury injection. The lithology factor ranged from 0.08 to 0.36 and was found to be smaller in lower permeability rocks (Purcell, 1949).

The contact angle through the liquid phase can also be calculated from Eq. 6 once the capillary pressure curve and the lithology factor are known. Note that the contact angle calculated in such a way may be different from that defined in a capillary tube or on a flat solid surface. Actually, this value may represent the macroscopic average contact angle of the fluid-rock system. Such a contact angle may be named as an apparent contact angle for the sake of convenience.

Assuming that Eq. 1 applies in two-phase flow, it is written as follows:

$$k_w = F\phi(\sigma\cos\theta_w)^2\int_0^{S_w}\frac{dS_w}{P_c^2} \qquad (7)$$

where k_w and θ_w are the effective permeability of the wetting phase and the contact angle through the wetting phase. Because F is a parameter representing lithology, it was assumed in this study that it does not vary with the saturation of the wetting phase.

Substituting Eq. 2 into Eq. 7, the following equation is obtained:

$$W_{iw} = \sqrt{(\frac{\lambda+2}{\lambda})(\frac{k_w}{FS_w^*\phi})}\,\frac{P_c}{\sigma} \qquad (8)$$

where W_{iw} is the wettability index, defined as $\cos\theta_w$, at the wetting phase saturation of S_w. The effective permeability of the wetting phase and the capillary pressure in Eq. 8 are a function of the wetting phase saturation. In terms of relative permeability, Eq. 8 can also be expressed as follows:

$$W_{iw} = \sqrt{(\frac{\lambda+2}{\lambda})(\frac{k}{F\phi})(\frac{k_{rw}}{S_w^*})}\frac{P_c}{\sigma} \qquad (9)$$

where k_{rw} is the relative permeability of the wetting phase. According to Eq. 9, the wettability of gas-liquid-rock systems at any water saturation could be determined once the experimental data of the capillary pressure and the relative permeability are available.

We can see from the process of the derivation of Eq. 9 that the method could be used to determine the wettability in either gas-liquid-rock or liquid-liquid-rock systems. This is because there are no special restrictions or assumptions assigned to a specific system during the derivation.

It can be seen from Eq. 9 that if the wettability of a fluid-rock system does not change with the fluid saturation, as it is usually assumed, then $\sqrt{(\frac{k_{rw}}{S_w^*})}P_c$ should be constant. This may be verified by using the data from the simultaneous measurements of capillary pressure and relative permeability curves. The experimental confirmation will be discussed later in more detail.

Another important significance of Eq. 9 is that it may be possible to determine the wettability of steam-water-rock systems by using the data from a simple spontaneous water imbibition experiment. Because the relative permeability and the capillary pressure at a specific water saturation can be calculated simultaneously from one single spontaneous water imbibition test according to the method developed by Li and Horne (2000a), the wettabiblity index could be obtained using Eq. 9. Therefore, we may obtain the wettability information without measuring the whole capillary pressure curve if the wettability does not vary with the water saturation.

The rock property factors, including the pore size distribution index λ, the permeability k, the porosity ϕ, and the lithology factor F, may be reduced when Eq. 9 is used to compare the wettability differences between two different fluid pairs such as air-water and steam-water (in the same rock). The ratio of the wettability index of fluid pair 1 to fluid pair 2 at the same water saturation and in the same rock can be obtained from Eq. 9 as follows:

$$\frac{W_{iw}^1}{W_{iw}^2} = \frac{k_{rw}^1}{k_{rw}^2}\frac{P_c^1}{P_c^2}\frac{\sigma^2}{\sigma^1} \qquad (10)$$

where W_{iw}^n, k_{rw}^n, P_c^n, and σ^n (n=1, 2) are the wettability index, the relative permeability of the wetting phase, the capillary pressure, and the interfacial tension in fluid pair n (=1, 2) respectively. It is only necessary to obtain the capillary pressure and the relative permeability data in order to compare the wettability in two different fluid systems.

