PROCEEDINGS, Twenty-Second Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 27-29, 1997
SGP-TR-155

EXPERIMENTS OF BOILING IN POROUS MEDIA

Cengiz Satik

Stanford Geothermal Program
Stanford University
Stanford, CA 94305-2220

ABSTRACT

The objective of this work is to improve the understanding of the process of boiling in porous media. The ultimate goal is to obtain the two important but currently unknown functions of relative permeability and capillary pressure functions. One horizontal and one vertical experiment were conducted using Berea sandstone core samples. Difficulties were encountered in analyzing the results of the first preliminary boiling experiment: namely the apparent existence of a steam phase at inappropriately low temperatures. These results suggested several improvements to the design of the experimental apparatus. Upon the completion of these modifications, further horizontal and vertical experiments were conducted Three-dimensional porosity and steam saturation distributions were determined using an X-ray CT scanner. The maximum difference between the centerline and wall temperatures for the horizontal experiment was found to be less than **2** °C, therefore, wall measurements were shown to be adequate to represent the temperature of a circular slice along the core. The steam saturation distributions calculated from the X-ray CT data did not show a significant steam override in any of the experiments. Steady-state steam saturation data showed a progressive boiling process with the formation of the three regions of steam, two-phase and liquid as the heat flux was increased The previous problem of steam existing at inappropriate temperatures was not observed in the later vertical experiment. A comparison of the three-dimensional saturation profiles from both experiments showed a longer two-phase zone in the horizontal boiling case than that in the vertical case.

INTRODUCTION

The process of boiling in porous media is of significance in geothermal systems as well as in many other applications such as porous heat pipes, drying and nuclear waste disposal. Despite its importance in these applications, the fundamentals of this process are poorly understood. Most of the problems arise from the lack of the understanding of the mechanics and dynamics of this complex process.

A look at the previous literature shows that many attempts have been made in both experimental and theoretical directions to investigate and to describe the process of boiling in porous media (Satik, **1994).** Most previous studies have used continuum formulations which made use of Darcy's law extended to multiphase flow with relative permeability and capillary pressure functions derived from isothermal gas-liquid displacement processes. These processes have major differences to boiling displacement which involves additional phenomena such as heat transfer, nucleation and phase change. Moreover, the continuum approaches are also limited by the assumption of capillary control at the pore level (low Capillary and Bond numbers). Due to these restrictions and uncertainties, it is unclear whether the relative permeability and capillary pressure functions currently used for modeling the process of boiling in porous media are appropriate.

At the same time, fundamental studies focusing at the microscopic pore scale have been very limited. In a recent study by Satik and Yortsos **(1996),** numerical and experimental pore networks were used to model boiling in porous media at a microscopic pore scale. Satik and Yortsos **(1996)** developed a numerical pore network model for boiling in a horizontal, two-dimensional porous medium and conducted visualization experiments by using glass micromodels. Although progress was made, their model was developed only for a single bubble growth problem in a horizontal porous medium, ignoring the effects of gravity. Therefore, further work is still needed to improve the understanding and to resolve the issues raised by the continuum formulations (see Satik, **1994,** for details) and eventually to obtain correct forms of the relative permeability and capillary pressure functions.

In this work, we used a different technique to study this problem. We conducted boiling experiments with real core samples such as from Berea sandstone. Using an X-ray computer tomography (CT) scanner, we visualized the process and determined the three-dimensional fluid distributions within the core while the experiment was in progress. By using thermocouples, pressure transducers and heat flux sensors under the control of a data-acquisition system, we obtained temperature, pressure and heat flux values along a core, respectively. The comparison of the experimental data with the results of a numerical simulator will give us an opportunity to check the results Moreover, using an optimization tool along with a numerical simulator combined with experimental results, the appropriate form of the relative permeability and capillary pressure functions can be obtained. Our ultimate goal is to be able to carry out these experiments with core samples taken from The Geysers geothermal field in California. Concurrent efforts are being directed towards the construction of an apparatus that can be used to carry out boiling experiments with low permeability core samples.

This paper reports on the results of two experiments conducted using Berea sandstone core samples. The core was positioned horizontally in the first experiment while it was vertical in the second one. Two complete sets of experimental data were collected. These will be discussed in detail here. The paper is organized as follows: We first describe the experimental apparatus, discuss the procedure followed and finally present the results of the two experiments.

EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic of the experimental apparatus is shown in Figure]. The apparatus consists of a core holder, a data acquisition system, a vacuum pump, a liquid pump and a balance. Ten pressure taps and thermocouples are placed along the core length to measure pressures and temperatures, respectively. A heater and a heat flux sensor are placed in the specially designed inlet end of the core holder. In addition, several heat flux sensors are placed along the core to measure heat losses. During an experiment, the core holder is placed inside the high resolution X-ray CT equipment to obtain ***in-situ*** saturation profiles along the core. During CT scanning, an X-ray source is revolved around the object to take various projections at many angles and the data collected are then used to reconstruct the internal image. The method causes an averaging of X-ray attenuation as X-ray beams travel through the object while changes in density and/or thickness of the material cause differences in X-ray attenuation (Johns ***et al.***, **1993).**

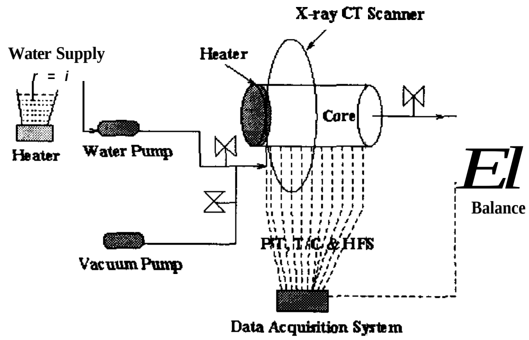


Figure 1: Schematic of the experimental apparatus.

The experimental procedure is as follows. First, air inside the pore space is removed by vacuuming the core. The core is then scanned at predetermined locations to obtain dry-core CT **(CT,,,)** values. Next, deaerated water is injected into the core. This step continues until the core is completely saturated with water, at which time the core is X-ray scanned again at the same locations to obtain wet-core CT **(CT,,,)** values. Also, pressure readings are taken at this time to calculate the absolute permeability of the core. Steady-state boiling experiments mainly involve the injection of heat into the core at varying power levels. During the experiment, the heating end of the core is closed to fluid flow while the other end is connected to a water reservoir placed on a balance. The balance is used to monitor the amount of water coming out of the core during the process. The core holder is covered with a 4 inch thick layer of insulation material to reduce the heat losses. In addition, several heat flux sensors are placed along the core to measure the actual heat losses. Continuous measurements of pressure, temperature and heat flux are taken during each heat injection rate step until steady state conditions are reached. During the boiling process each step continues until the water production rate becomes zero, and the pressures, temperatures and heat fluxes stabilize; these are indications of steady-state conditions. At the onset of steady-state conditions, the core is scanned again at the same locations to obtain CT **(CT,,,)** values corresponding to the particular heat flux value. To complete the set of measurements, pressure, temperature and heat flux readings are recorded again. The heat flux is then changed, and the full procedure is repeated. After the experiment is completed, the porosity and saturation distributions ire calculated from the **CT** values. More complete details of the calculation method were given in Satik *et al.* (1995).

The porosity distributions at various locations along the core are calculated by inserting **CT„** and **CT„** values into the following equation:

$$\phi = \frac{CT_{wet} - CT_{dry}}{CT_{water} - CT_{air}} \qquad (1)$$

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

Steam saturation distributions are also calculated by using the following equation:

$$S_{steam} = \frac{CT_{wet} - CT_{exp}}{CT_{wet} - CT_{dry}} \qquad (2)$$

RESULTS

Two experiments were conducted using two different Berea sandstone core samples. The core sample was positioned horizontally in the first experiment while it was positioned vertically in the second experiment. Two complete sets of experimental data were obtained from these experiments for the case in which the heat flux was increased. These included porosity and saturation distributions determined using the X-ray CT data, and also pressure, temperature and heat flux readings. The results obtained from these two experiments are discussed below.

The length and diameter of the cores used in both experiments were 43 cm and 5.04 cm, respectively. Before being used in each experiment, both cores were scanned using the X-ray CT scanner at various locations to ensure that they were free of inhomogeneties. Both cores were found to have very similar X-ray CT images. By using the Darcy equation with the results of the wet-core step during each experiment, the absolute permeability of both cores was calculated to be around 500 md. During both experiments, we scanned a total of 42 slices along the core. Using Equation (1) and dry and wet X-ray CT data, a three-dimensional porosity profile of each core was constructed. All of those slices for each core indicated a fairly homogenous core. The porosity data were then averaged over each circular slice in order to obtain porosity profiles given in Figure 2. The figure shows a uniform porosity distribution for both cores. The minimum, maximum and average porosity values were calculated to be 0.196, 0.208 and 0.2012 for the first core and 0.1826, 0.1881 and 0.1865 for the second core, respectively.

