PROCEEDINGS, Twenty-Eighth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 27-29, 2003
SGP-TR-173

DIRECT MEASUREMENT OF IN-SITU WATER SATURATION IN THE GEYSERS ROCK

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ABSTRACT

An experimental apparatus was designed and built to measure the in-situ steam and water saturations in The Geysers rock by using an X-ray CT technique. Water saturation was measured at a temperature of about 120^{o}C but at different pressures. The pressure in the core sample ranged from 0 to about 50 psi. The experimental data from The Geysers rock were also compared to the theoretical results from a zero-dimensional model. X-ray beam-hardening effects are frequently reduced by the installation of core systems in water jackets or in sand packs. Such a method may not be convenient and may not work in some cases. A new approach was developed to measure fluid saturations by inclining the core to the scanning plane to reduce X-ray beam-hardening effects.

INTRODUCTION

The energy reserve and recovery rate in vapor-dominated geothermal reservoirs are strongly dependent on in-situ water saturation. The Geysers geothermal field in Northern California is the largest vapor-dominated field in the world. Determining in-situ water saturation at The Geysers will improve the understanding of the resource and allow for a more effective energy recovery.

Despite its long history of production, the underground state of fluids in The Geysers reservoir has never been fully known. It is not known how much water (and steam) The Geysers originally contained or how much it contains now. Nor is it known where the injected wastewater has distributed itself in the reservoir – a significant fraction has been produced again as steam, but we do not know whether the remainder has resaturated only the injection well vicinity or has been dispersed widely into the reservoir. Knowledge of how much water was originally in the reservoir, and how it is distributed currently, will be of great importance in making strategic decisions regarding the future utilization of the resource.

Reyes and Horne (2002) analyzed the available data on The Geysers geothermal field to estimate in-situ water saturation in the reservoir. The pressure and temperature performance data of many of the wells demonstrate "dry-out" due to the formation of superheated steam. Reyes and Horne (2002) inferred the in-situ water saturation of the reservoir by using zero-dimensional models derived from mass and energy conservation equations by Belen and Horne (2000).

The direct measurements of in-situ fluid saturations in The Geysers rock will be helpful to understand the steam and water flow mechanisms and will also be useful to compare to model results such as those reported by Reyes and Horne (2002). Li *et al.* (2001) developed a technique to measure the in-situ fluid saturations in Berea sandstone. However experimental measurements of the in-situ steam and water saturations in The Geysers rock have been few. To this end, an experimental apparatus was designed and built. Steam and water saturations in The Geysers rock were measured. Fluid saturations in the rock sample were monitored and measured using an X-ray CT scanner.

A problem of using the X-ray CT method to measure fluid saturations along the longitudinal direction in the core samples was solved in this study. Significant X-ray beam-hardening effects occur when the core sample is scanned in the longitudinal direction. Installation of core systems in water jackets or in sand packs has been a frequently used method to reduce beam-hardening effects. Such a method may not be convenient and may not work in some cases. A new approach was developed to measure fluid saturations in the longitudinal direction. The main idea is to scan core samples at a specific angle deviated from the longitudinal direction to avoid the edges of the core and the coreholder. The shape of CT images obtained in such a way is elliptical. The fluid saturation in the longitudinal direction can then be inferred according to the angle of deviation.

METHOD

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

$$S_w = \frac{CT_{\exp}(T) - CT_{dry}(T)}{CT_{wet}(T) - CT_{dry}(T)} \qquad (1)$$

where $CT_{wet}(T)$, $CT_{dry}(T)$ are CT numbers of the core sample when it is fully saturated by water and steam 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 of the core measured by using an X-ray CT technique is computed using the following expression:

$$\phi = \frac{CT_{wet}(T) - CT_{dry}(T)}{CT_{water}(T) - CT_{air}(T)} \qquad (2)$$

where CT_{water} and CT_{air} are the CT numbers of water and air respectively.

EXPERIMENTS

Rock and Fluids. The liquid phase used in this study was distilled water; the specific gravity and viscosity were 1.0 and 1.0 cp at 20°C. Steam was the gas phase; the surface tension of water/steam at 20°C was 72.75 dynes/cm, which was assumed to be the same as the surface tension of water/air. The values of the surface tension at high temperatures were calculated from the steam property software developed by Techware Engineering Applications, Inc.

