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# Steam-Water Relative Permeability

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## ABSTRACT

Reliable measurement of steam-water relative permeability functions is of great importance for geothermal reservoir performance simulation. Despite their importance, these functions are poorly known due to the lack of fundamental understanding of steam-water flows, and the difficulty of making direct measurements. The Stanford Geothermal Program has used an X-ray CT (Computer Tomography) scanner to obtain accurate saturation profiles by direct measurement. During the last five years, we have carried out experiments with nitrogen-water flow and with steam-water flow, and examined the effects of heat transfer and phase change by comparing these sets of results.

In porous rocks, it was found that the steam-water relative permeabilities follow Corey type relationships similar to those in nitrogen-water flow, but that the irreducible gas phase saturation is smaller for steam than for nitrogen. The irreducible saturations represent substantial fractions of the recoverable energy in place yet are hard to determine in the field. Understanding the typical magnitude of irreducible saturations will lead to a much clearer forecast of geothermal field performance. In fracture flow, indirect measurements suggested that the relative permeabilities follow a linear (or "X-curve") behavior — but there is still considerable uncertainty in the knowledge of this behavior.

## Introduction

The flow of steam and water through the interstices of geothermal rocks is governed by complex physical phenomena involving mechanical interaction between the two fluids, water and steam, as well as by the thermodynamic effects of boiling heat transfer. This complex interaction is commonly described in terms of the steam-water relative permeabilities, defined as a modification of Darcy's Law for single-phase flow:

$$q = \frac{k}{\mu} \mathrm{A} \left(\frac{\Delta p}{L}\right) \tag{1}$$

where $q$, $k$, $\mu$, $A$, $L$, $\Delta p$ are volumetric fluid flow rate, absolute permeability, fluid viscosity, cross-sectional area, length and pressure drop over the length $L$, respectively. When steam and water flow simultaneously, each phase is governed by an independent flow equation:

$$k_i = k\,k_{ri} = \frac{q_i\,\mu_i\,L}{\mathrm{A}\,\Delta p_i} \quad ; \quad i = steam, water. \tag{2}$$

Here $k_i$ is effective permeability to phase $i$, $q_i$ is volumetric fluid flow rate of phase $i$, and $\mu_i$ is viscosity of phase $i$. The nondimensional form of effective permeability, called the relative permeability ($k_r$), is defined as the ratio of effective permeability to absolute permeability ($k_{ri}=k_i/k$). Relative permeabilities are generally expressed as a function of the wetting phase saturation (usually water in the case of steam-water flow).

Steam-water relative permeabilities have been shown to make a significant impact on the performance of geothermal reservoirs (Bodvarsson, O'Sullivan and Tsang, 1980), however in practice they are extremely difficult parameters to measure. For homogeneous porous media the commonly assumed relative permeabilities are the Corey expressions (Corey, 1954):

$$\begin{aligned} k_{rl} &= S^{*4} && (S^* < 1) \\ k_{rg} &= (1 - S^*)^2 (1 - S^{*2}) && (S^* < 1) \\ S^* &= (S - S_{lr})/(S_{gr} - S_{lr}) \end{aligned} \tag{3}$$

where $S_{gr}$ and $S_{lr}$ are the irreducible or residual saturations for liquid and gas, respectively. For fractured media, it has been more common to assume that the relative permeabilities follow the linear relationships known as the "X-curves":

$$
\begin{aligned}
k_{rl} &= S^* & (S^* < 1)\\
k_{rg} &= (1 - S^*) & (S^* < 1)\\
S^* &= (S - S_{lr})/(S_{gr} - S_{lr})
\end{aligned}
\tag{4}
$$

where it is common to assume the residual saturations $S_{gr}$ and $S_{lr}$ to be zero. These two types of relative permeability curve are illustrated in Figure 1.