Recently, we reported the preliminary results from an earlier horizontal boiling experiment (Satik and Home (1996). Rather unusual temperature profiles were found in the experiment. Comparison of the steam saturation profiles obtained from the X-ray CT scanning with the corresponding temperature and pressure profiles indicated an inconsistency. The steam saturation profiles showed non-zero values up to temperatures of as low as 50 °C. Although pressures were not measured during this experiment they were assumed to be above atmospheric pressure since the outlet of the core was connected a water reservoir placed next to the core. This unusual behavior was initially attributed to air trapped inside porous medium and air dissolved in the water used to saturate the porous medium (Satik and Home, 1996). To remedy this problem, the experimental procedure was changed to remove any possible preexisting gas phase in the system. During the new procedure, the core was first vacuumed to 0.00319 psi before the experiment. The water used to saturate the core was then deaerated by preboiling it in a container.

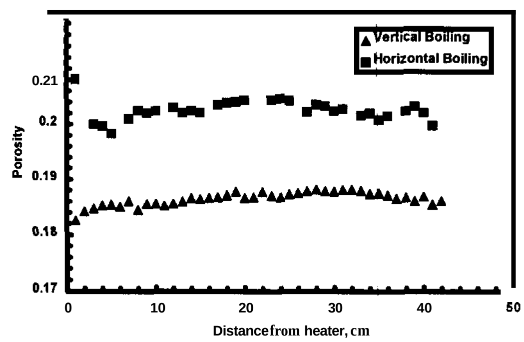


***Figure 2:** Average porosity profiles along the core, calculated from X-ray CT data obtained during both boiling experiments.*

During the first experiment, in which the core was horizontal, the core was scanned and three-dimensional porosity distributions were obtained eight times before and after heating in order to observe the first formation of the steam phase. These three-dimensional porosity distributions were then averaged over each circular cross-section of the core that was scanned in order to obtain the average porosity profiles, four of which are given in Figure 3. All of the curves displayed in the figure, except the curve at 2770 min, show a fairly uniform porosity profile along the core and are within close proximity to each other. The deviation of the curve at **2770** min at distances closer to the heater suggests the first appearance of the steam phase. The comparison of all eight porosity curves with pressure and temperature data indicated that a steam phase did not appear until the appropriate boiling temperature. This results is important because it confirms that air was successfully removed from both porous medium and the water used to saturate it.

Both boiling experiments were conducted by increasing the heater power setting incrementally to reach a desired heat flux value. Figure 4 shows the history of the heater power settings and the heat flux values obtained from heat flux sensors for both horizontal and vertical experiments. The same heater was used in both experiments, thus the magnitude of the power generated by the heater was similar in both cases at the same power setting value.

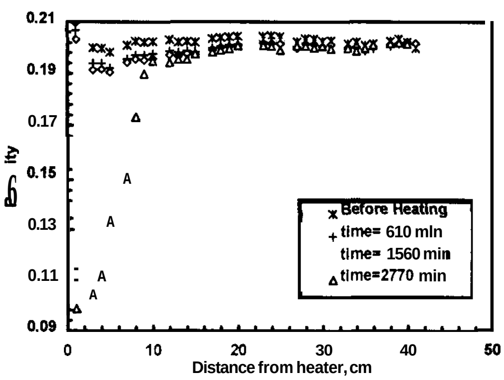
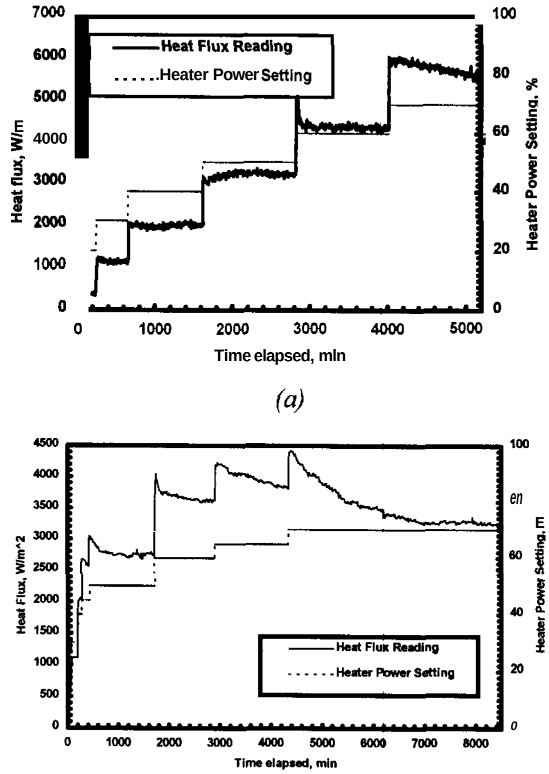


