BENCH-SCALE EXPERIMENTS IN THE STANFORD GEOTHERMAL PROGRAM

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The emphasis of the smaller scale laboratory of the Stanford Geothermal Program is on improving the understanding of the physics of flow through porous materials in a geothermal environment. Three major investigations are in progress: (1) examination of the phenomenon of vapor pressure lowering in porous media, (2) determination of the temperature dependence of absolute and relative permeabilities of steam and water in sandstones under high confining pressures, and (3) observation of steady and unsteady, single- and two-phase flows of water or brine through permeable cores. In addition, development continues on the dielectric constant liquid content detector--a device which would prove extremely useful in these and subsequent experiments.

Vapor Pressure Lowering

Due to the presence of solid boundaries, the saturated vapor pressure of water in a consolidated sandstone core may be lowered by as much as 15 psia at temperatures between 200°F and 290°F. See Fig. 1 (from Chicoine, Strobel, and Ramey[1]). As a result, the water boils at a higher temperature. It is anticipated that vapor pressure lowering is due to capillarity and/or adsorption-desorption phenomena at low water saturation (below the irreducible water saturation).

Initial theoretical analysis of the experimental data of Calhoun, Lewis and Newman[2] produces strong evidence that the phenomenon is due to adsorption/desorption rather than capillary effects. Three facts are indicative of this:

(1) If the pore size implies a radius of curvature 10 Å in the experimental porous medium, which is about the minimum radius for which capillarity may be considered (for water), then vapor pressure lowering due to capillarity would result in a vapor pressure 0.61 times the "flat surface" value. In fact, the observed value is much lower (~0.03).

The relative orders of the effects of capillarity and adsorption can be estimated from the equation:

Capillarity: $$\ell n \frac{p}{p_o} = - \frac{2rV}{RT} \frac{1}{R_m}$$ (from Leverett[3]) (can be obtained from thermodynamics) where p/p_o is the saturated vapor pressure relative to that on a flat surface, Γ is the surface tension, V is the molar volume, R is Boltzman's constant, T temperature, and R_m the mean radius.

Adsorption: $$\frac{P}{x(p_o - p)} = \frac{1}{x_m c} + \frac{c-1}{x_m c} + \frac{P}{P_o}$$ (the BET eq., Brunauer, Emmett & Teller[4])

for $0.05 < \frac{P}{P_o} < 0.35$

where x is the value of fluid adsorbed at pressure P and x_m is the volume of fluid required for monolayer adsorption. c is the ratio of activation energy for rock/water and water/water interactions.

(2) It can be seen from these equations that the adsorption effect is a function of surface area and not necessarily of permeability and porosity. Calhoun's[2] data show this surface area dependence.

(3) In Calhoun's[2] experimental data there is no noticeable hysteresis in the vapor pressure/saturation curve during a drainage/imbibition cycle. Such hysteresis would be anticipated if capillarity were significant, as the water/vapor interface would have a different shape during filling and emptying a pore.

The objectives of the program are to reevaluate the results of Chicoine, et al.[1], using steady rather than time-varying experiments. This should represent the phenomenon of vapor pressure lowering better because it is not a transient effect. It is also intended that the range of temperatures for the experiment be increased.

Permeability to Water and Brines--Effects of Temperature

Experimental studies of fluid flow through porous media have shown that temperature and the confining pressure affect both relative and absolute permeabilities. Several workers in the past have demonstrated that relative permeability is a temperature-dependent property of rocks (e.g., Weinbrandt[5]), but results published on absolute permeabilities show a lack of consistency.

Under the sponsorship of the Stanford Geothermal Program, Cassé[6] sought to clarify these results by investigating the combined effects of mechanical and thermal stresses. In his work, water, nitrogen, and mineral oil were used to find absolute permeabilities of three consolidated sandstone samples for confining pressures ranging from 450 to 4000 psia and temperatures ranging from room temperature to 325°F. Results from these experiments showed that the temperature effects on permeability depended on the nature of the saturating fluid. For water-saturated cores, permeability reductions of up to 65% were observed over the temperature range studied.