The Geysers rock sample from a depth of about 1410.1m was obtained from the Energy and Geoscience Institute; its porosity measured using an X-ray CT technique was about 3.1 %. The matrix permeability of the rock sample has not been measured yet because of the fractures in epoxy between the core sample and the coreholder. The permeability of a nearby sample measured by nitrogen injection was about 0.56 md (after calibration of gas slip effect), which is probably attributed mainly to the fracture permeability. The length and diameter of this rock sample were 8.89 cm and 8.56 cm.

X-ray CT Scanner. Distribution of water saturation in the core sample was measured using a Picker^{TM} 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. An apparatus was developed to measure in-situ water saturation in The Geysers rock at high temperature. A schematic of the apparatus is shown in Fig. 1.

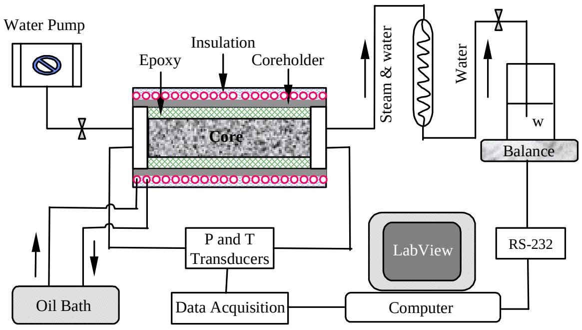

Fig. 1: Schematic of the apparatus used to measure in-situ water saturation.

The apparatus was composed of core and coreholder system, temperature controlling system, pump system (water delivering pump and vacuum pump), production metering system (using a balance), pressure transducers, thermal couples, and data acquisition system. The vacuum pump is not shown in Fig. 1. The data acquisition software used was LabView 6.0 by National Instrument Company.

The vacuum pump (Welch Technology, Inc., Model 8915) was used to remove the air in the core sample in order to generate the steam-water environments. A 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.

Water 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. The water injected into or produced from the core sample was recorded in time by the balance and the real-time data were measured by a computer through an RS-232 interface.

The temperature in the core was controlled automatically using an oil bath (manufactured by VWR, Model 9401) through an external aluminum coil mounted closely on the outside of the coreholder. Aluminum was used to be transparent to the X-rays. In order to obtain a uniform temperature distribution along the core, the aluminum coil was designed as shown in Fig. 2. The oil-in tubing was arranged close to the oil-out tubing. There are two ways to realize this arrangements. One way is to make the aluminum tubing a U-shape first. One end of the U-shape tubing is the oil inlet and another end is the oil outlet. The oil-in and oil-out tubes are put together and then wrapped on the coreholder. Another way is to wrap the oil-in (or oil-out) tube on the coreholder first, from the inlet to the outlet of the coreholder. A U-turn can be made on the end surface of the coreholder and then the tube wrapped back from the outlet to the inlet, as shown in Fig. 2. We chose the latter technique. In such a tubing arrangement, the cooling of the oil temperature in the oil-out tubing could be compensated almost instantly by the oil with high temperature in the oil-in tubing.

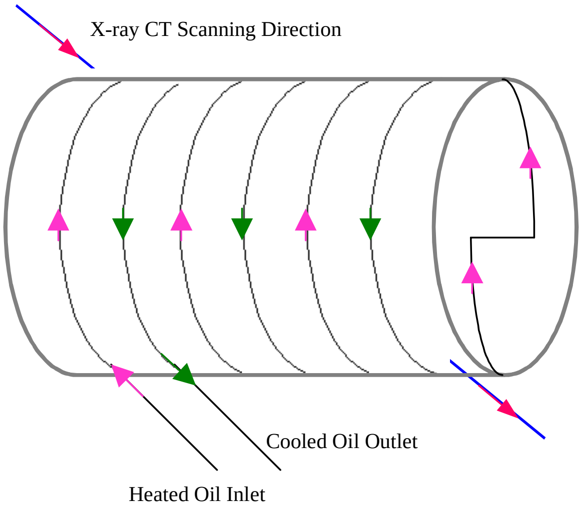

Fig. 2:Schematic of the aluminum coil used to control the temperature in the core.