Figure 3: ***Average porosity profiles along the core, obtained*** *from* ***the X-ray*** *CT* ***scanning conducted at four times during the horizontal boiling experiment.***

During the horizontal experiment, we recorded both the centerline and wall temperatures at ten locations along the core. The centerline temperatures were measured in thermowells extending to the center of the core. The wall temperatures were measured over the outer layer of the epoxy and next to the thermowells. In Figure 5, we show the comparison of the histories of the centerline and wall temperatures obtained at four locations along the core length. The figure shows both transient and steady state (where the temperature profile flattens) sections of the temperature profiles at each heater power value. The maximum temperature reached during the first experiment was 225°C. As shown in Figure 5, the maximum difference between the two temperature profiles was less than **2°C.** This suggested that the radial temperature gradient along the core was not significant for this set of experimental conditions and therefore it would be adequate to measure wall temperatures only.



(b)

Figure 4: Heater power settings and corresponding heat flux values obtained *from* ***the heat flux sensor: (a) horizontal experiment, (b) vertical experiment***

The core was scanned several times to obtain three-dimensional steam saturation distributions during the experiment. These three-dimensional steam saturation distributions were then averaged over each circular cross-section of the core that was scanned in order to obtain the average steam saturation profiles. In Figure ***6***, we show four of these saturation profiles. The saturation profile at **2770** min shows a two-phase (steam and water) zone followed by a completely water-filled zone while the profile at 5**130** min shows three distinct regions of completely steam, two-phase and completely water. As expected, the steam saturation is higher at locations closer to the inlet, where the heater is located, and decreases towards the outlet.

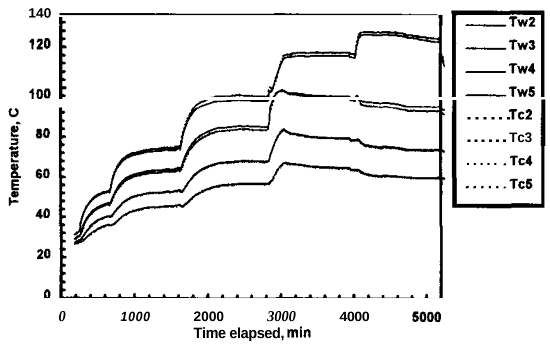


Figure 5: Comparison of the histories of four centerline and wall temperatures during the horizontal boiling experiment.

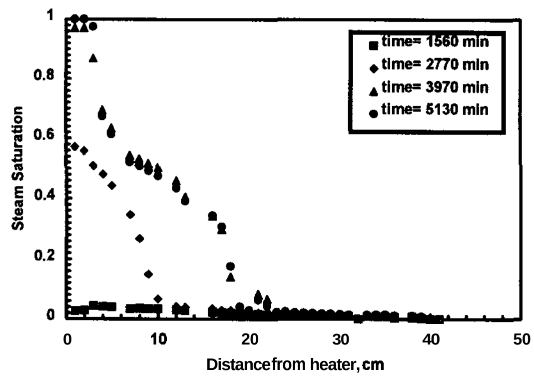


Figure 6: Average steam saturation profiles along the core, calculated from X-ray CT data during the horizontal experiment.

The comparison of the saturation profile with the corresponding centerline temperature profile at 5130 min is shown in Figure 7. Steam saturation at 100^oC is about 56% and vanishes at about 52^oC. This suggests that the previous problem of the apparent existence of a steam phase at inappropriate temperatures still existed. This behavior was also observed on the other profiles obtained at different.

Following the horizontal experiment, another experiment was conducted with the core holder positioned vertically to study the effect of gravity on the results. Since the core used for the horizontal experiment had developed extensive cracks during the cooling stage, another core that had similar properties was prepared and used for the vertical experiment. This experiment was also carried out by varying the heater power setting from 20% to 70% incrementally (Figure 4b). Again, to ensure the removal of any gas phase existing in the porous medium or dissolved in the water saturating it, the procedure employed in the first experiment was also used in the vertical experiment.

