PROCEEDINGS, Twenty-Fourth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 25-27, 1999
SGP-TR-162

AN EXPERIMENTAL INVESTIGATION OF BOILING HEAT CONVECTION WITH RADIAL FLOW IN A FRACTURE

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ABSTRACT

Experimental apparatus containing circular disks of Geysers core (graywacke), highly porous sandstone, and non-porous aluminum were used to investigate and compare the temperature gradients that develop during boiling with liquid injection into a radial fracture. These experiments were designed to quantify the heat flux associated with water flashing to steam in a fracture, and to investigate the degree of coupling between the heat flux, flow rate, and the vapor fraction in the fracture. A preliminary comparison of data from experiments with porous and nonporous materials indicates that while heat transfer on nonporous surfaces is strongly coupled to the flow regime and vapor fraction, the heat flux to porous rock surfaces appears to be much less sensitive to the flow regime and vapor fraction. The magnitude of boiling heat fluxes and temperature gradients for Geysers graywacke, sandstone, and non-porous aluminum are compared and discussed.

BOILING ON NON-POROUS AND POROUS SURFACES, BACKGROUND

It is well documented that the boiling heat flux on non-porous surfaces is highly dependent upon the flow regime, and especially the vapor fraction in contact with the heated surface (Carey, 1992). Boiling on porous rock surfaces, however, exhibits phenomena unlike boiling on non-porous surfaces because vaporization occurs at some depth beneath the surface. Calhoun (1947), Udell (1982) and others have described the physics of vaporization in porous media. These works describe and model the fundamental thermodynamics of boiling in porous media since the temperature and pressure required for the expansion of vapor in a pore can be related to capillary pressure, which is associated with pore size and interfacial tension.

The interaction of rock and fluid properties on porous surfaces has been further investigated by Solevev (1984), Stryrikovich (1987), and Kovalev (1987). For example, Kovalev illustrates the major differences between boiling on non-porous and porous surfaces with an illustration similar to Figure 1. This simplified and adapted figure qualitatively illustrates the shape of the relation between heat flux and excess temperature, (ΔT_e), for porous and non-porous materials, where ΔT_e is defined as the temperature of a surface above the saturation temperature of the fluid. Kovalev points out that the magnitude of the heat flux for the porous boiling curve is only greater when the porous material has a high thermal conductivity and a large permeability, which is the case illustrated in Figure 1.

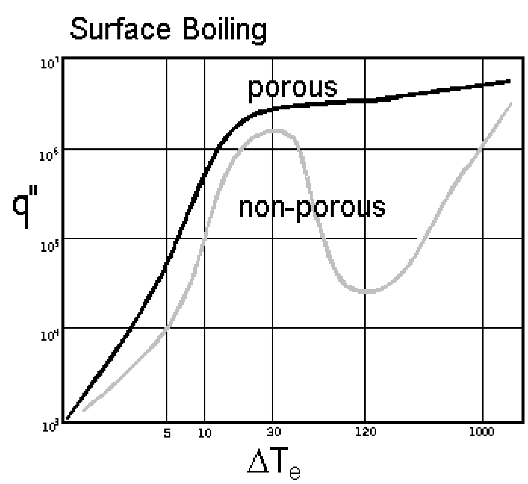

Figure 1. A qualitative illustration of boiling curves for porous and non-porous surfaces.

Two significant differences between surface boiling of porous and non-porous materials are described by this simplified figure.

First, boiling on a porous surfaces occurs with a higher heat flux at lower ΔT_e. Second, there is no local maximum followed by a decline in heat flux with increasing ΔT_e for the porous surface, as occurs with non-porous surfaces. This decline in heat flux for non-porous surfaces is due to an increasingly large vapor fraction in contact with the surface, which lowers the overall thermal conductivity of the fluid in contact with the surface. This figure suggests that boiling on a rock fracture surface may be, to some degree, de-coupled from the vapor fraction of the fluid in that fracture. We hypothesize this is due to the fact that boiling occurs within the pores adjacent to the fracture surface, not on the surface itself. The results and some discussion of experiments designed to investigate these phenomena follow.