Eq. 10 could be reduced to the form of the Slobod and Blum (1952) model, which is expressed in Eq. 11, if the relative permeabilities of the wetting phase in the two fluid pairs are equal.

$$W_r = \frac{W_{iw}^1}{W_{iw}^2} = \frac{P_c^1}{P_c^2}\frac{\sigma^2}{\sigma^1} \qquad (11)$$

where W_r is the ratio of the wettability index of fluid pair 1 to fluid pair 2. As stated previously, it was assumed that the contact angle through the liquid phase in the gas-liquid-rock system was zero in the Slobod and Blum model (1952). Hence W_{iw}^2 (representing wettability index of the gas-liquid fluid pair) is equal to one in this case. Note that the relative permeabilities of the wetting phase measured using two different fluid pairs may not be always equal.

EXPERIMENTS

Experimental data of relative permeability and capillary pressure measured simultaneously in the same rock and at the same temperature have been rare in the literature, especially for steam-water flow. Mahiya (1999) and Li and Horne (2000b) reported such a set of data for steam-water flow in Berea sandstone. These experimental data of steam-water relative permeability and capillary pressure were used in this study to determine the wettability of such a geothermal system.

The experimental apparatus test procedures, and the properties of the rock and fluid samples, were described by Mahiya (1999) and Li and Horne (2000b). For convenience, a brief summary of the steam-water flow tests is given 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 from the steam property software from Techware Engineering Applications, Inc., based on the measured values of pressure and temperature. The surface tension of vapor/water at 20^{o}C was 72.75 dynes/cm. A Berea sandstone sample fired at a temperature 450^{o}C was used; its permeability and porosity were 1400 md and 24.8%; the length and diameter were 43.2 cm and 5.04 cm, respectively.

RESULTS

As stated previously, the method developed in this study to determine the wettability of gas-liquid-rock systems could also be used in oil-water-rock systems.

To verify the method we developed, the experimental data of relative permeability and capillary pressure of oil-water flow in porous media from Kleppe and Morse (1974) were used to calculate the wettability indices at different water saturations. We could also verify if the wettability varies with the fluid satruation. The imbibition oil-water capillary pressure data from Kleppe and Morse (1974) are shown in Fig. 1 in log-log coordinates to obtain the value of the pore size distribution index λ.

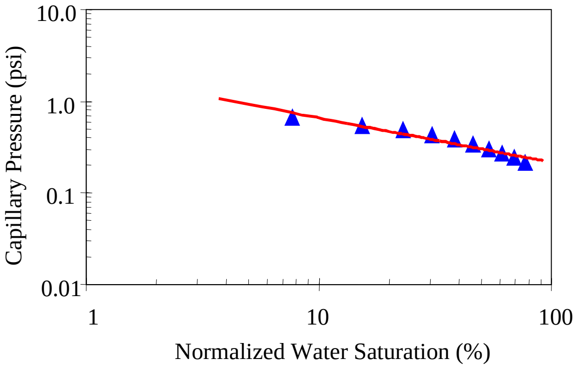

Figure 1: Imbibition oil-water capillary pressure data from Kleppe and Morse (1974).

The capillary pressure data shown in Fig. 1 were measured in a Berea sandstone sample by water injection. The porosity and permeability of the core sample were 22.5% and 290 md respectively. The oil phase was kerosene. We can see from Fig. 1 that the relationship between the capillary pressure and the normalized water phase saturation is linear. So the relationship could be represented by Eq. 2 suggested by Brooks and Corey (1966). The value of the pore size distribution index λ that we obtained was about 2.06. This value is reasonable according to the study of Brooks and Corey (1966).

Because the value of the lithology factor is unknown for this rock sample, both the minimum and maximum values determined by Purcell (1949) were used in the calculation of the wettability index. The calculated results may show whether the effect of the lithology factor on the wettability index is significant or not.

The values of the lithology factor determined by Purcell (1949), as previously described, ranged from 0.08 to 0.36 for the rock samples with permeability ranging from 3 to 1500 md. The permeability of the rock sample used by Kleppe and Morse (1974) was about 290 md which was within this range. The wettability indices and the corresponding contact angles in the oil-water-rock system studied by Kleppe and Morse (1974) were calculated using the method developed in this work (see Eq. 6) and the results are listed in Table 1.

Table 1: Results of Wettability Index and Contact Angle Using Different Values of the Lithology Factor F.

F (Lithology Factor)	W_i (Wettability Index)	θ (Contact Angle)
0.08	0.12	83.1
0.36	0.06	86.8

The calculated results in Table 1 demonstrate that the effect of the lithology factor on the contact angle is not very significant in this case. Therefore the minimum value, 0.08, of the lithology factor determined by Purcell (1949) was used in the rest of the calculations in this study. Note that the effect of the lithology factor on the contact angle may be significant at some specific cases.