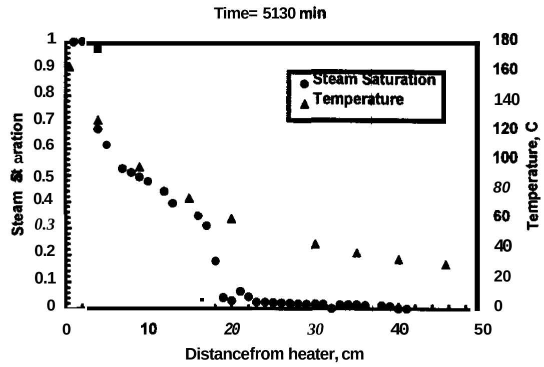
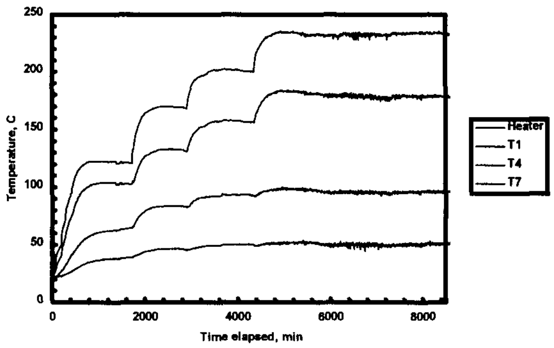


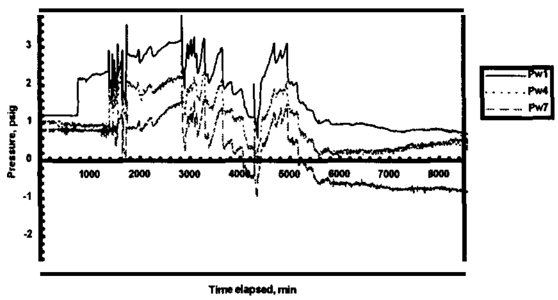
Figure 7: Comparison of the steam saturation and temperature profiles along the core during the horizontal boiling experiment.

Measurements of temperature and pressure were taken at ten locations along the core during the experiment. The temperature profiles in Figure 8a show the transient and stabilization stages of each power change. On the other hand, the pressure profiles seem to exhibit an oscillatory behavior until about 5500 min at which time they start to stabilize (Figure 8b). Although not recognizable due to the scale of the graph in Figure 8a, these oscillations also exist in the temperature profiles.

In Figure 9, we show pressure, temperature and saturation profiles obtained at four times during the vertical experiment. Each profile was obtained at the onset of steady-state conditions after each time the heater power was changed. At the beginning of the heating (the curves at 0.022 min), temperatures, pressures and steam saturations along the core was at room temperature, hydrostatic pressure and zero, respectively. After the heater power was increased to 50% (see also Figure 4b) temperatures close the heater started to raise (Figure 8a). The saturation profile at 1610 min shows about 60% steam saturation at the closest location to the heater. The corresponding pressure profile is consistent with the saturations, showing higher pressures closer to the heater that may also indicate the formation of steam phase. As the heater power was increased further, dry-out conditions occurred, leading to existence of the three zones of dry steam, two-phase and liquid water zones (profiles at 2795, 4230 and 8550 min). However, the pressure profiles at 4230 and 8550 min show an unusual behavior, a decrease at all locations along the core. Currently we do not understand the cause of this pressure drop but it could be attributed to a small leak in the core or to a complication with pressure transducers. The pressures increased again during the cooling stage of the experiment, indicating a possible problem with the pressure transducers. To improve the accuracy of pressure measurements in the experiments, the acquisition of more accurate pressure transducers is in progress.