Temperatures at both the inlet and the outlet of the core were measured during the experiment. We found that temperatures at the inlet were equal to those at the outlet in most cases.

The procedure to make the core system is described briefly as follows. The core was machined and inserted into an aluminum cylinder filled with high temperature epoxy. The core and coreholder system with epoxy was then cured at a temperature of about 160^{o}C. A specific length of the top and the bottom sections of the coreholder with the core sample inside were cut off to remove the epoxy on the top and the bottom surfaces of the core sample. Two end plates with O-rings were then installed to seal the core and the coreholder system using eight screws.

Small cracks in the epoxy between the outside surface of the core sample and the inner side of the coreholder were found after the epoxy was cured. This might be caused by the different heat expansion coefficients among aluminum, rock, and epoxy. Note that we could still measure in-situ water saturation in the core sample by using an X-ray CT technique even with cracks in the epoxy. However we could not measure the permeability of the core in this case.

A picture of the core and the core holder system prior to wrapping insulation material is shown in Fig. 3. The black rubber tubes were the insulation material for the oil-in and oil-out tubing connected to the oil bath. The gantry of the X-ray CT scanner is visible right hand side.

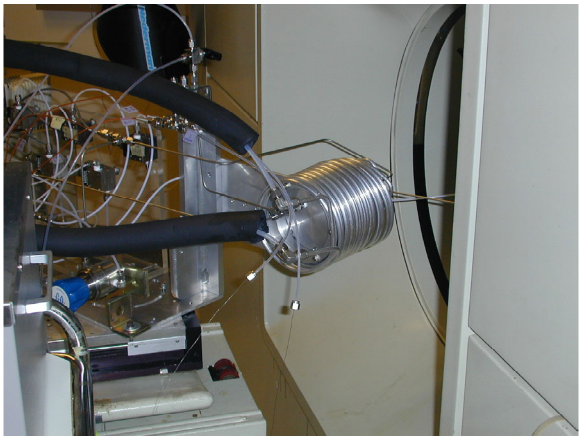

Fig. 3: Picture of the core and core holder system prior to wrapping insulation material.

A picture of the back view of the apparatus after wrapping insulation material over the coreholder is shown in Fig. 4.

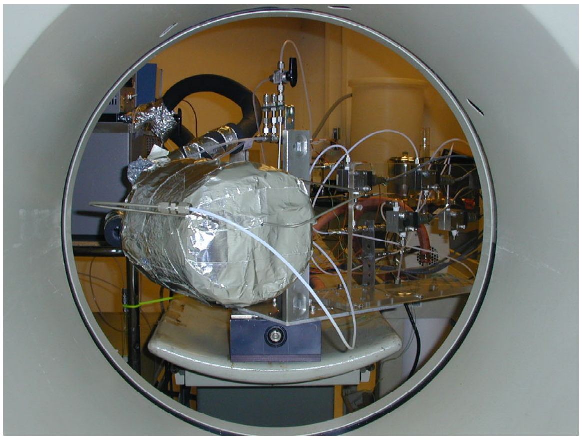

Fig. 4: Picture of back view of the apparatus.

Fig. 5 shows a picture of the whole apparatus. A web camera (installed on the tripod in Fig. 5) was used to monitor the status of the experiments. Because of the long test time, some devices may fail to function. Using the web camera, we could monitor the laboratory whenever we wanted to and from wherever we were, once an internet access is available. We found that it was very convenient and helpful to have the web camera installed.

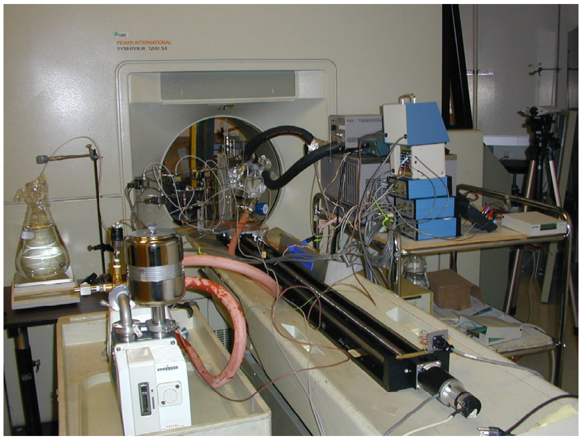

Fig. 5: Picture of the whole apparatus used to measure in-situ water saturation.