EXPERIMENTAL PREPARATIONS

The apparatus illustrated in Figure 2 was designed to provide a relatively uniform temperature on the bottom of a rock sample and to quantify the heat flux and temperature gradients associated with liquid water flashing to steam on a uniformly smooth rock fracture surface. Because experiments with Geysers core were conducted in October, 1998, while experiments with sandstone and non-porous aluminum were conducted this January, the preparation of heater assemblies and rock samples differ slightly. These differences are discussed below, but the experimental apparatus is essentially described by Figure 2.

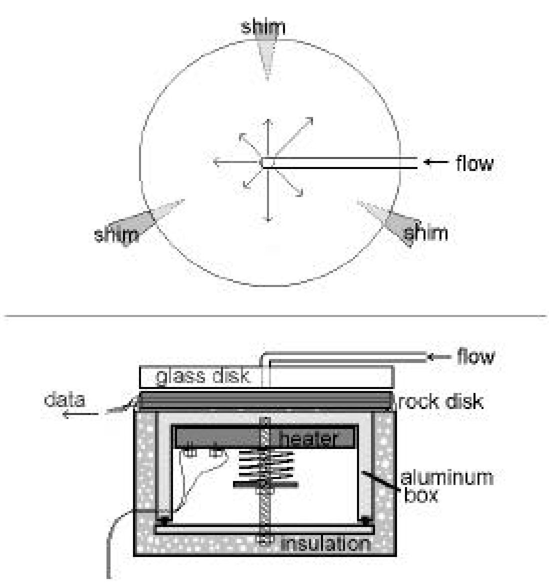

Figure 2. Heat flux-Temperature gradient measurement experimental apparatus design.

Preparation of Geysers core rock sample

The left side of Figure 3 illustrates how thermocouples were placed between thin slices of rock at three levels from the top of the graywacke disk. Six thermocouples were positioned in the interior of the rock disk and three were placed on its bottom surface along with a heat flux sensor. As illustrated in Figure 2, the top surface of the rock was separated from a glass disk with small shims. The aperture between the rock disk and the glass formed a uniform and smooth fracture. The glass disk on top has a hole at its center for the injection of fluid into the fracture.

The three thin rock disks were prepared with a surface grinder to achieve flat well-mated surfaces. Thermocouples were placed on the aluminum heater box, and at each interface between rock disks. The outer edge of the rock was sealed with epoxy and silicone to prohibit radial flow within the rock and to restrain radial heat conduction. The thermocouples were located on the interfaces between disks radially 1.5 centimeters from the center. The circular aluminum box and rock disks were about 11.5 centimeters in diameter, and the sides and bottom of the aluminum were insulated with fiber board insulation and coated on the outside with RTV silicone. Thus, both the heat flux and temperature gradient normal to the surface of the rock would be measured near the center.

In order to have good thermal contact with the rock, a heat sink compound was used between the rock and the metal box containing the heating element. The rock surface closest to the heater was coated with a thin film of high temperature epoxy to prevent the spontaneous imbibition of oil from the heat sink compound from entering the rock. The other surfaces were not treated except that shallow grooves were cut in the rock surfaces to provides spaces for the placement of thermocouples.

The top surface of the heating element box was machined for the thermocouples and heat flux sensor to rest beneath the base of the rock disk. Three thermocouples were placed 1.5 cm radially out from the center, separated from one another by an angle of 120 degrees, at two levels within the rock. Each of the rock disks, from the bottom to the top surface of the rock were, respectively, 3.10 mm, 4.19 mm, and 3.58 mm thick. These dimensions determined the distances between the thermocouples and the fracture surface.

Preparation of sandstone and aluminum samples

Thermocouples were placed somewhat differently in the aluminum and sandstone disks. As shown on the right side of Figure 3, these disks had small holes drilled for a close tolerance fit at 4 different levels within each material. Again, the thermocouples were placed 1.5 cm radially out from the center

Also, a better insulated copper heating element box was built for the more recent experiments to minimize undesired heat losses. It was machined to hold two heat flux sensors on the surface above the electric heating element. Although not illustrated here, the heating element box was essentially the same as that pictured in Figure 2, but it was better insulated.