(a)

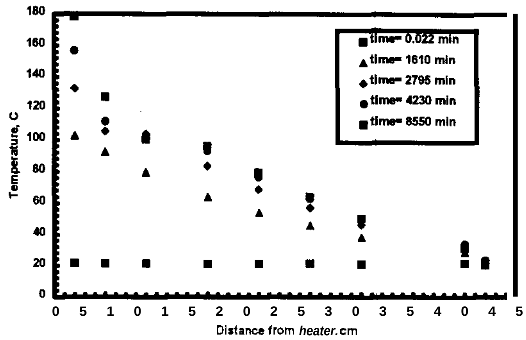


(b)

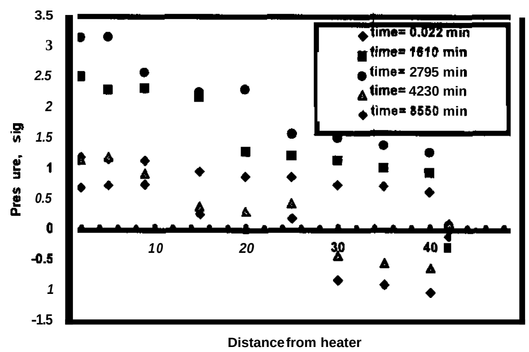
Figure 8: Histories of (a) temperature and (b) pressure obtained during the vertical boiling experiment.

The temperature profiles showed consistent behavior this time. The previous problem of steam phase existing at inappropriate temperatures did not exist in this experiment. **As** illustrated in Figure10, the steam saturation profile indicates a dry steam zone and a liquid water zone connected by a two-phase region. Temperatures are consistent with saturations: **A** substantial temperature drop in the *dry* steam zone is due to the low steam-phase thermal conductivity, a rather small temperature gradient in the two-phase zone is due to the pressure gradient and heat losses and the temperature profile in liquid water zone.

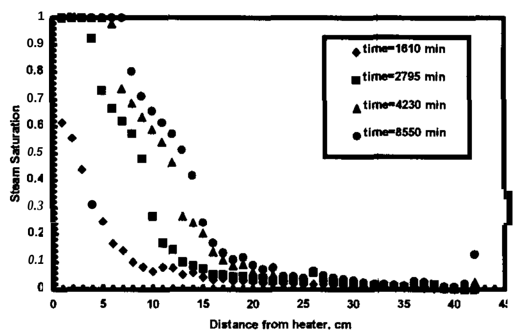
In Figure 11, we show three-dimensional steam saturation profiles, obtained by X-ray CT scanning, at four times during the vertical experiment. The time values corresponding these four images are 1610, **2795, 4230,** and 8550 min. The first image shows a two-phase zone followed by liquid water zone while the other three images have the three regions of steam, two-phase and liquid water. These images also show that the boundary between the *dry* steam and two-phase zone is sharp, indicating a uniform temperature distribution within the *dry* steam zone. The two-phase zone, on the other hand, has **a** different behavior. Within the two-phase zone, steam saturation is higher towards the edges of the core while the water saturation is higher closer to the centerline of the core, indicating a possible two-phase convection.



(a)



(b)



(c)

Figure 9: Steady state (a) pressure, (b) temperature and (c) steam saturation profiles along the core, obtained during the vertical boiling experiment.

Finally, in Figure 12 we show a comparison of the steam saturation profiles of both horizontal and vertical experiments at the same power values. These results show the effect of gravity. In the horizontal case, the length of the dry steam zone is shorter and he two-phase zone is longer than those in the vertical :ase. These results are expected since the two-phase zone, which has large compressibility, is expected to ;hrink in the vertical case simply due to the gravity of the liquid layer overlaying it.

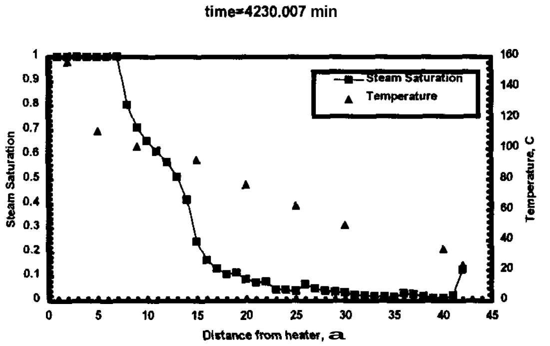


Figure 10: Comparison of the steam saturation and temperature profiles along the core during the vertical boiling experiment

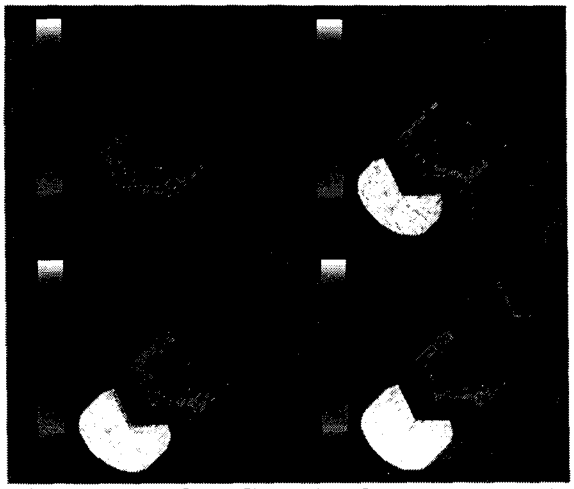


Figure 11: Three-dimensional steam saturation distributions along the core, calculated from the X-ray CT data obtained at four times during the vertical experiment.