It can also be seen from Table 1 that the oil-water-rock (Berea sandstone) system is water-wet, which is consistent with the actual wettability. The significance of the value of the wettability index in Table 1 may not be exactly the same as those of the wettability index obtained by the Amott (1959) and the USBM (Donaldson *et al.*, 1969) methods. However, it is certain that the closer the value of the wettability index to 1.0, the stronger the wettability of the liquid phase.

To calculate the wettability index using Eq. 9 with two-phase flow data, it is necessary to have the corresponding relative permeability data. The imbibition oil-water relative permeability data from Kleppe and Morse (1974) are shown in Fig. 2

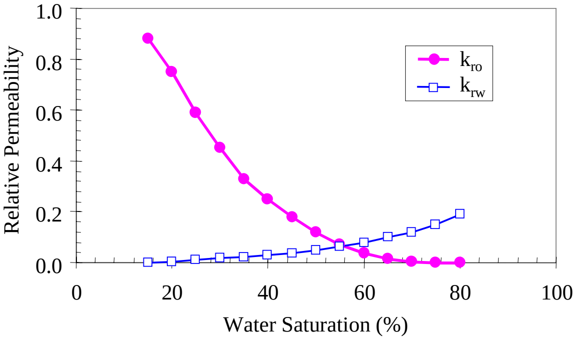

Figure 2: Imbibition oil-water relative permeability data from Kleppe and Morse (1974).

Even though it is usually assumed that the wettability does not vary with water saturation, there are few experimental data available to verify this assumption due to the scarcity of methods to evaluate the wettability at specific values of water saturation. For this purpose, the values of the wettability index and the corresponding contact angle at different water saturations were calculated using Eq. 9 with the measured data of the oil-water capillary pressure and the relative permeability from Kleppe and Morse (1974). The calculated results are plotted in Fig. 3.

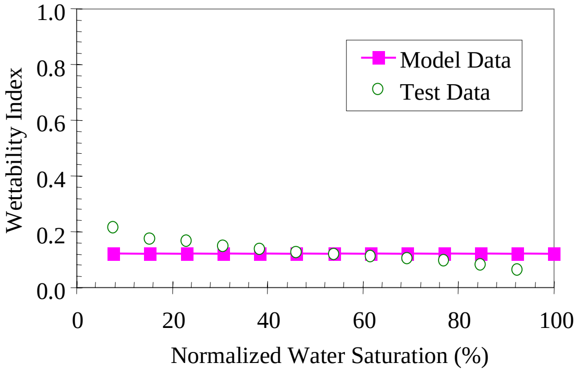

Figure 3: Wettability index calculated using the data of relative permeability and capillary pressure from Kleppe and Morse (1974).

The "model data" shown in Fig. 3 were calculated using the data of the capillary pressure and the relative permeability from modeling. In this study, the capillary pressure data were calculated using Eq. 2 and the relative permeability data were computed using the Purcell model, which is expressed as follows:

$$k_{rw} = (S_w^*)^{\frac{2+\lambda}{\lambda}} \tag{12}$$

The reason we used the Purcell model was that Li and Horne (2001b) found it the best fit to the wetting phase relative permeability.

It can be seen from Fig. 3 that the wettability index does not vary significantly with the water saturation and is very close to the model data. The wettability index calculated using the modeling capillary pressure and the relative permeability data is equal to that calculated using Eq. 6 (in which only capillary pressure data were used).

The calculated results of the corresponding contact angle are shown in Fig. 4. Accordingly, the contact angles calculated at different water saturation are almost constant and close to the model results. This implies that we may be able to determine the wettability index or the apparent contact angle using the relative permeability and the capillary pressure at only one point of specific water saturation instead of over the whole range of the curve. This is interesting because Li and Horne (2000a) reported that the relative permeability of the wetting phase and the capillary pressure at specific water saturation could be calculated simultaneously from spontaneous water imbibition tests in gas-saturated rocks.

