Quarterly Report for

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Stanford Geothermal Program

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1. MEASUREMENTS OF STEAM-WATER RELATIVE PERMEABILITY

This research project is being conducted by Research Assistant Glenn Mahiya and Professor Roland Horne. The aim of this project is to measure relative permeability relations experimentally for steam and water flowing simultaneously in rocks.

1.1 INTRODUCTION

In the last quarterly report, we described briefly the modifications intended for the experimental determination of steam-water relative permeability. An adiabatic experiment will replace the non-adiabatic setup that has been used previously. Conducting measurements in an adiabatic environment eliminates the need to account for heat losses when calculating the relative permeabilities to water and to steam, and hence reduces the uncertainty in the values computed. Aside from this, steady-state can be reached more easily with an adiabatic system and hence the duration of the experiment can be reduced, or more data points can be obtained within the same period of time. While the improved coreholder and insulating fiber provide much needed thermal insulation, there are still heat losses encountered along the core when the system is used as it is. To achieve a loss-free condition, we will use flexible thin-film heaters that do not cause significant interference to X-rays during the CT scans. These heaters will be wrapped around the coreholder to put back the heat that would otherwise escape through thermal conduction. The heat provided by the guard heater will be carefully controlled by an automated system to maintain a net heat loss of zero.

In this report, we describe in more detail the flexible heaters and the data acquisition system that we have recently acquired specifically for this project.

1.2 EXPERIMENTAL DESIGN

The main component of the experiment is a Berea sandstone core along which pressure, temperature and radial heat flux are measured at various points. The core is enveloped by a coreholder that provides a boundary for fluid flow, mechanical support, and thermal insulation to a limited extent. Despite a thick layer of insulation around the coreholder, there is still considerable heat escaping from the core. By supplying the exact amount of heat that is lost back to the system, the overall heat loss will be zero. We have purchased flexible heaters custom-made for this experiment. Figure 1.1 shows a schematic of one of the Kapton-insulated flexible heaters.

Since single-sheet heaters that are long enough to completely cover the core system are not available, we have obtained separate 8”x10” and 9”x10” sheets. Holes with 0.53” diameters are provided to ensure complete contact between the heater and the coreholder despite the presence of protruding pressure ports along the core length. Each sheet is an array of eight or nine independent 1”x10” strips of heating elements that can be controlled separately. In effect, we have seventeen (17) different heaters rated at 2.5 W/in^2 at 115 volts. Since the heaters require only a small amount of current to operate, we will use a transformer to step-down the voltage from 120 VAC to 60 VAC. At the end of each strip of heater, two Teflon-insulated wires connect the element to a channel in the voltage output control module of the computer, and to the power supply.