CONCLUDING REMARKS

Two boiling experiments were conducted by using Berea sandstone core samples: one with a horizontal core and another with a vertical core. In a previous paper (Satik and Home, 1996), we reported on the results of the first preliminary horizontal boiling experiment during which we observed an inconsistency in the apparent existence of a steam phase at inappropriately low temperatures.

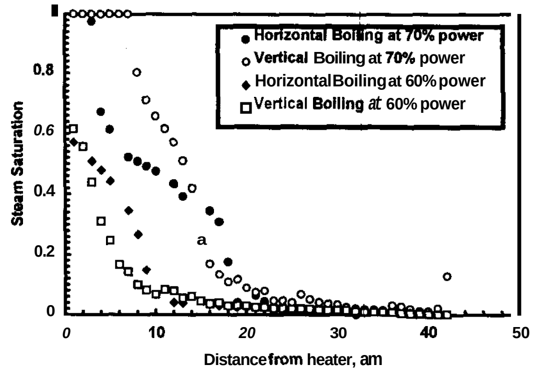


Figure 12: Comparison of the steam saturation profiles obtained at the same heater power values during the horizontal and vertical experiments.

Analysis of the results suggested several improvements on the design of the experimental apparatus and procedure (Satik and Home, **1996).** With the new apparatus and procedure, one horizontal and one vertical experiment were conducted. Using an X-ray CT scanner, three-dimensional porosity and steam saturation distributions were obtained during the experiments, Temperatures, pressures and heat fluxes were also measured. In the new experimental method, both the core and the water used to saturate it were deaerated before the experiments. Both centerline and wall temperatures were measured during the horizontal experiment. The maximum difference between the centerline and wall temperatures was found to be less than 2°C, hence the wall temperatures were found ta be adequate to represent the temperature of a circular slice along the core. Steady-state steam saturation distributions showed a progressive boiling process with the formation of the three regions of steam, two-phase and liquid as the heat flux was increased. The steam saturation distributions obtained using the X-ray CT data did not indicate any significant steam override in either experiment. The previous problem of steam existing at inappropriate temperatures was not observed in the vertical experiment although it persisted to a small extent in the horizontal case. The cause of this effect is still undetermined. Comparison of the three-dimensional saturation profiles from both experiments indicated a longer two-phase zone in the horizontal case than that in the vertical case. This result is expected since the two-phase zone has higher compressibility. Pressure data obtained from both experiments indicated possible problems with pressure transducers. Improvements to the accuracy of the pressure measurements are currently in progress.

,EDGMENTS

I'his work was supported by DOE contract DE-
ꟳG07-95ID13370 through Stanford Geothermal
ᴾrogram, the contribution of which is gratefully
tcknowledged. The author also would like to thank
I'hembile Mtwa for his assistance with the
ꞓxperimental work.

REFERENCES

[. Johns, J.R., Steude, J.S., Castanier, L.M. and Roberts, P.V., 1993, "Nondestructive Measurements 3f Fracture Aperture In Crystalline Rock Core Using X-Ray Computed Tomography", *J. Geophys. Res.*,)8(B2), 1889-1900

2. Satik, C., 1994, "Studies In Vapor-Liquid Flow In Porous Media", ***Ph.D. Thesis,*** University of Southern California, Los Angeles, CA

3. Satik, C., Ambusso, W., Castanier, L.M. and Horne, R.N., 1995, "A Preliminary Study of Relative Permeability In Geothermal Rocks", ***Trans. GRC,*** 19,539

4. Satik, C. and Yortsos, Y.C., 1996, "A Pore Network Study Of Bubble Growth In Porous Media Driven By Heat Transfer", ***J. Heat Transfer,*** 118

5. Satik, C. and Horne, R.N., 1996, "An Experimental Study of Boiling In Porous Media", ***Trans. GRC,*** **20**, 839