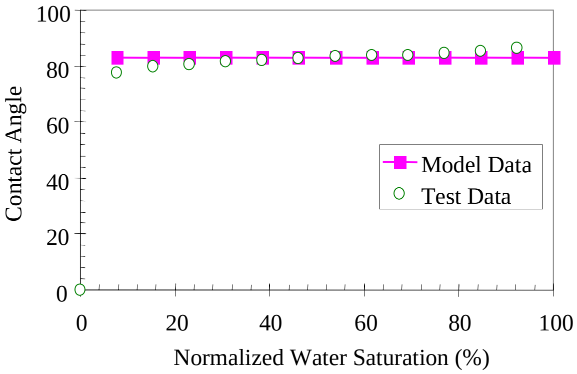

Figure 4: Apparent contact angle calculated using the data of relative permeability and capillary pressure from Kleppe and Morse (1974).

Now we will discuss the calculations of the wettability index in steam-water-rock systems. The steam-water capillary pressure curves from Li and Horne (2000b) were used. Both the drainage and the imbibition capillary pressure curves are plotted in Fig. 5 in log-log coordinates to obtain the values of the pore size distribution index λ for the calculations using Eq. 6 or Eq. 9. These data were measured in a fired Berea sandstone sample at a temperature of about 120°C using a steady-state flow method. The values of λ in the drainage and the imbibition cases were 0.543 and 0.715 respectively.

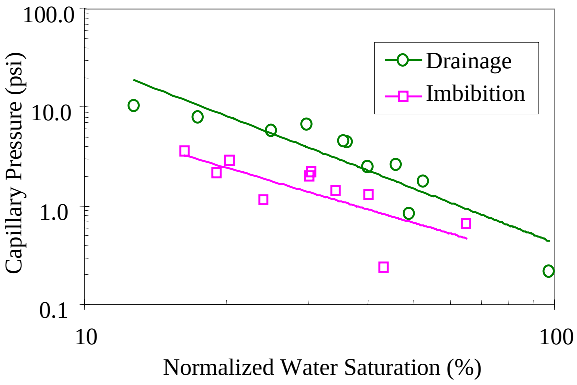

Figure 5: Drainage and imbibition steam-water capillary pressure data from Li and Horne (2000b).

The experimental data of the steam-water relative permeability from Mahiya (1999) are plotted in Fig. 6. These data were measured simultaneously along with the capillary pressure shown in Fig. 5. The relative permeabilities of the water phase in the drainage and the imbibition processes are closely similar. The two solid lines in Fig. 6 are regression curves for the drainage process. Note that the steam relative permeability data shown in Fig. 6 have been calibrated under the consideration of gas slip effect

(Klinkenberg Effect) in two-phase flow measured by Li and Horne (2001c).

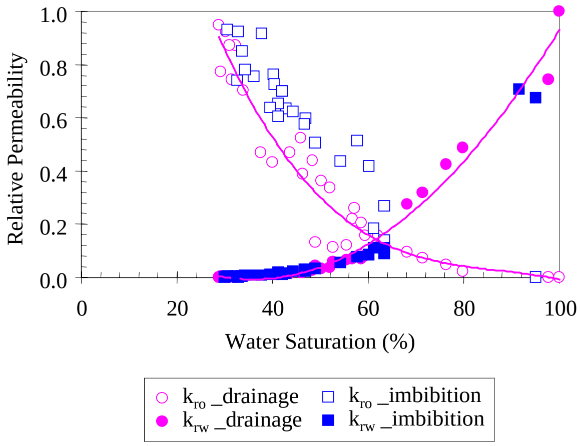

Figure 6: Steam-water relative permeability data from Mahiya (1999).

Fig. 7 shows the values of the wettability index calculated using Eq. 9 with the model data of the steam-water capillary pressure and the relative permeability representing the experimental data from Li and Horne (2000b) and Mahiya (1999). The results calculated directly using the measured data are not plotted in Fig. 7 because several values of the wettability index are greater than 1.0, which is not reasonable. The reason may be due to the scattering in the steam-water capillary pressure data. It takes a long time to conduct steady-state steam-water flow tests in porous media and it is very difficulty to keep the steam-water flow in constant adiabatic environment for such a long time.