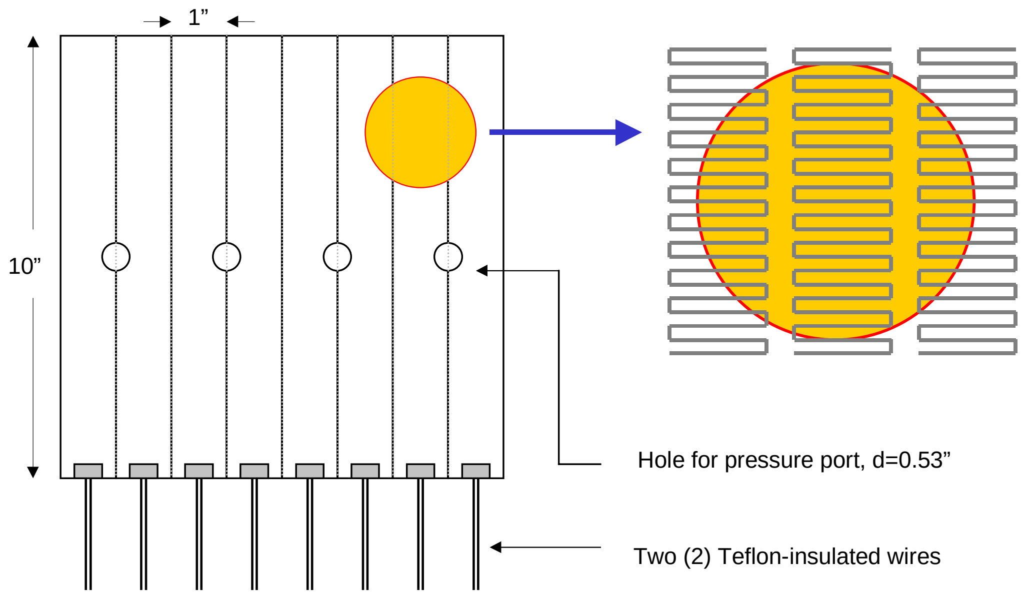

Figure 1.1: Schematic diagram of flexible heaters

To control the individual heating elements, we have purchased a National Instruments SCXI 1163-R module. This module consists of 32-channels with optically-isolated digital output/solid-state relays that have no moving parts and hence are not subject to the limited lifetimes of electromechanical relays. In the closed state, each relay has a maximum resistance of 8Ω and carries up to 200 mA of current. The SCXI-1326 terminal block will be used to connect the heaters to the module installed in the SCXI chassis. Figure 1.2 illustrates how the flexible heaters and the data acquisition module are configured.

As in previous non-adiabatic experimental setups, heat flux sensors will be positioned between the coreholder and the heating blanket to monitor heat loss. These sensors are connected to a separate data acquisition module (SCXI-1100), and the measurements can be displayed in the graphical programming software for instrumentation that we use (LABVIEW). We aim to be able to control the heaters automatically and maintain a net flux of zero using the LABVIEW platform, based on the heat flux sensor measurements instead of manually varying the power supplied to the heater.

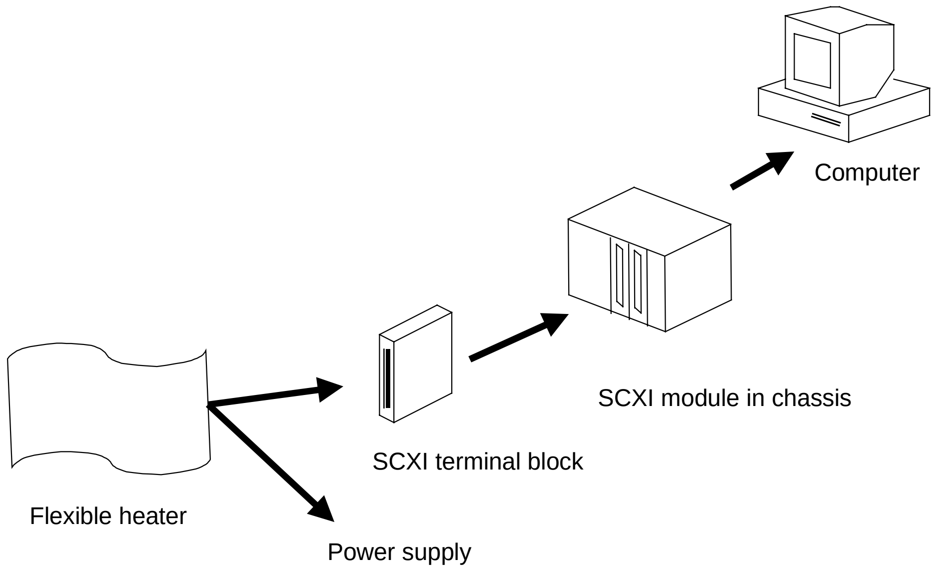

Figure 1.2. Schematic diagram of flexible heaters

1.3 FUTURE WORK

The new heaters and data acquisition module are currently being assembled. We will initially test the 32-channel solid-state relays on flexible heaters other than the custom-made ones and attempt to control them with feedback from heat sensor measurements. This entails an extensive use of LABVIEW capabilities. Once the automatic control system is developed, we will proceed with the experiments, starting with measuring absolute permeability and porosity using the X-ray CT scanner. This is an important step since enhancement of permeability through removal of fine grains may have caused the results of the last experiments conducted in June to vary considerably from those reported in the Quarterly Report for January-March 1998.

