# FUNDAMENTALS OF STEAM-WATER FLOW IN POROUS MEDIA

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### *Project Background and Status*

The Stanford Geothermal Program (SGP) is focusing on the understanding of the fluid flow theory that governs geothermal reservoir performance. One of the most important concerns in the geothermal industry in recent years is reservoir decline. Injection of condensate and waste water in geothermal reservoirs is an important and practical solution. Accordingly, SGP has been investigating the problems related to liquid injection into geothermal reservoirs. The research has also focused on the estimation of recoverable reserves in geothermal reservoirs by developing methods of decline curve analysis based on fluid flow theory. SGP completed the projects that planned in the previous fiscal year.

### *Project Objectives*

The main objective is to improve the ability of engineers and scientists to forecast the future performance of geothermal reservoirs. By understanding the production characteristics, development decisions can be made sooner and with greater certainty. This will result in more efficient utilization of the geothermal energy resource. Another objective is to provide engineers and scientists direct methods to estimate the energy production rate of geothermal reservoirs and practical models of steam-water flow properties, including steam-water relative permeability and capillary pressure models.

### *Approaches*

The Stanford Geothermal Program uses both theoretical and experimental approaches to conduct the research. We use numerical simulation for modeling work and we use an X-ray CT scanner as one of our main experimental tools to measure in-situ water saturation and its distribution. We also design and construct purpose-built apparatus to conduct the experiments needed.

### *Research Results*

SGP completed the projects that were planned in the previous fiscal year. The main accomplishments are as follows:

#### *Decline Curve Analysis Method Based on Fluid Flow Mechanisms*

As pointed out by Raghavan (1993), "Until the 1970s, decline curve analysis was considered to be a convenient empirical procedure for analyzing performance; no particular significance was to be attributed to the values of $D_i$ and $b$. To an extent this is still true even today."

To this end, an analytical decline curve analysis model was developed based on the theory of fluid flow mechanisms with relative permeability, capillary pressure, and gravity included. We avoided the empiricism in the papers by Arps (1945) and by Fetkovich (1980). The model reveals a linear relationship between the production rate and the reciprocal of the cumulative production. The present work developed the theoretical significance for the two constants describing the decline rate (although actually these are not the same parameters as $D_i$ and $b$).

We applied the model to the production data of over 20 production wells in The Geysers geothermal field and found a linear relationship between the production rate and the reciprocal of the cumulative production for most of the wells, especially at the late period of production. An example of the application is shown in Fig. 4.1.1. This implies that we may be able to estimate the reservoir properties and the reserves.

#### *Wettability of Geothermal Fluid-Rock Systems*

Wettability of geothermal systems is one of the important parameters governing the efficiency of water injection. The more the rock is water wet, the more the water can be imbibed and the greater the water injection efficiency. The wettability in

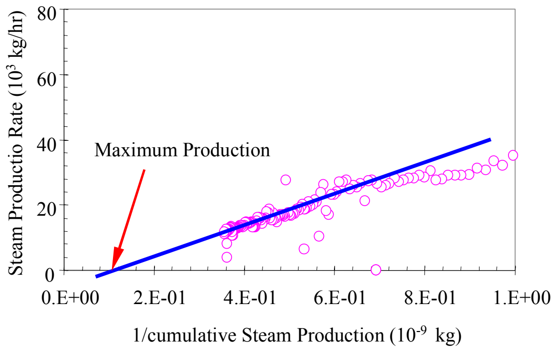


*Figure 1. Relationship between the steam production rate and the reciprocal of the accumulative steam production (Well 1).*

different gas-liquid-rock systems may not be the same (as is often assumed). However, few approaches are available to evaluate the wettability in gas-liquid-rock systems. For this purpose, a method was developed to infer the wettability of steam-water-rock systems based on the relationship between permeability and capillary pressure by Purcell (1949). 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 drainage was greater than that in imbibition, which has been proven experimentally. 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.

Figure 2 shows the values of the wettability index of steam-water-rock systems in both drainage and imbibition calculated using our model.

We may be able to determine where the water should be injected in geothermal reservoirs once the distribution of the wettability index is available. We may also be able to explain why water injection yields greater increase of energy production in some reservoirs but not in others.

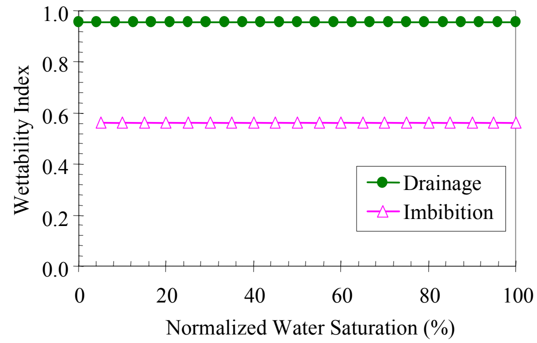


*Figure 2. Wettability indices calculated using the experimental data from Li and Horne (2001) and Mahiya (1999).*

## Steam-Water Relative Permeability from Capillary Pressure Data

Steam-water relative permeability plays important role in controlling reservoir performance for water injection into geothermal reservoirs. However, it is very difficult to measure steam-water relative permeability due to the phase transformation and the significant mass transfer between the two phases as pressure changes. It would be helpful for reservoir engineers to be able to calculate steam-water relative permeability once steam-water capillary pressure is available.