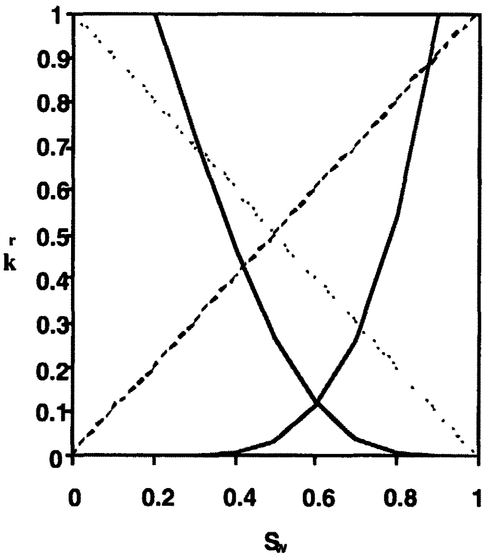


**Figure 1.** Corey (solid lines) and linear (dashed lines) relative permeability curves.

The principal problems in obtaining steam-water relative permeabilities experimentally are in measuring: (1) the in-place saturations, and (2) the flow rates of the two phases. In oil-water relative permeability experiments, the saturations and flow rates are determined easily by direct measurement of the in-flows and outflows of the two phases, but in the case of steam and water the phases can easily change from one to the other, hence the difficulty. Table 1 summarizes 25 years of work in the determination of steam-water relative permeability, including the methods used to measure saturation. Despite the number of independent studies, the results have proven to be inconsistent, hence confidence in the use of the results for commercial reservoir simulation has been low.

The Stanford Geothermal Program has conducted steam-water relative permeability experiments in two campaigns, one in the 1970s (Arihara, 1974, Chen et al., 1978, Counsil and Ramey, 1979) and more recently in the 1990s (Ambusso, 1996, Tovar, 1997, Satik, 1998, Mahiya, 1999). Since 1996, the Stanford measurements have used X-ray CT (Computer Tomography) methods to determine the in-place steam saturation. This powerful and accurate method allows for the steam-water distribution to be obtained at any place within the core (see Figure 2). Nonetheless, repeated studies still had difficulty in producing repeatable results that were consistent with earlier literature – the difficulty of determining the individual steam and water flow rates remained. One of our first successful measurements was by Ambusso (1996), Figure 3, who suggested that the steam-water relative permeabilities were best described by the X-curves. However, later measurements by Satik (1998), Figure 4, failed to confirm this, and indicated that Corey type behavior was more likely (as had also been seen elsewhere for unconsolidated materials by Sanchez and Schechter, 1990).