Procedure. The apparatus was installed according to the schematic shown in Fig. 1. The core sample assembled in the coreholder was dried by heating to a temperature of about 120^{o}C while pulling a vacuum for approximate 48 hours. The core was scanned from time to time to monitor the variation of water saturation in the rock until the core was dry. The CT value of the dry core (CT_{dry}) was obtained. The core was then saturated with water by pulling a vacuum after the core and the coreholder system was cooled to room temperature. After the saturation of water, the core sample was pressurized to about 75 psi and kept at this pressure for about five days to let the core sample saturate with water completely. The core sample was flooded by water injection following that. The core sample was scanned after saturating with water. The CT value of the wet core (CT_{wet}) was obtained. Porosity of the rock was then calculated using Eq. 1 with these CT values.

The temperature of the core saturated with water was increased from room temperature to about 120^{o}C step by step using the oil bath through the aluminum coil wrapped outside the coreholder. The pore pressure in the core sample was kept about 50 psi, far above the saturation pressure, 14.4 psig, at a temperature of 120^{o}C. The core was scanned from time to time to obseve the effect of temperature on CT values of the core sample.

Pressure in the core sample was decreased gradually to the atmospheric pressure to investigate the dependence of in-situ fluid saturation in the core sample on temperature and pressure. The production was recorded with time.

RESULTS

Fluid saturation in the core sample was measured using a modified X-ray CT technique. As stated previously, scanning the core in a direction at an angle (see Fig. 2) deviated from the axis of the core may reduce X-ray beam-hardening effect caused by sharp edges of rectangular objects. By inclining the core, the cross-section is made elliptical and we were able to obtain the distribution of the CT values from the inlet to the outlet of the core sample through just one scanning.

Fig. 6 shows the CT image obtained by scanning the core sample in the regular longitudinal direction before installed in the coreholder. Significant beam-hardening effect (dark X-shape) can be seen in the diagonal directions on the rectangular area. The core sample was positioned vertically. The CT images obtained by scanning the core sample in the direction perpendicular to the longitudinal axis demonstrated that the image did not have the X-shape distribution of CT values (see Fig. 6). The X-shape beam-hardening effect is often observed if the scanning direction is in the longitudinal direction. Other types of beam-hardening effect may also be observed. All the artifacts caused by the X-ray beam-hardening effect reduce the accuracy of calculating fluid saturations significantly. It is important to obtain CT images without artifacts caused by X-ray beam-hardening effect.

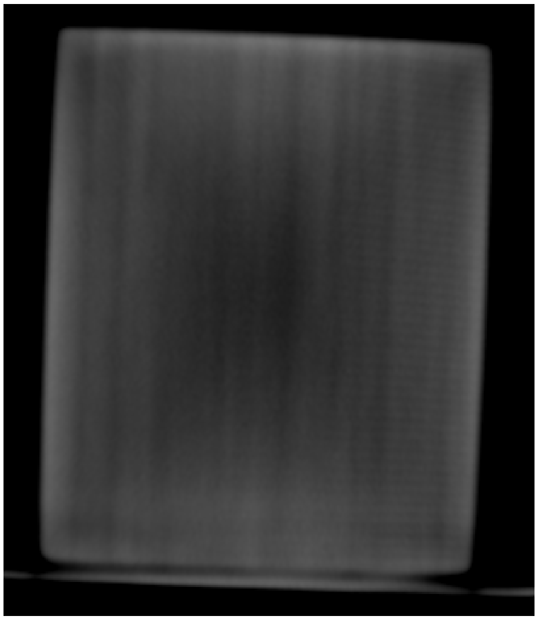

Fig. 6: CT image obtained by scanning the core sample in the longitudinal direction.

The CT image obtained by scanning the core sample at an angle to the longitudinal direction is shown in

Fig. 7. The image shape presented to the scanner becomes elliptical, and the X-ray beam-hardening effects are avoided.