Because of the lack of absolute permeability variation with temperature for both nitrogen and mineral oil, Cassé[6] concluded that the temperature effect is not caused by changes in physical properties of the fluids, such as viscosity or density, or by thermally-induced mechanical stresses. Instead, the unique results obtained for water suggest that a temperature-dependent rock-fluid interaction was the dominant factor responsible for permeability reductions for water.

In order to verify the results of these and other previous studies, and to investigate the causes for the observed behavior, Aruna[7], also under SGP sponsorship, extended the work of Cassé to clay-free systems, and to unconsolidated sands under the theory that the main effect was water-silica development (Aruna, et al.[8]). Figure 2 shows Aruna's results for permeability variation with temperature for water flowing through a consolidated sandstone core. Additional tests using octanol-saturated cores did not show temperature effect of permeability. From these results, Aruna concluded that the permeability reduction for water flowing through sandstone cores is due to attractive forces between silica and water molecules at elevated temperatures. Further evidence for this conclusion was derived from a series of tests using a water-saturated limestone core which did not show permeability change with temperature, and tests with clean, unconsolidated sands and water which did show a large effect.

The work now continues with similar apparatus. The new objectives are to evaluate the relative permeabilities of steam and water or brine at different temperatures under high confining pressure. It should also be possible to evaluate the immobile water saturation in an all-water system, and the irreducible water saturation in a two-phase system, by using traced water (e.g., brine). It will also be interesting to determine whether steam absolute permeabilities are temperature dependent in sandstones, as other gases tested to date were not.

Two-Phase Flow of Water and Brine

A third bench-scale apparatus has been developed to investigate the flow of water and brine through porous materials.

Relative permeability/saturation relationships are needed to forecast the mass and energy recovery from geothermal reservoirs. Steam and water relative permeability/saturation data have not been presented in the literature. Since brine geothermal fields are common, answers to the following questions are needed: (1) where does salt deposit in the reservoir when boiling occurs? (2) does salt deposition affect the rock permeability?

In an earlier study, temperature profiles were measured by Arihara[9] during steam injection into a cold water saturated core. Injection rates were low enough that a steam front and hot water region was calculated from the experimental data and found to be only slightly higher than that calculated for hot water injection. It was believed that the difference might have resulted from a small error in estimating the position of the steam front. It was recommended that future steam injection studies be designed to achieve stagnation of the steam front, and steady state in the hot water zone.

Relative permeabilities of steam and water were determined by Chen[10] (see Fig. 3); however, results indicated an irreducible water saturation larger than 60%, a figure which requires further investigation. This work continues to provide quantitative information that can be used to evaluate the performance of two-phase flow computer simulation programs, which is an important objective of the study. At present, emphasis is being placed upon:

(1) studying the pressure, temperature, and salt deposition characteristics of high temperature depletion and approximate steady flow processes for a variety of brine concentrations, and

(2) improving the materials and design features of high temperature flow equipment in order to obtain detailed data on relative permeabilities.

The Capacitance Probe

This device is being developed further for use in both the vapor-pressure lowering and relative permeability/brine experiments. The probe has been used previously in the Stanford Geothermal Program by Chen[10] as a means of determining the water saturation. The probe (see Fig. 4) is positioned inside a glass tube cemented into the center of a synthetic core, and its capacitance may be calibrated to give a measure of the fluid saturation. The two-phase flow apparatus will now be used to calibrate the probe signal with liquid water saturation as a function of frequency. An optimum frequency can then be selected to linearize the correlation between capacitance and water saturation as closely as possible.

References

1. Chicoine, S.D., Strobel, C.J., and Ramey, H.J., Jr.: "Vapor pressure lowering in two-phase geothermal systems," paper SPE 6767 presented at the 52nd Annual Fall Meeting of SPE, Denver, Oct. 1977.