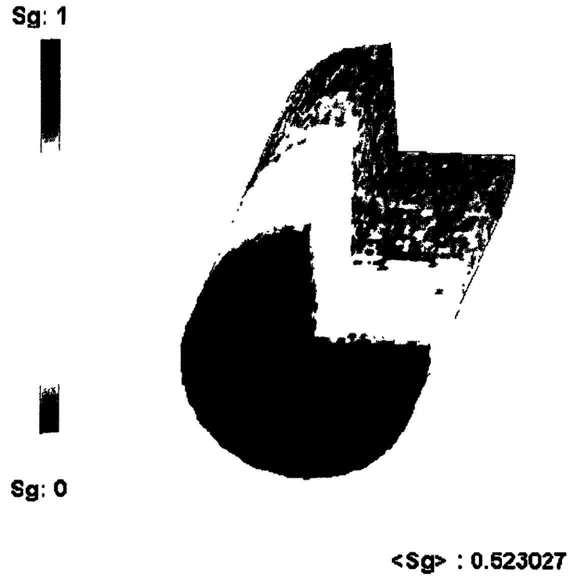


**Figure 2.** Steam distributions measured by X-ray CT, from Satik (1998).

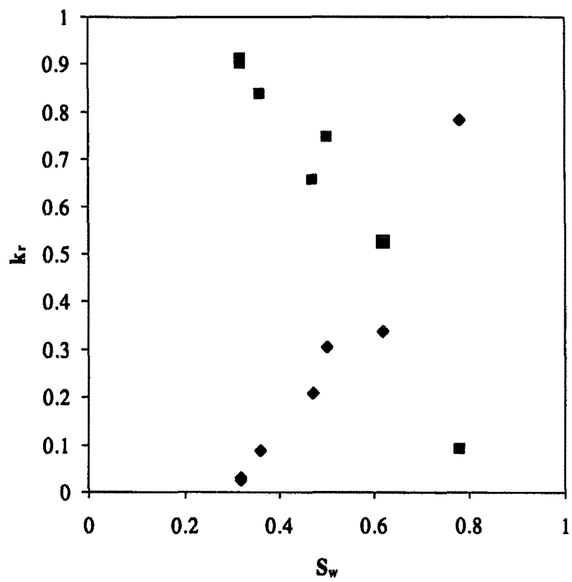


**Figure 3.** Experimental results from Ambusso (1996).

The study by Sanchez and Schechter (1990) had used an adiabatic experiment, maintaining the heat in the sample by use of guard heaters. The experiments of Ambusso (1996) and Satik (1998) were nonadiabatic, mainly because ferrous heaters placed around the core would attenuate the X-rays and cause artifacts in the saturation measurement. In the nonadiabatic experiments,

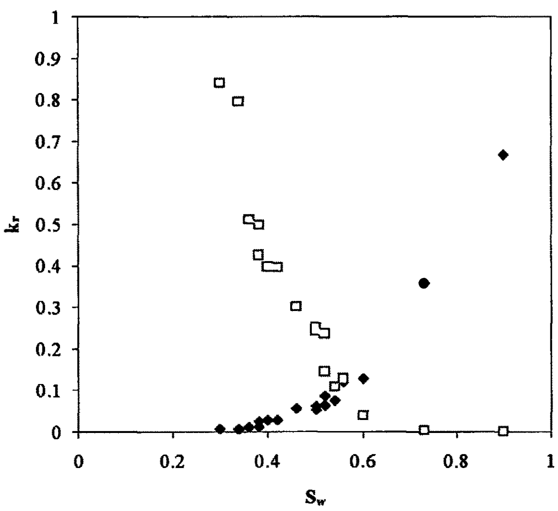


**Figure 4.** Experimental results from Satik (1998).

the phase flow rates were computed after carefully measuring the heat fluxes from the core; nonetheless, this computation increased the uncertainty of the results. Since the results of Satik (1998) differed from those of Ambusso (1996) (although similar to the results of Sanchez and Schechter, 1990) and were difficult to reproduce, in 1999 Mahiya undertook a new study, combining the adiabatic approach of Sanchez and Schechter (1990) with the X-ray CT measurement of saturation as used by Satik (1998). The study used a very thin film heater which avoided the problem of X-ray attenuation. The measurements attained by Mahiya (1999) demonstrated repeatability of Satik's 1998 results, and were close to those of Sanchez and Schechter (1990). Thus it was finally possible to associate confidence to these measurements, and to conclude that steam-water relative permeability relationships are of the Corey type. The measurements and experimental methodology described by Mahiya (1999) will be one of the main topics of this paper.

## Experiments

The physical parameters required to establish relative permeability curves are pressure, temperature, heat flux, flow rates and saturation. The experimental apparatus used by Satik (1998) and Mahiya (1999) made use of a nonmetallic coreholder made of the material PEEK, with a series of pressure and temperature measurements made along the interior axis of the core. Steam and water were injected independently into two separate ports at the inlet end of the coreholder, each with their own positive-displacement pump. The water used for injection was deaerated by preboiling, and then reheated by immersion heaters that were constructed within the inlet endplate of the coreholder. This configuration reduced heat losses between the heater and the core entry that had been a concern to Sanchez and Schechter (1990). Heat losses from the core were cancelled out using thin-film guard heaters under automatic computer control.

### *Experimental Configuration*

Figure 5 shows a schematic of the apparatus that allowed real-time measurement of the required quantities. The experiment used a 43 cm Berea sandstone core with a nominal absolute permeability of 1200 md and a measured porosity of 24%. This was the same core used in experiments by Satik (1998). Pressures and temperatures were measured through ports at eight positions along the core spaced 5 cm apart. These ports connected the core to pressure transducers via plastic tubings, and provided tapping points into which thermocouple wires were inserted for temperature readings. A blanket of insulating fiber around this assembly partially reduced the escape of heat.