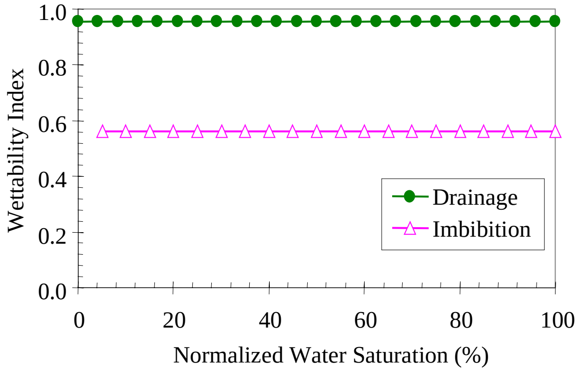

Figure 7: Wettability indices calculated using the experimental data from Li and Horne (2000b) and Mahiya (1999).

We can see from Fig. 7 that the wettability index in the imbibition process is less than that in the drainage, which is theoretically correct and has been proven experimentally by Morrow and McCaffery (1978). The ratio of the wettability index in the imbibition process to that in the drainage is about 0.59.

The values of the corresponding apparent contact angle were calculated using the wettability index data from Fig. 7 and the results are shown in Fig. 8.

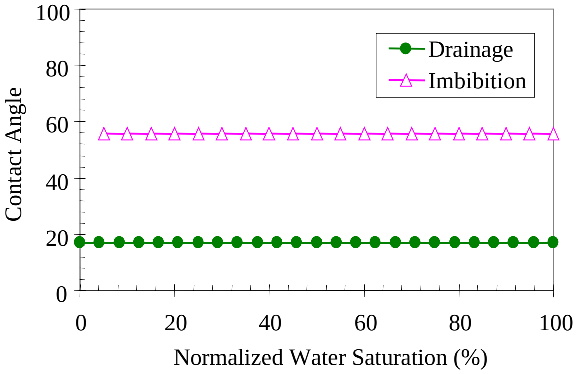

Figure 8: Apparent contact angle calculated using the experimental data from Li and Horne (2000b) and Mahiya (1999).

The apparent contact angle related to the drainage process is usually referred to as the receding contact angle and that related to the imbibition process as the advancing contact angle. As expected, Fig. 8 shows that the receding contact angle is smaller than the advancing contact angle.

Comparing the values of the wettability index in Fig. 7 to those in Fig. 3, we found that the wettability indices (W_i=0.96 for drainage and 0.56 for imbibition) in steam-water-rock systems are much greater than that (W_i=0.12) in oil-water-rock systems as expected. This observation demonstrates that the method developed in this study to determine the wettability of steam-water-rock systems would be useful. An important feature of this method is that it is not only appropriate for liquid-liquid-rock systems but also for gas-liquid-rock systems.

DISCUSSION

Using the method developed here, we demonstrated that the steam-water-rock system is much more water-wet than the oil-water-rock system, as expected. The apparent contact angle in the drainage process is much smaller than that in imbibition, which is reasonable and consistent with the existing experimental results. One fundamental concern in the study of geothermal fluid flow is the wettability difference between the steam-water-rock and air-water-rock systems. It is possible to determine the wettability difference between the two systems once the corresponding experimental data are available. These data include the capillary pressure of both the steam-water and the air-water flow in the same rock and at the same temperature. The experimental data of relative permeability in both steam-water and air-water flow would also be useful. Unfortunately such data have been very few.

The significance of the method that we developed to determine the wettability is the ability to compare the wettability difference between any two systems, either gas-liquid-rock or liquid-liquid-rocks.

CONCLUSIONS

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

1. A method was developed to determine the wettability of steam-water-rock systems using the data from experimental measurements of steam-water capillary pressure and relative permeability.
2. The method is appropriate to determine the wettability of the gas-liquid-rock systems as well as the liquid-liquid-rock systems.
3. It is possible to determine the wettability at any specific water saturation by using the method developed in this study although we verified that the wettability would not change with water saturation in the cases studied.
4. The wettability index calculated using the method in the imbibition case is smaller than that in the drainage, which has been proven experimentally.
5. The values of the wettability index in the gas-liquid-rock systems are much greater than that in oil-water-rock systems, which is reasonable and consistent with existing observations.

ACKNOWLEDGEMENTS

This research was conducted with financial support to the Stanford Geothermal Program from the Geothermal and Wind division of the US Department of Energy under grant DE-FG07-99ID13763, the contribution of which is gratefully acknowledged.