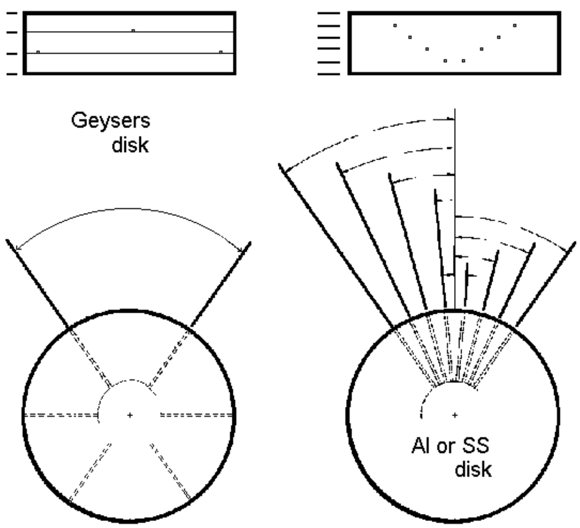

Figure 3. Cutting or drilling and placement of thermocouples in Geysers graywacke, sandstone, and aluminum disks.

The sandstone disk was machined circular and ground flat at 2 cm thick, and had epoxy applied to the bottom surface to prevent the oil from thermally conductive paste from imbibing into the sample. Holes were drilled at levels 2.7 mm, 6.1 mm, 9.9 mm, and 13.5 mm from the top (fracture) surface. The aluminum disk was prepared similarly, except its total thickness was a little greater than 2.5 cm with holes drilled at 4 even increments about 5.1 mm from the bottom to the top surface. Stainless steel shims 0.508 mm thick were used to create an aperture of uniform dimension in these more recent experiments.

EXPERIMENTAL PROCEDURE

Data were collected with the apparatus exposed to atmospheric pressure. The fracture was horizontally oriented and a small positive displacement pump was used to pump water though a copper coil immersed in boiling water to provide fluid near saturated temperature. The pump was adjusted to supply discrete rates of 15, 30, and 60 ml/min, and the fracture aperture was fixed at either 0.102 mm or 0.889 mm for the Geysers disk, and 0.508 mm with the sandstone and aluminum disks. The average flow velocity was thus varied more than an order of magnitude with Geysers rock, and by a factor of 4 in more recent experiments. With liquid water these rates are well within the range of laminar flow. With boiling, however, the velocity was further increased as liquid flashed to vapor in the fracture.

Two types of experiments were conducted. The first was a single phase experiment that was done to measure the thermal conductivity of the sample by comparing the heat flux measured with ice water injected into the fracture to the steady state temperature gradient. Recognizing this is not strictly valid for the experimental geometry, but assuming one dimensional heat conduction, Fourier's law $q'' = K\,\Delta T/L$ describes the relationship between the heat flux and the temperature gradient, where the proportionality factor K is the thermal conductivity of the rock. During the single phase experiments temperatures were recorded at one minute intervals from each thermocouple location as ice water was pumped at 15, 30, and 60 ml/min.

The second type of experiment conducted was a steady state boiling experiment with much higher maximum temperatures and saturated conditions with liquid and vapor flow in the fracture. During this experiment 70-100 volts and about 2.5 amps were supplied to the heater and were maintained at those levels for the duration of the entire experiment. Again, temperatures were recorded every minute for many hours while the flow rate and fracture aperture were adjusted and the times of steady state conditions were noted. Unfortunately the heat flux sensors failed during all these experiments. At heat fluxes above 10,000 or 12,000 W/m^2 the signal from the sensor either reached a maximum or dropped to 0 and would not provide information on heat flowing into the sample disks. Therefore, the rock conductivity measured with the single phase experiments was calculated from the temperature gradient and the temperature change of the fluid. This is possible because an energy balance between the rock and the fluid shows that the heat conducted through the rock increased the internal energy of the fluid, raising its temperature. Thus $q'' = k\,\Delta T / \Delta X$ in the rock = $(m\,C_p\,\Delta T) / A$ in the fluid, where k is the rock conductivity, $\Delta T/\Delta X$ is the temperature gradient, m is the mass flow rate of the fluid, C_p is its heat capacity, ΔT is the temperature gain of the fluid from inlet to outlet, and A is the surface area of the fracture.