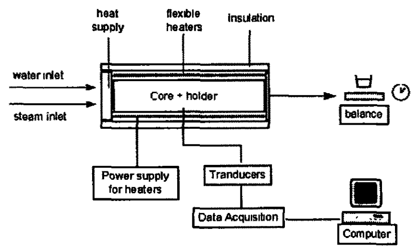


**Figure 5.** Experimental apparatus for the flow-through experiment using heat guards.

In order to achieve two-phase conditions in the core, dry steam and hot liquid water were injected separately into two ports at the inlet using two independent constant-displacement pumps. Injection rates were typically between 0 and 10 ml/min. Each stream of fluid used deionized water pumped from a common reservoir to a boiler and then to a condensing loop. This process eliminated dissolved air that would introduce errors in the saturation measurements. The deaerated water was then delivered to the heating head in the core inlet where each of the two streams was reheated to either steam or hot water. Steam and water then became mixed in the first few centimeters of the porous medium. Injection temperatures were typically of order 120°C, although the value varied somewhat from one step to the next. Fluid exited the core at atmospheric pressure and was directed to the sink where volumetric rate was checked using a

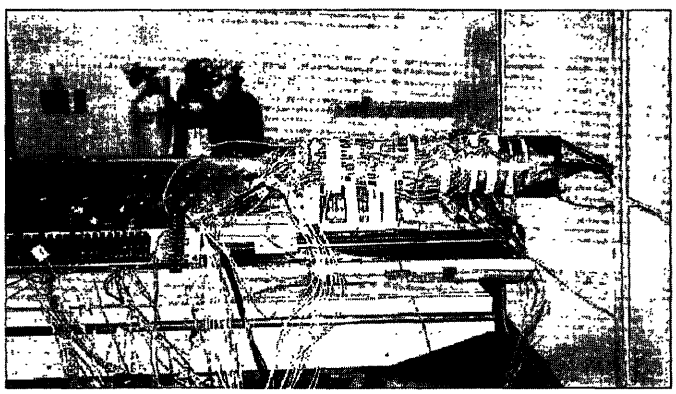

**Figure 6.** Core assembly mounted on stepper motor drive in the X-ray CT scanner.

graduated cylinder and timer, and compared with the injection rates specified at the two inlet pumps.

In-situ saturation values were determined from CT image arrays generated by the X-ray CT scanner. The core assembly was mounted and secured on a stepper motor that allowed movement of the core in and out of the X-ray gantry with 1 cm interval. We were able to take measurements at 41 sections along the core, Figure 6. shows the major components of the experimental apparatus and the CT scanner.

## *Flexible Guard Heaters*

Despite the thick layer of insulation around the coreholder, there was still considerable heat escaping from the core in Satik's 1998 experiments. In the new experiment, the exact amount of heat that was lost was supplied back to the system, so that overall heat loss would be negligible, if not zero. We designed flexible heaters custom-made for this purpose. Figure 7 shows a schematic of one of the Kapton-insulated flexible heaters.