Various capillary pressure approaches were used to calculate steam-water relative permeabilities using the measured data of steam-water capillary pressure in both drainage and imbibition processes. The calculated results were compared to the experimental data of steam-water relative permeability measured in sandstone core samples. The steam-water relative permeability and capillary pressure were measured simultaneously. The differences between the Purcell model (1949) and the measured values were almost negligible for water phase relative permeability in both drainage and imbibition but not for the steam phase. The lack of significance of the effect of tortuosity on the wetting phase was revealed. A physical model was developed to explain the insignificance of the tortuosity. Steam phase relative permeabilities calculated by other models were very close to the experimental values for drainage but very different for imbibition as expected. The same calculation was made for nitrogen-water flow to confirm the observation in steam-water flow. The results showed that it would be possible and useful to calculate steam-water relative permeability using the capillary pressure method, especially for the drainage case. One of the comparisons between calculated and measured steam-water relative permeabilities is shown in Figure 3.

The general conclusion based on this study was that the Purcell model (1949) can be used to calculate the water phase relative permeability and the Corey model (1954) can be used to calculate the steam phase relative permeability.

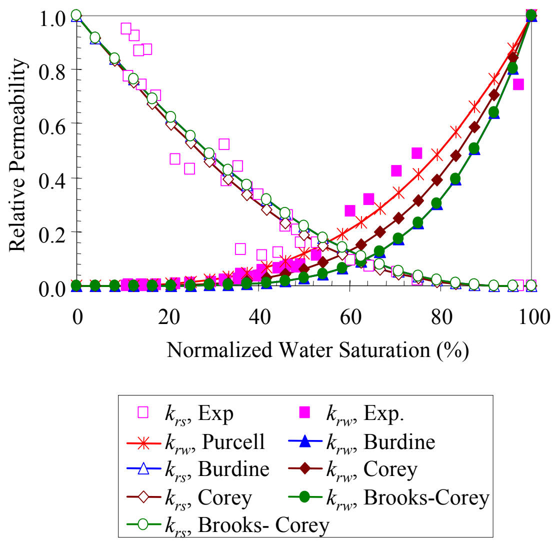


*Figure 3. Calculated steam-water relative permeability and the comparison to the experimental data in the drainage case.*

## Water Injection into Geothermal Reservoirs

Water injection has proven to be a successful engineering technique to maintain reservoir pressure in geothermal reservoirs and to sustain well productivity. However, many questions related to water injection into geothermal reservoirs still remain unclear. For example, how the in-situ water saturation changes with reservoir pressure and temperature, and the reservoir pressure influences well productivity. To answer these questions, we studied the effects of temperature and pressure on the in-situ water saturation in a core sample using an apparatus developed for the purpose. The in-situ water saturation decreases very sharply near the saturation pressure but not to the residual water saturation. When the mean pressure in the core sample decreases further, the in-situ water saturation decreases sharply again to the residual water saturation at a pressure much less than the saturation pressure. This demonstrated the significant effects of steam-water capillary pressure and physical adsorption on the in-situ water saturation.

Also investigated were the effects of pressure on the well productivity index (see Figure 4 as an example). The well productivity increased with an increase of mean reservoir pressure within a certain range and then decreased. The well productivity reached the maximum value at a pressure close to the saturation pressure. The results of this study should be useful to evaluate projects such as the waste water injection scheme at The Geysers.

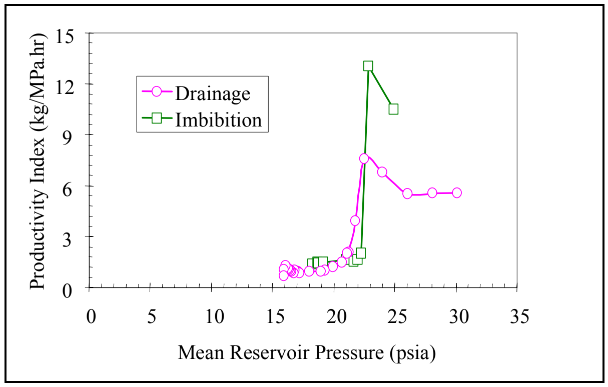


*Figure 4. Effect of reservoir pressure on the productivity index.*

## Relative Permeability in Fractures

The mechanism of two-phase flow through fractures exerts an important influence on the behavior of geothermal reservoirs. Currently, two-phase flow through fractures is still poorly understood. In this study, nitrogen-water experiments were conducted in both smooth- and rough-walled fractures to determine the governing flow mechanisms. The experiments were done using a glass plate to allow visualization of flow. Digital video recording allowed instantaneous measurement of pressure, flow rate and saturation. Saturation was computed using image analysis techniques. The experiments showed that the gas and liquid phases flow through fractures in nonuniform separate channels (see Figure 5).