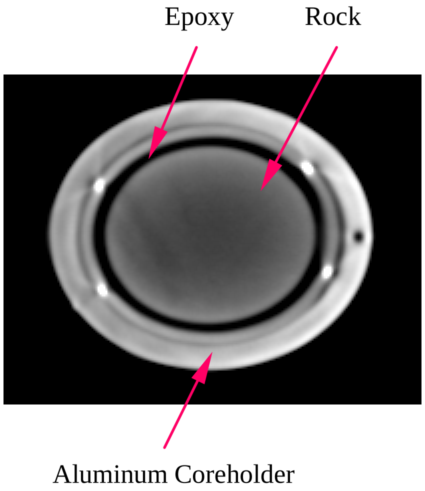

Fig. 7: CT image obtained by scanning the core sample inclined to the longitudinal direction.

One can see from Fig. 7 that the beam-hardening effect was reduced significantly by using the modified scanning technique. Note that the CT image in Fig. 7 has different size from that in Fig. 6. This is because the scanning size (diameter of scanning area) was changed for the image in Fig. 7 to fit the position requirements for the installation of the coreholder.

Li and Horne (2001) observed a significant effect of temperature on the CT value of Berea sandstone saturated with water. However the effect of temperature on CT value of The Geysers rock saturated with water was found to be almost negligible, as shown in Fig. 8. The reason may be because of the small porosity of The Geysers rock. The temperature varied from room temperature to about 120^{o}C.

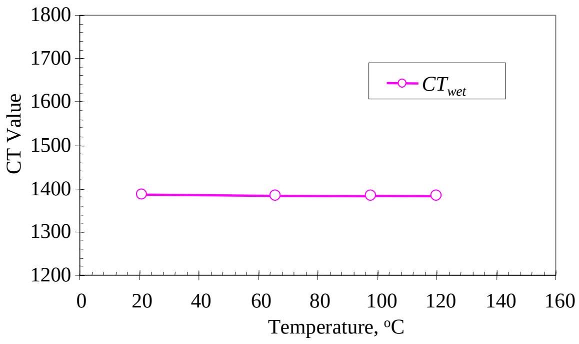

Fig. 8: Effect of temperature on the CT value of the core sample saturated with water.

In the blowdown experiment, the CT value of The Geysers rock saturated with water at a temperature of about 120^{o}C decreased with decrease in the pore pressure, as shown in Fig. 9.

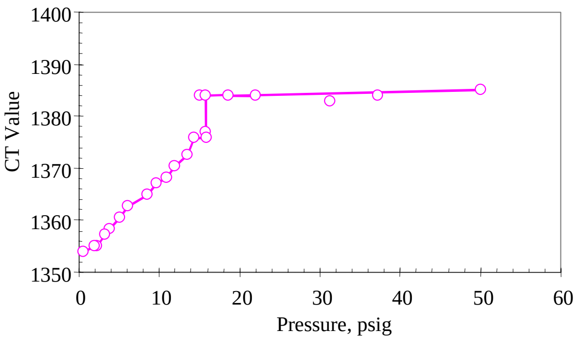

Fig. 9: Pressure and CT value history of The Geysers rock saturated with water.

The values of the in-situ water saturation were calculated using Eq. 1 with the CT data shown in Fig. 9. The results are plotted in Fig. 10. The variation of the in-situ water saturation with pressure is similar as the variation of the CT value (CT_{wet}) with pressure (see Fig. 9).

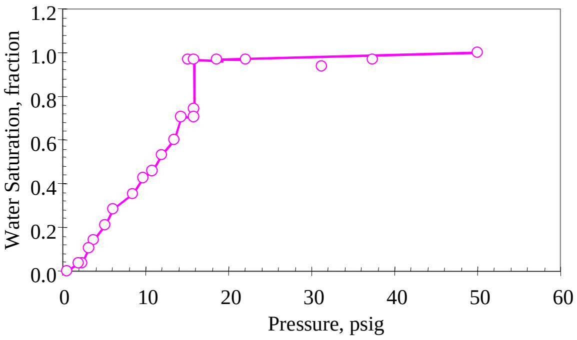

Fig. 10: Variation of in-situ water saturation in The Geysers rock with pressure at a temperature of 120^{o}C.