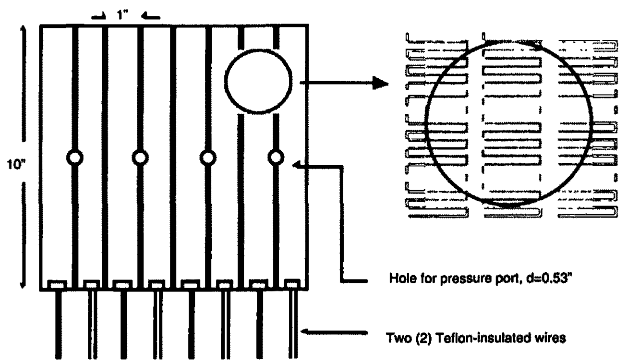


**Figure 7.** Schematic of flexible heaters.

Since single-sheet heaters long enough to completely cover the core were not available, we used two separate 20x25 cm and 23x25 cm sheets. Holes with 1.34 cm diameters were provided to allow for the protruding pressure ports along the core length. Each sheet was an array of eight or nine 2.5x25 cm strips of heating elements that could be controlled independently. In effect, we had 17 different heaters, each rated at 0.4 W/cm² at 115 volts. Since the heaters required only a small amount of current to operate, we used a transformer to step-down the voltage from 120 VAC to 60 VAC. The flexible thin-film heaters did not cause significant X-ray interference.

Each of the 17 independent heating strips was controlled in response to its own heat flux sensor placed under the heater on the surface of the coreholder. The voltage to the heater strip was switched on and off with an on-time sufficient to supply enough heat to balance the energy being lost from the core. In most cases the switching cycle was 20-30 times a minute. Each strip was controlled independently, using a 32-channel National Instruments SCXI 1163-R solid-state relay output module.

## *Experimental Process*

The core preparation procedure involved drying the core by subjecting it to 120°C in an oven and simultaneously pulling a vacuum. The core had previously been baked at higher temperatures for the purpose of deactivating clays in the rock. Once dried, the core was assembled into the coreholder, and bonded in place using epoxy. A dry X-ray scan was then made to obtain the CT attenuation values $CT_{dry}$. The core was then fully saturated with water and scanned to obtain the values of $CT_{wet}$, and from these the porosity distribution was obtained. The next step was to flow hot liquid water to obtain $CT_{hw}$ which was necessary for calculating experimental saturations. The completion of this scan marked the start of the actual flow-through experiments. The electrical power was increased in stages by changing the voltage settings of the two heaters that generated dry steam and hot water. During this staged procedure the wetting phase (water) was displaced by the nonwetting phase (steam) and hence the flow was a drainage process. At each stage, two-phase flow in the core was allowed to stabilize before an X-ray scan was performed. Pressure, temperature and heat fluxes from the core were measured at every stabilization. The maximum steam saturation was reached by injecting only steam at the inlet. Once maximum steam saturation was achieved, input power to the steam and water heaters was gradually decreased to create an imbibition process whereby liquid water displaced steam. The values of relative permeability to steam and water were then computed after choosing sections of the core in which the saturation could be seen (in the CT scans) to be constant. One important aspect of the computation was the requirement to correct for the Klinkenberg slip effect, as described by Li and Horne (1999).

## *Results*

The results of the 1999 experiments by Mahiya are shown in Figure 8. The behavior of the relative permeability curves in these measurements is clearly of the Corey type, and shows little difference between drainage and imbibition processes. The relative permeability values are in close agreement with the values of both Satik (1998), for the same rock, and with the values of Sanchez and Schechter (1990), for an unconsolidated sand. Figure 9 shows the comparison in terms of $k_{rs}$ vs. $k_{rw}$, showing the agreement between these three measurements, and the substantial difference of the results of Ambusso (1996). Also shown on are the relative permeability values for nitrogen and water (imbibition process), as measured by Li and Nassori in the same core and experimental apparatus used by Mahiya (1999) – although similar in shape, it is clear that the relative permeability to nitrogen is less than that to steam, mainly because the irreducible nitrogen saturation (about 0.3) is significantly greater than the irreducible steam saturation (about 0.2). The same data, plotted as a function of water saturation in Figure 10 shows that it is the gas relative permeability that differs most prominently betweem steam and nitrogen — the water relative permeabilities are almost the same.

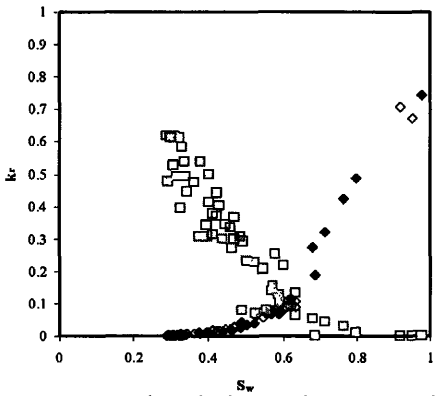


**Figure 8.** Experimental results from Mahiya (1999) adiabatic experiment. Closed symbols, drainage curves; open symbols, imbibition curves.