2. Calhoun, J.C., Jr., Lewis, M., Jr., and Newman, R.C.: "Experiments on the capillary properties of porous solids," Trans. AIME, 186 (1949), 189-96.

3. Leverett, M.C., "Capillary behavior in porous solids," Trans. AIME, 142 (1941), 152-69.

4. Brunauer, S., Emmett, P.H., and Teller, E.: "Adsorption of gases in multimolecular layers," J. Am. Chem. Soc., 60 (1938), 309-19.

5. Weinbrandt, R.M.: "The effect of temperature on relative permeability," Ph.D. Dissertation, Stanford University, 1972.

6. Cassé, F.J.: "The effect of temperature and continuing pressure on single-phase flow in consolidated rocks," SGP-TR-3, 1974.

7. Aruna, M.: "The effects of temperature and pressure on absolute permeability of sandstones," SGP-TR-13, 1976.

8. Aruna, M., Arihara, N., and Ramey, H.J., Jr.: "The effect of temperature and stress on the absolute permeability of sandstones and limestones," presented at the American Nuclear Society Meeting, April 12-14, 1977, Colorado School of Mines, Golden, Colorado.

9. Arihara, N.: "A study of nonisothermal single- and two-phase flow through consolidated sandstones," SGP-TR-2, 1974.

10. Chen, H.K.: "Measurement of water content in porous media under geothermal fluid flow conditions," SGP-TR-15, 1976.

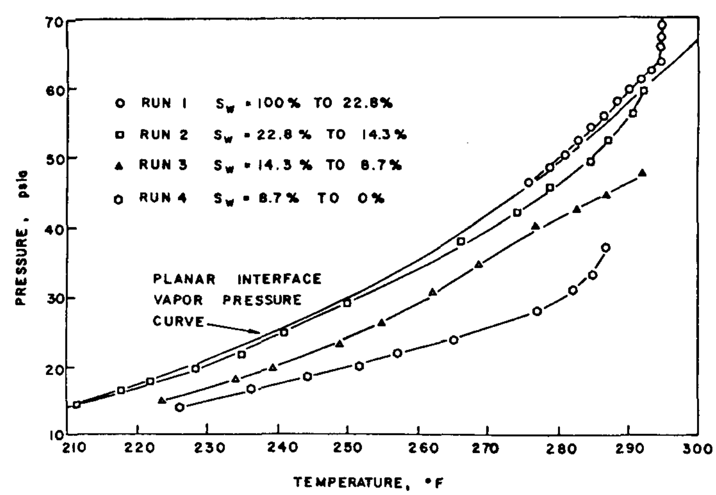

Fig. 1 - Pressure vs. temperature for the two-phase zone. (K=80 md, ø = 0.18)