NOMENCLATURE

F = lithology factor
k = absolute permeability
k_w = effective permeability of the wetting phase
k_{rw} = relative permeability of the wetting phase
k_{rw}^n = relative permeability of the wetting phase in fluid pair *n* (=1, 2)
P_c = capillary pressure
P_c^n = capillary pressure in fluid pair *n* (=1, 2)
P_e = entry capillary pressure
S_{nwr} = residual saturation of the nonwetting phase
S_w = water saturation
S_{wr} = residual water saturation
S_w^* = normalized water saturation
W_i = wettability index
W_{iw} = wettability index at the wetting phase saturation of S_w
W_{iw}^n = wettability index in fluid pair *n* (=1, 2)
W_r = ratio of the wettability index of fluid pair 1 to fluid pair 2
ϕ = porosity
λ = pore size distribution index
θ = apparent contact angle through liquid phase
θ_w = apparent contact angle through water phase at the water saturation of S_w
σ = interfacial tension
σ^n = interfacial tension in fluid pair *n* (=1, 2)

REFERENCES

Al-Siyabi, Z.K., Danesh, A., Tohidi, B., and Todd, A.C.: “Measurement of Gas-Oil Contact Angle at Reservoir Conditions,” Proceedings of 1997 European Symposium on Improved Oil Recovery, The Hague, The Netherlands, Oct. 20-22.

Amott, E.: "Observations Relating to the Wettability of Porous Rock," *Trans. AIME*, (1959), **216**, 156.

Brooks, R. H. and Corey, A. T.: "Properties of Porous Media Affecting Fluid Flow", *J. Irrig. Drain. Div*., (1966), **6**, 61.

Donaldson, E.C., Thomas, R.D., and Lorenz, P.B.: "Wettability Determination and Its Effect on Recovery Efficiency," SPEJ (March 1969), 13-20.

Horne, R.N., Satik, C., Mahiya, G., Li, K., Ambusso, W., Tovar, R., Wang, C., and Nassori, H.: “Steam-Water Relative Permeability,” presented at World Geothermal Congress, Kyushu-Tohoku, Japan, May 28-June 10, 2000.

Kleppe, J. and Morse, R. A.: "Oil Production from Fractured Reservoirs by Water Displacement," SPE 5084, presented at the 1974 SPE Annual Technical Conference and Exhibition, Houston, TX, USA, October 6-9, 1974.

Li, K. and Firoozabadi, A.: “Experimental Study of Wettability Alteration to Preferential Gas-Wetness in Porous Media and its Effect,” *SPEREE* (April 2000), 139-149.

Li, K. and Horne, R. N. (2000a): “Characterization of Spontaneous Water Imbibition into Gas-Saturated Rocks,” SPE 62552, presented at the 2000

SPE/AAPG Western Regional Meeting, Long Beach, California, June 19–23, 2000

Li, K. and Horne, R.N. (2000b): “Steam-Water Capillary Pressure,” SPE 63224, presented at the 2000 SPE Annual Technical Conference and Exhibition, Dallas, TX, USA, October 1-4, 2000.

Li, K. and Horne, R.N. (2001a): “An Experimental Method of Measuring Steam-Water and Air-Water Capillary Pressures,” paper 2001-84, presented at the Petroleum Society’s Canadian International Petroleum Conference 2001, Calgary, Alberta, Canada, June 12–14, 2001.

Li, K. and Horne, R.N. (2001b): “Steam-Water Relative Permeability by the Capillary Pressure Method,” proceedings of the International Symposium of the Society of Core Analysts, Edinburgh, UK, September 17-19, 2001.

Li, K. and Horne, R.N. (2001c): “Gas Slippage in Two-Phase Flow and the Effect of Temperature,” SPE 68778, presented at the 2001 SPE Western Region Meeting, Bakersfield, CA, USA, March 26-30, 2001.

Mahiya, G.F.: “Experimental Measurement of Steam-Water Relative Permeability,” MS report, Stanford University, Stanford, CA, USA, 1999.

Morrow, N.R. and McCaffery, F.G.: “Displacement Studies in Uniformly Wetted Porous Media,” *Wetting, Spreading, and Adhesion, Academic Press*, New York, 1978, 289-319.

Purcell, W.R.: "Capillary Pressures-Their Measurement Using Mercury and the Calculation of Permeability", *Trans. AIME*, (1949), **186**, 39.

Slobod, R.L. and Blum, H.A.: "Method for Determining Wettability of Reservoir Rocks", *Trans. AIME*, (1952), **195**, 1.