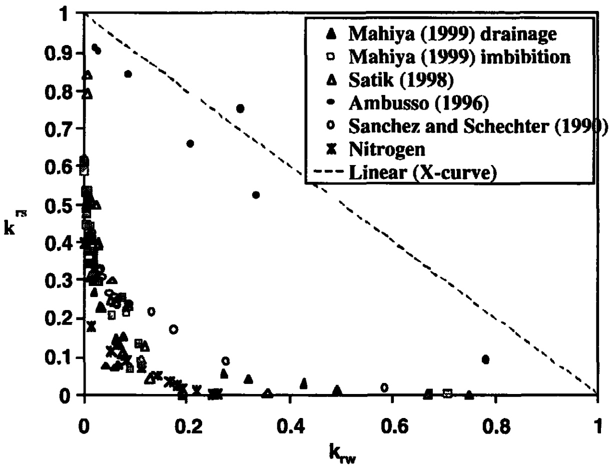


**Figure 9.** Comparison of results, $k_{rs}$ vs. $k_{rw}$.

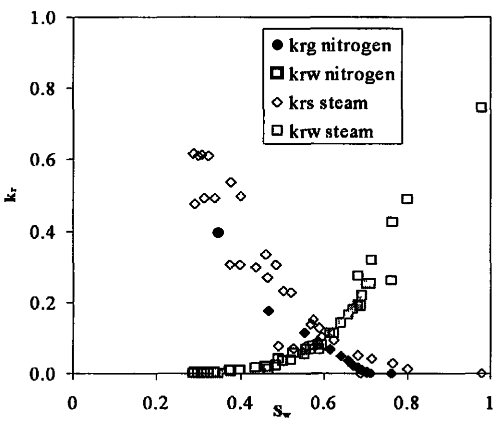


**Figure 10.** Comparison between steam-water (open symbols) and nitrogen-water imbibition (closed symbols) relative permeabilities on the same rock core.

Although we may call the results of the experiments of "Corey type", in fact the values of the relative permeabilities are better fit to more general relations, of the type suggested by Honarpour et al. (1982):

$$
\begin{aligned}
k_{rs} &= k_{rs0}\frac{(1-S_w-S_{sr})^{n_s}}{(1-S_{wr}-S_{sr})} \\
k_{rw} &= k_{rw0}\frac{(S_w-S_{wr})^{n_w}}{(1-S_{wr}-S_{sr})}
\end{aligned}
\qquad (5)
$$

where $S_{wr}$ and $S_{sr}$ are the water and steam irreducible saturations respectively. Figure 1 shows a match to the data from the combined drainage and imbibition results of Mahiya (1999). The values of the best fit parameters are $k_{rs0} = 0.63$, $k_{rw0} = 0.49$, $S_{sr} = 0.13$, $S_{wr} = 0.27$, $n_s = 2.04$ and $n_w = 2.65$. The value of $n_s$ (2.04) is very close to the Corey value of 2 from Equation 3, while the value of $n_w$ (2.65) is less than the Corey value of 4.