*Figure 5. Examples of gas-water flow channels.*

The data from the experiments were analyzed using Darcy's law and using the concept of friction factor and equivalent Reynold's number for two-phase flow. For both smooth- and rough-walled fractures a clear relationship between relative permeability and saturation was seen. The calculated relative permeability curves follow Corey-type behavior, as shown in Figure 6. The sum of the relative permeabilities of the two phases is not equal to one, indicating phase interference. The equivalent homogenous single-phase approach did not give satisfactory representation of flow through fractures. The graphs of experimentally derived friction factor with the modified Reynold's number do not reveal a distinctive linear relationship.

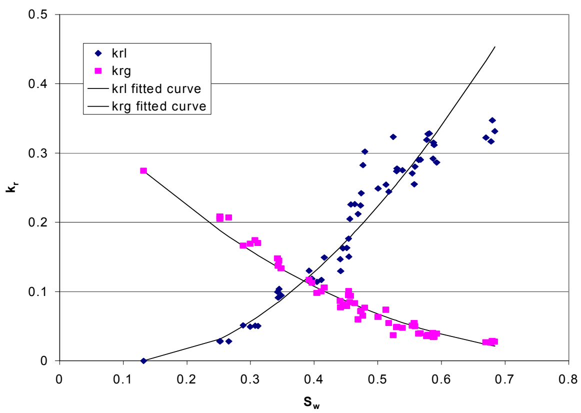


*Figure 6. Drainage relative permeability curves in a rough-walled fracture.*

<u>*Constant-Pressure Measurement of Steam-Water Relative Permeability*</u>

A series of steady-state experiments established the relative permeability curves for two-phase flow of water in a porous medium. These experiments have minimized uncertainty in pressure, heat loss, and saturation. By maintaining a constant pressure gradient, the experiments have provided a baseline from which to determine the effect of temperature on relative permeability. The experimental data of steam-water relative permeability from this study and the comparison to the published data are shown in Figure 7.

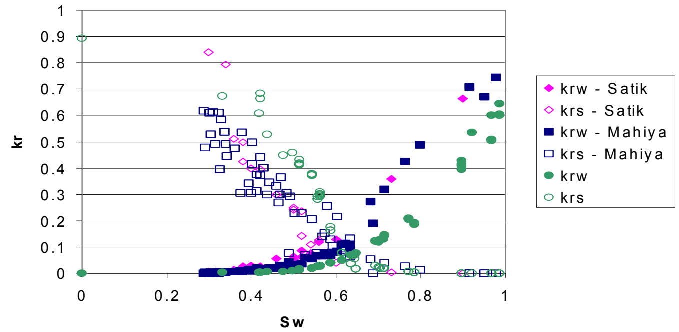


*Figure 7. Comparison of results with previous experiments.*

***Summary***

1. Eight papers and two major reports were published in the last fiscal year.
2. Four graduates and one research associate were funded; two students graduated from the Stanford Geothermal Program and obtained the M.S. degree, with two more still working on their degrees.
3. Three different sets of laboratory apparatus were developed.

***Future Plans***

Our future research plans are addressed as follows:

1. Application of the analytical decline curve analysis method in geothermal reservoirs.
2. Scaling of experimental data of spontaneous water imbibition.
3. Measurement of steam-water relative permeability through fractures.
4. Effect of initial water saturation on spontaneous water imbibition.
5. Development of apparatus and techniques to measure relative permeability in extremely low permeable geothermal rocks.

***Major Papers Published in Fiscal Year***

Li, K., Nassori, H., and Horne, R.N.: “Experimental Study of Water Injection into Geothermal Reservoirs,” proceedings of the GRC 2001 annual meeting, August 26-29, 2001, San Diego, USA; *GRC* Trans. V. 25 (2001).

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

Li, K. and Horne, R.N.: “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.: “Differences between Steam-Water and Air-Water Capillary Pressures,” presented at the 26th Stanford Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA 94043, USA, January 29-31, 2001.

Li, K. and Horne, R.N.: “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.

Li, K. and Horne, R.N.: “Wettability Determination of Geothermal Systems,” presented at the 27th Stanford Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA 94043, USA, January 28-30, 2002.

Li, K. and Horne, R.N.: “An Experimental and Theoretical Study of Steam-Water Capillary Pressure,” *SPEREE* (December 2001), p.477-482.

Li, K. and Horne, R.N.: “Characterization of Spontaneous Water Imbibition into Gas-Saturated Rocks,” *SPEJ* (December 2001), p.375-384.

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Diomampo, G.P.: "Relative Permeability Through Fractures," June 2001.

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