This calculated rock conductivity was then used to calculate the heat fluxes from the temperature gradients in boiling experiments. We recognize that the temperature gradient varies with radial position and acknowledge that the thermal conductivity measured under lower temperature conditions changes with temperature because a mixture of liquid and vapor exists in the pores. However, without modifying and repeating the experiment, there was no other way of quantifying and comparing heat fluxes. Therefore, the absolute value of the heat fluxes is uncertain, but relative magnitudes of heat fluxes under different flow conditions were compared.

EXPERIMENTAL DATA AND OBSERVATIONS

The steady state temperatures from an ice water experiment with Geysers rock are plotted in Figure 4. With single phase flow, the steady heat flux observed was 11064 W/m^2, and a temperature drop of about 130 ^{o}C was measured across the 10.9 mm net thickness of rock. The overall thermal conductivity of the three rock disks was thus calculated at 0.92 W / m K, but the bottom rock disk which had the epoxy and thermally conductive paste applied to one surface measured 0.53 W / m K. The middle and top rock disks showed thermal conductivities of about 1.25 W / m K. While the bottom rock disk displays a thermal conductivity lower than the others, possibly due to its treatment with epoxy, the conductivity of the top two disks appears to be consistent, which is indicated by the uniform slope of the temperature gradient in the plot of Figure 4.

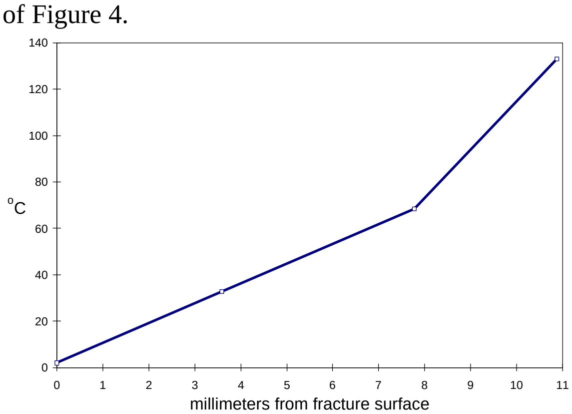

Figure 4. Steady state temperature distribution with ice water injection.

Data from the much higher temperature boiling experiments are shown in Figure 5, and the temperatures from two steady states with water injected at 60 ml/min and 15 ml/min are displayed in that figure. As noted earlier, the heat flux sensor read a continuous maximum after the apparatus reached steady state at high temperature, so the heat flux was calculated from the interior temperature gradient and an assumed thermal conductivity from the single phase experiment of 1.25 W / m K. Using these parameters a heat flux of about 25100 W/m^2 was observed to be practically independent (within the uncertainty of measurement) of flow velocity and vapor fraction. Figure 5 shows only a slight difference in the temperature gradient developed after significant changes in flow rate and vapor fraction.

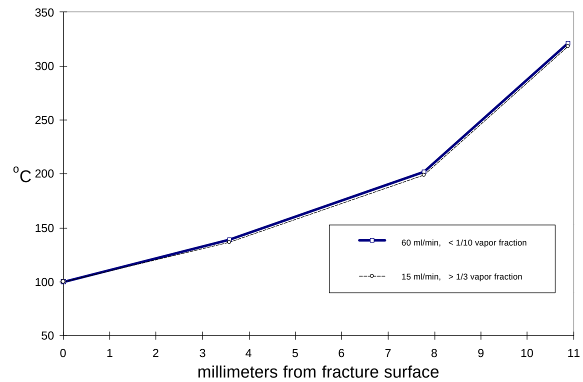

Figure 5. Steady state temperature distribution during injection / boiling flow.

Figure 6 plots the temperature gradients that were measured with boiling flow in the sandstone disk. Visual observation of this experiment revealed that the fracture aperture did not influence the flow pattern to any significant degree because the injected fluid penetrated into the sandstone at the center and exited predominantly along the outer edge. While observation and the internal temperatures indicated boiling, the temperature of the fluid measured at the perimeter of the fracture was a few degrees less than the saturated temperature. This indicates that not all of the fluid in the sandstone flowed at saturated temperature and that mixing at the exit lowered the overall fluid outlet temperature.