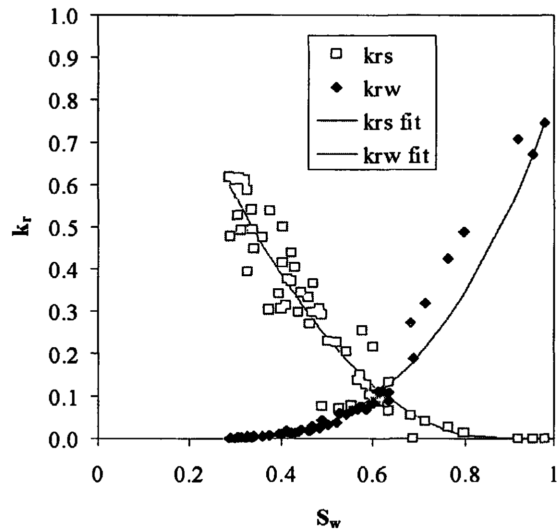


**Figure 11.** Fit to Mahiya (1999) results.

## Fracture Flow Experiments

The relative permeabilities resulting from multiphase flow in fractures have received considerably less attention in published literature than those in porous media. The classically assumed X-curves (Figure 1) originated from experiments by Romm (1966) using oil-water flow in smooth fractures divided into strips in the flow direction. In Romm's experiments, the limiting values of the relative permeabilities $k_{ro0}$ and $k_{rw0}$ were both 1.0, and the residual saturations were both 0.0. That is, the sum of the relative permeabilities would always be one. More recent oil-water experiments in smooth fractures by Pan et al. (1996) also showed the residual saturations to be both 0.0, but the limiting $k_{ro0}$ and $k_{rw0}$ values were less than 1.0. Similar results were inferred in air-water flow in rough-walled fractures by Rangel-German et al. (1999).

Other experiments in rough-walled fractures have shown different kinds of relative permeability behavior. Fourar et al.

(1993) conducted air-water experiments in both smooth- and rough-walled fractures, and proposed that the relative permeability concept was not useful to describe multiphase flow in fractures since the apparent relative permeability values would be functions of velocity. Even so, the apparent relative permeability curves shown in Fourar et al. (1993) do not appear to follow either X-curve or Corey behavior at any velocity. Persoff and Pruess (1995) measured air-water relative permeabilities in rough-walled fractures, and also concluded that the values differ from either Corey or linear behavior (showing lower values than either of those two models, see Figure 12).

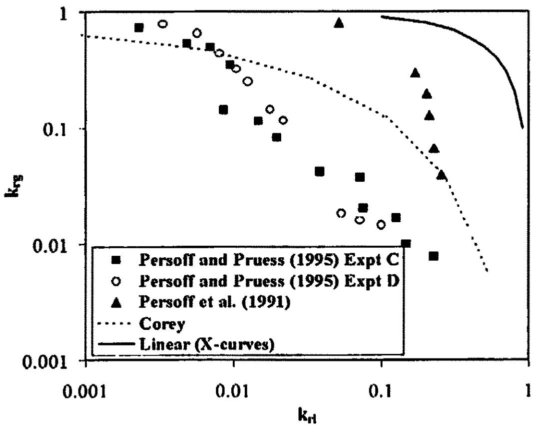


**Figure 12.** Some measurements of air-water relative permeabilities in rough-walled fractures.

The theoretical study by Pruess and Tsang (1990) suggested that relative permeabilities in fractures may add up to considerably less than one, although the theory specifically excludes the possibility of "blobs" of one phase being conveyed by the other. The study also predicted ranges of saturation values at which neither phase can flow at all. In another study that released the "blob transport" exclusion, Rossen and Kumar (1992) advanced a theory that suggests a range of possibilities between the "sub-Corey" results of Pruess and Tsang (1990) at the lower end and the X-curves at the upper end.

All of the experimental studies mentioned so far in this section have been for air-water or oil-water flow. However, in fractures steam-water flow experiments have proven to be much more difficult, for the same reasons described in Section 1 for porous media. In one study, Wang and Horne (1999) inferred the steam-water relative permeabilities indirectly from experiments in a rough-walled fracture made of two plates of shower glass. 100°C water and steam flowed radially inward through the fracture towards a central port at which a vacuum was applied. Matching the observed temperature distribution in the fracture revealed that the observations could be replicated using a numerical simulation only if the relative permeability model was of the X-curve type (Figure 13).