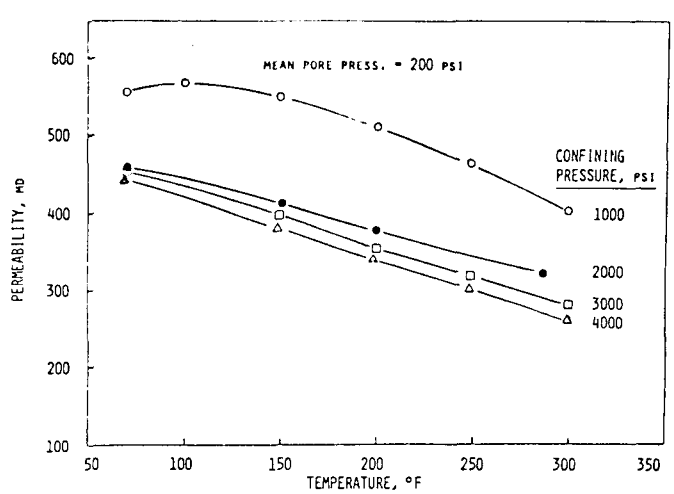

Fig. 2. Water Permeability vs. Temperature, Massillon Sandstone Core No. 2

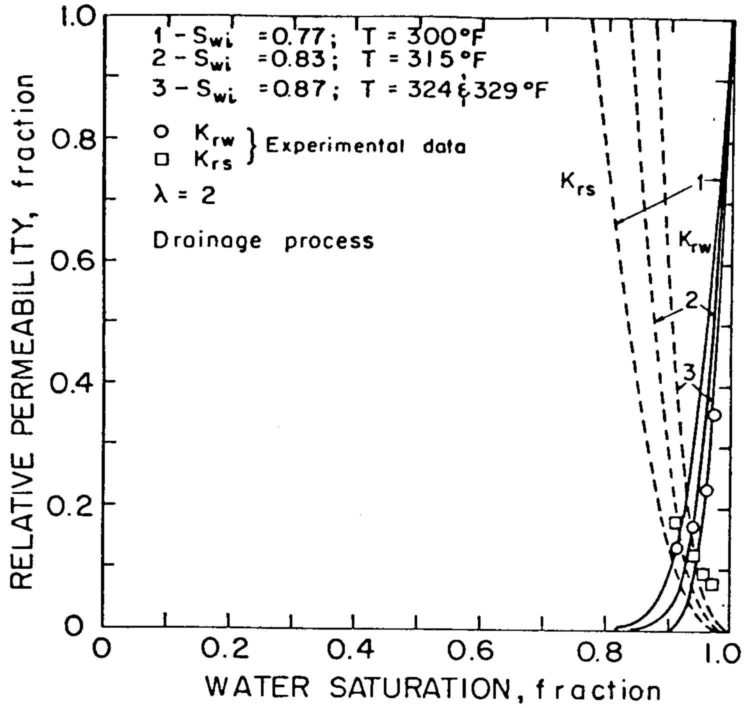

FIGURE 3. RELATIVE PERMEABILITY TO STEAM AND WATER VS. WATER SATURATION FOR A SYNTHETIC CONSOLIDATED SANDSTONE CORE

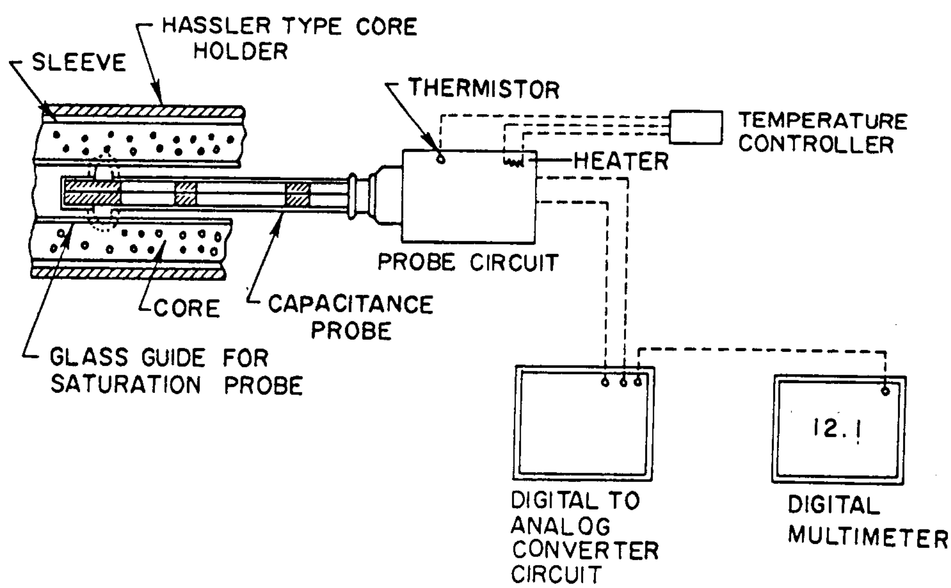

FIGURE 4 SCHEMATIC DIAGRAM FOR IN SITU MEASUREMENT OF WATER SATURATION IN STEAM-WATER FLOW IN SYNTHETIC CONSOLIDATED SANDSTONE CORE