2. BOILING IN A FRACTURE

This project is being conducted by Research Assistant Robert DuTeaux, and Professor Roland Horne. The goal of this study is to analyze advective heat transfer with boiling flow in a fracture. Research continued this past quarter with further experimental investigation of temperature gradients and fluid flow in low porosity, low permeability fractured rock.

2.1 INTRODUCTION

The experimental apparatus containing thin circular slices of Geysers core (graywacke) was modified and used to investigate the heat flux and temperature gradients that develop during boiling with injection in a fracture. This apparatus was designed to quantify the heat flux associated with liquid water flashing to steam in a fracture, similar to the vaporization of injectate in a fractured steam reservoir. The transient experiment (with concentric glass tubes, as illustrated in previous reports) was not used this past quarter because the glass in the apparatus broke once again. However, a comparison of data from that apparatus with recent experiments indicates that while heat transfer on nonporous surfaces is strongly coupled to the flow regime, the heat flux to porous rock surfaces appears to be much less sensitive to the fluid velocity, provided the vapor fraction of the flow is not too great. This may be a positive development for the numerical modeling of discrete fractures because data indicate the quantity of heat transferred from the rock to the fluid in a fracture is not as strongly coupled to the flow regime as it is in the tubes and channels of heat exchangers.

These experimental data are presented and discussed in this report.

2.2 EXPERIMENTAL PREPARATIONS

Figure 2.1 shows a diagram of the assembly with thermocouples between thin slices of rock, an electrically powered heater, and a glass disk forming the boundary of a fracture. The apparatus was designed to provide a uniform heat flux through the rock normal to the flow in the fracture. This apparatus was used to investigate the steady state heat flux and temperature gradients that develop with boiling flow on the surface of a rock fracture. The apparatus contains three thin rock disks that 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 the rock disks. The outer edge of the rock was sealed with epoxy and silicone to prohibit radial flow of water within the rock and to restrain heat conduction to be parallel to the mated rock surfaces. Additionally, a heat flux sensor was placed in the center beneath the rock adjacent to the heated box, and 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 were measured near the center of the fracture.