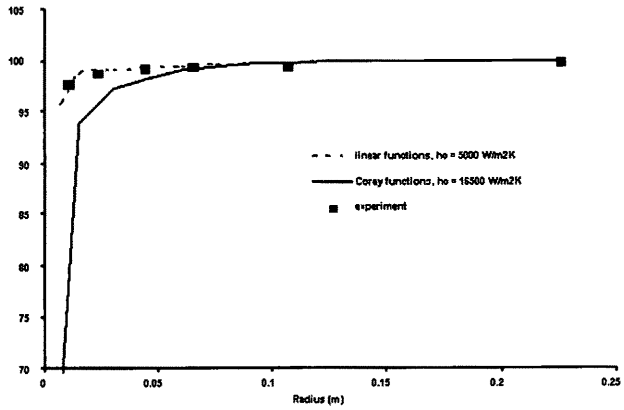

**Figure 13.** Fracture flow (temperature vs. radius) results from Wang and Horne (1999). Match using X-curves shown as dashed line, match using Corey curves shown as solid line.

## Discussion

The combined results of Satik (1998) and Mahiya (1999) established repeatability of the relative permeability measurements, and confirmed that these parameters follow the Corey type of behavior for flow in a porous rock. The similarity to the measurements of Sanchez and Schechter (1990) in unconsolidated sand adds further credence to this observation.

An important question to be raised is why the results of Ambusso (1996) were so different. The prominent deviation found by Satik (1998) provided significant confusion as to which of the two styles of relative permeability curve is the more appropriate. The confirming measurements by Mahiya (1999) suggest that it is the Corey type of behavior that is correct. It could be concluded that the rock in the Ambusso (1996) experiment had cracked, perhaps at the epoxy confinement, or maybe that the less sophisticated method of determining steam and water flow rates resulted in greater experimental error.

## Conclusions

1. Steam-water relative permeabilities in a porous rock have been shown to follow Corey-type behavior.
2. This behavior has been confirmed in repeated experiments, and by comparison with earlier published results.
3. Proper interpretation of steam-water experiments at close to atmospheric pressure must include the influence of Klinkenberg slip effect.
4. Steam-water flow is similar to nitrogen water flow, except that the relative permeability to steam is greater than that to nitrogen, and the irreducible nitrogen saturation is greater than the irreducible steam saturation.

**Table 1.** Previous experiments relevant to steam-water relative permeabilities, 1974-1999.

| Reference | Year | Experiment type | Saturation technique | Core type |
|---|---|---|---|---|
| Mahiya | 1999 | Steam-water | CT scanner | Berea sandstone |
| Satik | 1998 | Steam-water | CT scanner | Berea sandstone |
| Ambusso | 1996 | Steam-water | CT scanner | Berea sandstone |
| Piquemal | 1994 | Steam-water | Gamma ray | Unconsolidated sand |
| Closmann and Vinegar | 1988 | Steam-water-oil | CT scanner | Natural core |
| Sanchez and Schechter | 1987 | Steam-water | Tracer | Unconsolidated sand |
| Verma and Pruess | 1986 | Steam-water | Gamma ray | Unconsolidated sand |
| Monsalve et al. | 1984 | Surfactant-steam-water | Tracer | Berea sandstone |
| Counsil and Ramey | 1979 | Steam-water | Capacitance probe | Consolidated synthetic |
| Horne and Ramey | 1978 | Steam-water | Production history | Field study |
| Chen et al. | 1978 | Steam-water | Capacitance probe | Consolidated synthetic |
| Grant | 1977 | Steam-water | Production history | Field study |
| Trimble and Menzie | 1975 | Steam-water-oil | Did not measure | Berea sandstone |
| Arihara | 1974 | Steam-water | Did not measure | Consolidated core |

5. Steam-water relative permeabilities for flow in fractures are still unknown. Some steam-water and oil-water fracture flow experiments imply X-curve (linear) type of behavior, however other experiments using air and water imply even lower phase mobility than would be implied by Corey-type behavior.

In a real geothermal rock, steam and water will flow simultaneously in both fractures and in the porous matrix. The combination of these two flow processes may result in an effective relative permeability behavior that differs from either the Corey-type or the X-curve type of flow. The effect of this combination of behaviors has yet to be determined.

## Acknowledgement

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