During the experiment illustrated in Figure 6 another unusual result is apparent in Table 1. It shows that the heat flux increased at the lower flow rates, presumably because boiling occurred over more of the surface area of the rock under these conditions. It appears that with injection at higher flow rates not all the fluid reached saturated temperature, and the heat flux decreased.

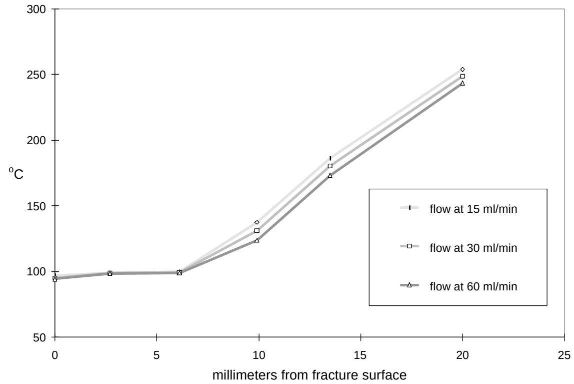

Figure 6. Steady state temperature gradients with boiling flow in sandstone disk.

Figure 7 plots the temperature gradient for the experiment with boiling on the surface of the aluminum disk. Although not easily seen on this scale, the slope of the temperature gradient increases slightly with increasing flow rate. Thus Table 1 shows an increasing heat flux with an increasing flow rate. Another similar observation is that as the vapor fraction in the fracture increases the heat flux decreases, while the temperature of the saturated fluid in the fracture remains constant.

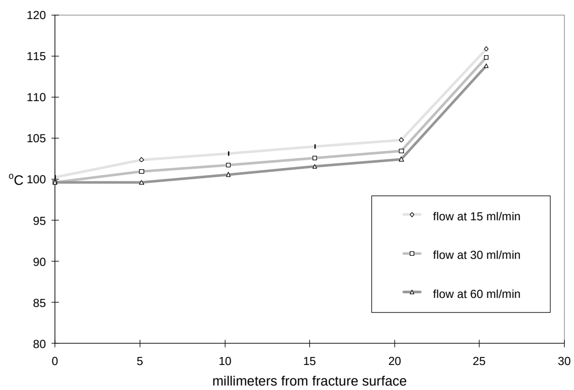

Figure 7. Steady state temperature gradients with boiling flow on aluminum disk.

Table 1 lists the heat fluxes calculated from an assumed constant thermal conductivity of each material. The vapor fractions listed were visually estimated volume fractions. It is interesting to note that the low porosity, low permeability graywacke showed little variation in heat flux with flow conditions and vapor fraction. The aluminum and sandstone, chosen for their extremes of no porosity and high porosity, have different heat flux trends. As the vapor fraction increased and flow rate decreased, the heat flux to the aluminum surface decreased. However, with sandstone, as the vapor fraction observed in the fracture increased, the heat flux also appeared to increase. This was indicated by a change in slope of the temperature gradient.

Flow rate,	Vapor fraction,	Heat flux,
Geysers core		
15 ml/min	40 %	24500 W/m^2
30 ml/min	20 %	
60 ml/min	10 %	25100 W/m^2
Aluminum disk		
15 ml/min	85 %	27400 W/m^2
30 ml/min	60 %	28500 W/m^2
60 ml/min	30 %	32300 W/m^2
Sandstone		
15 ml/min	95 %	34800 W/m^2
30 ml/min	85 %	31400 W/m^2
60 ml/min	35 %	22900 W/m^2

Table 1. Heat fluxes calculated from assumed thermal conductivity and internal temperature gradients.

DISCUSSION

Because the heat flux sensors failed, the absolute magnitude of the heat fluxes was uncertain, however, the relative magnitudes have been compared. In these experiments porous and non-porous materials behaved quite differently. The non-porous aluminum showed a thermal sensitivity that responded to the flowing conditions in the fracture. The high porosity sandstone, however, responded to flow conditions in its porous matrix, but not to the flow conditions in the fracture. At the higher flow rate the exit temperature of the liquid on the outer margin of the sandstone disk declined below the saturation temperature. It appeared that a layer of vapor formed inside the sandstone disk and some of the liquid injected on top of that vapor layer flowed out before being heated to saturation temperature. At the lowest flow rate, the heat flux through the sandstone increased slightly and fluid exited at saturation temperature, possibly because more uniform boiling occurred over its surface area.