One can see from Fig. 10 that there is a sharp drop in the water saturation at a pressure close to the saturation pressure (14.4 psig) at 120^{o}C. The corresponding in-situ water saturation is about 70%. This value should represent the immobile water saturation in the core sample. Note that this value obtained in The Geysers rock is much greater than those measured in Berea sandstone reported by Li *et al.* (2001) and Horne *et al.* (2000). Li *et al.* (2001), who conducted similar experiments in Berea sandstone, also observed a sharp drop in water saturation at a pressure close to the saturation pressure. The corresponding in-situ water saturation in Berea sandstone was about 38%. Note that water saturation was not measured using an X-ray CT technique in that study. Instead, a weighing method was used. So the water saturation measured by Li *et al*. (2001) represented the average value in the whole core.

Horne *et al*. (2000) measured steam-water relative permeability in Berea sandstone using an X-ray CT technique. The measured value of the immobile water saturation in the Berea sandstone sample with a permeability of 1200 md was about 27%. This value is much smaller than the value of 70% in The Geysers rock, as stated previously. The reason may be because of the extremely low permeability of The Geysers rock.

Estimates of the initial in-situ water saturation inferred using field data in a zero-dimensional model by Reyes and Horne (2002) for The Geysers geothermal reservoir ranged from 13.7% to 48.7%. Note that these are not inconsistent values, since there is no constraint that the initial water saturation be equal to the immobile water saturation.

Reyes and Horne (2002) reported that vapor-dominated geothermal reservoir under exploitation can be locally depleted of water to form a dry or superheated zone. One can also observe such a phenomenon in the experiments conducted in this study, as shown in Fig. 10. After the sharp drop, the in-situ water saturation in The Geysers rock decreased to zero gradually (see Fig. 10) as the pore pressure decreased to atmospheric pressure. Compared to Berea sandstone, the decrease in the in-situ water saturation in The Geysers rock is slower.

DISCUSSION

The experimental results reported in this article are preliminary because of the very limited number of experiments conducted. It took a long time for almost every step and procedure, even for saturating the core with water. One day after saturation with water by pulling a vacuum, the inlet and the outlet of the core system were closed. Following that, the pressure in the core sample was monitored continuously. It was found that the pore pressure in The Geysers rock went below the atmospheric pressure. We speculated that the reason might be because of the extremely low permeability of The Geysers rock. It may take a very long time for water to get into the rock with low permeability just by pulling a vacuum.

In order to saturate the core sample with water completely, water was injected continuously. The inlet and the outlet were closed after a specific period of water injection to see if the pore pressures were going down. Water injection did not stop until the pore pressure could stabilize after the inlet and the outlet ends were closed. Then the core sample was pressurized to about 50 psig to further saturate with water.

The in-situ water saturation in the Geysers rock was decreased from 100% to zero by decreasing the pressure in the core sample. It also took a long time to stabilize the pore pressure in the matrix of the core sample after drawing down the pressure in fractures by opening the outlet valve.

CONCLUSIONS

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

1. A technique was developed to reduce X-ray beam-hardening effects for the measurement of water saturation in a direction inclined to the axis of the core sample.
2. The apparatus developed in this study to measure in-situ water saturation directly works properly in The Geysers rock.
3. The immobile in-situ water saturation in The Geysers rock measured using the technique developed in this study was about 70%. This value represents the saturation of the rock matrix itself, since the core sample did not include large fractures such as may be present in the reservoir itself.
4. The water saturation in The Geysers rock can reduce to zero as pressure depleted below the saturation pressure.
5. The experimental observation is not inconsistent with the estimates of the water saturation based on field data.

ACKNOWLEDGEMENT

This research was conducted with financial support to the Stanford Geothermal Program from the California Energy Commission PIER, the contribution of which is gratefully acknowledged. The assistance of Will Whitted in the machining and assembling of the coreholder is gratefully acknowledged. Assistance of Chih-Ying Chen in programming is also acknowledged.

NOMENCLATURE

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_{exp} = CT number of a core sample when it is saturated with both water and air or steam
S_w = water saturation
T = temperature
ϕ = porosity

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