The low porosity and low permeability Geysers graywacke also behaved in a manner unlike the other two materials. The temperature gradient indicated that vaporization occurred beneath the fracture surface, isolating the boiling in the pores from the flow conditions in the fracture. Its low permeability also prevented the flow in the fracture from extending into the matrix.

Figures 5 and 6 also illustrate the dimensional scale of the temperature gradient that would initially develop with liquid injection into a superheated vapor-dominated fracture. They show the millimeter scale of the first transient temperature drop that would appear near a fracture surface. This temperature drop over a few millimeters also indicates the order of magnitude of the initial heat flux to the injected liquid.

During the boiling experiments conducted for this paper a thermal conductivity of 1.25 W/m K was assumed for Geysers graywacke, 3.5 W/m K was assumed for the sandstone, and 173 W/m K was assumed for aluminum in the calculation of the heat fluxes listed in Table 1. The temperature difference measured between the thermocouples placed inside the rock samples and the distance between those thermocouples was used to calculate these heat fluxes. This was done because the overall temperature drop across the thickness of the disk was affected by a high vapor saturation due to boiling near the fracture surface, and by the materials used to treat the bottom surface of the rock in contact with the heating element. As stated earlier, without heat flux sensor measurements the assumed thermal conductivity of these materials was not verified, therefore the magnitude of the heat fluxes is uncertain.

For the graywacke and sandstone experiments, an extrapolation of the linear trend from the middle of the rock disk to the saturation temperature of 100 ^{o}C potentially indicates the depth within the rock that liquid is circulating, vaporizing, and returning to the flow in the fracture. This idea is illustrated by the boiling temperature gradient of the Geysers core sample shown in Figure 8. In this figure the arrow indicates the location where boiling within the rock alters the temperature gradient to the fracture surface.

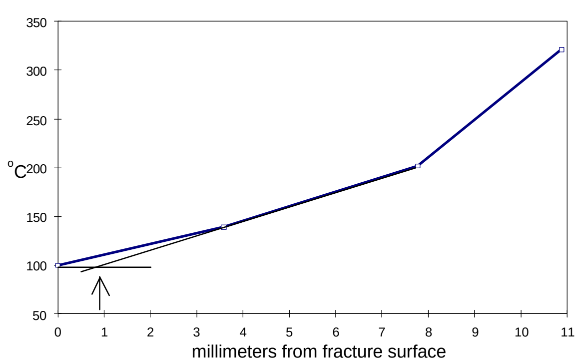

Figure 8. Extrapolated temperature gradient assuming uniform thermal conductivity.

One conclusion that can be drawn from this illustration is that boiling in a fracture is not strictly a surface phenomenon even in very low porosity and low permeability rock, but that the rock porosity and permeability play important roles in either reducing or enhancing the coupling between the heat flux and the liquid/vapor ratio of the flow in the fracture.

SUMMARY / PRELIMINARY CONCLUSIONS

A comparison of data from these experiments indicates that while heat transfer on nonporous surfaces is strongly coupled to the flow regime and vapor fraction, the boiling heat flux to porous rock surface appears to be much less sensitive to the quantity of vapor flowing along a rock fracture. The permeability of the rock also appears to influence boiling in unexpected ways. In the low permeability Geysers rock the lack of fluid circulation inside the rock seemed to allow porous vaporization to control the heat flux, which remained relatively constant during changing flow conditions in the fracture. In the sandstone, however, a layer of vapor inside the rock seemed to allow liquid at less than saturated temperature to flow near the fracture surface without boiling. Since this was the first time this experiment was done, these results should be reproduced and verified. Also, measuring the liquid and vapor fractions at the outlet would a much better way of calculating the average heat flux to the rock surface because this would allow the change in enthalpy of the fluid to be calculated.

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