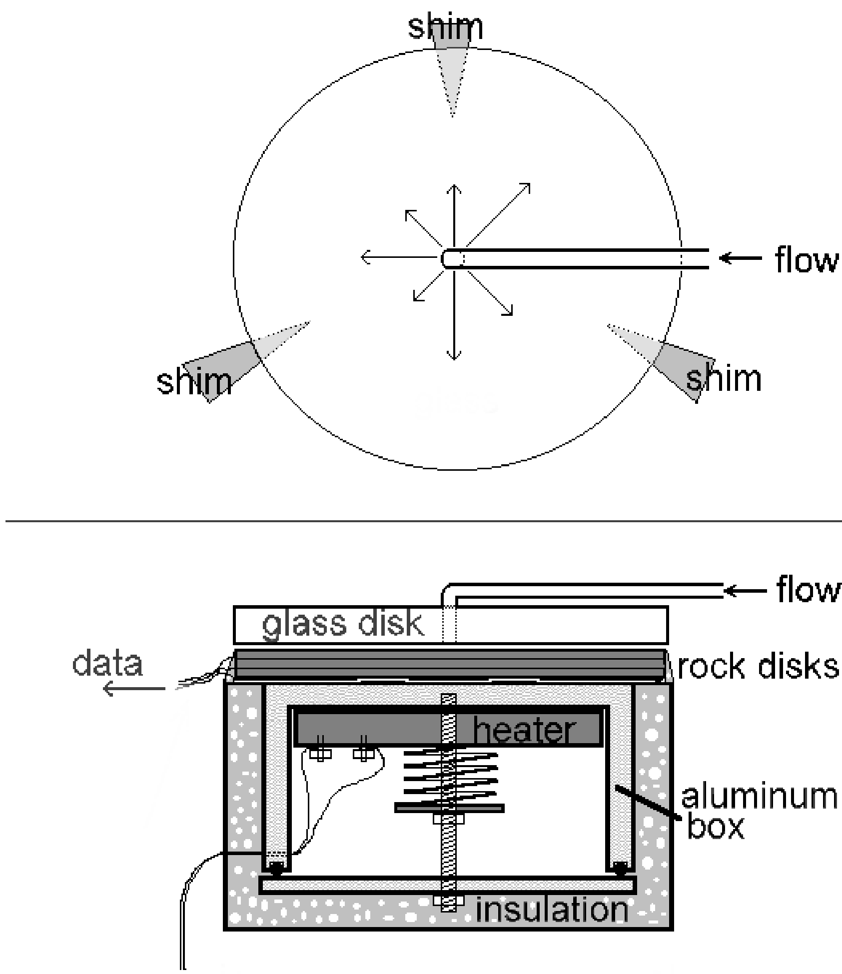

Figure 2.1: Heat flux - Temperature gradient measurement experiment. (Steady State)

A uniformly smooth circular fracture was created by compressing a glass disk against three small stainless steel shims which were placed at the outer edge of the rock. Glass was used to allow observation of the vapor fraction and flow characteristics. Stainless steel shims created an aperture of a precise dimension, and the glass disc contained a hole at its center for saturated liquid water to be pumped into the fracture and flow radially outward.

In order to obtain sufficient thermal contact with the rock, a heat sink compound was used between the rock and the aluminum heater box. The rock surface closest to the heater was coated on the heater side 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 for the placement of thermocouples. The heater box was engraved to the shape and thickness of the thermocouples and heat flux sensor was placed at the base of the rock. Upon each of the surfaces where temperatures were recorded, three thermocouples were placed 1.5 cm radially out from the center, separated from one another by an angle of 120 degrees. The thickness of each of the rock disks, from the bottom to the top respectively, were 3.10 mm, 4.19 mm, and 3.58 mm.

2.3 EXPERIMENTAL PROCEDURE

The apparatus was designed to be completely submersed in water to create consistent flow and temperature boundary conditions at the edge of the fracture. The data shown here, however, were collected without submersing the apparatus. The fracture was oriented horizontally and a small positive displacement pump was used to pump water though a copper coil immersed in boiling water to provide liquid at saturated temperature. The pump supplied constant rates of 15, 30, and 60 ml/min, and the fracture aperture was fixed at either 0.102 mm or 0.889 mm. The average flow velocity was thus varied more than an order of magnitude, and the velocity was further increased by vapor flow because of its smaller density. The average velocity was therefore directly proportional to both the pump rate and the vapor fraction multiplied by the ratio of the liquid/vapor densities.

Two types of experiments were conducted. The first was a single-phase experiment that was done to investigate the thermal conductivity of the rock by comparing the heat flux measured with ice water injected into the fracture to the steady state temperature gradient. 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. Three temperatures were recorded at ten minute intervals from each thermocouple location while a small amount of power was applied to the heater and ice water was pumped at 30 ml/min with a fracture aperture of 0.102 mm. Ice was also placed on top of the glass disk while temperatures and the heat flux were recorded under these conditions for more than one hour.

The second experiment was a steady-state boiling experiment with a much higher maximum temperature and saturated conditions with liquid and vapor flow in the fracture. During this experiment 70 volts and 2 amps were supplied to the heater and were maintained at those levels for the duration of the entire experiment. Again, temperatures were recorded every ten minutes 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 sensor failed during this experiment because the signal from the sensor reached a maximum and would not provide information on heat fluxes above 12022 W/m^2. Therefore, the rock conductivity measured with the single-phase experiment was used with the temperature gradient to calculate the heat flux in this experiment.

2.4 EXPERIMENTAL OBSERVATIONS AND RESULTS

The arithmetic average temperatures from the data recorded after a steady state had been established are displayed in the plot of Figure 2.2, while the average steady heat flux observed was 11064 W/m^2. A temperature drop of about 130 ^oC was measured across the 10.9 mm net thickness of rock. While the overall thermal conductivity of the three rock disks was calculated at 0.92 W/m-K, the bottom rock disk which had the epoxy applied to one surface measured 0.53 W/m-K, and the middle and top rock disks calculated thermal conductivities of about 1.24 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 in the plot.

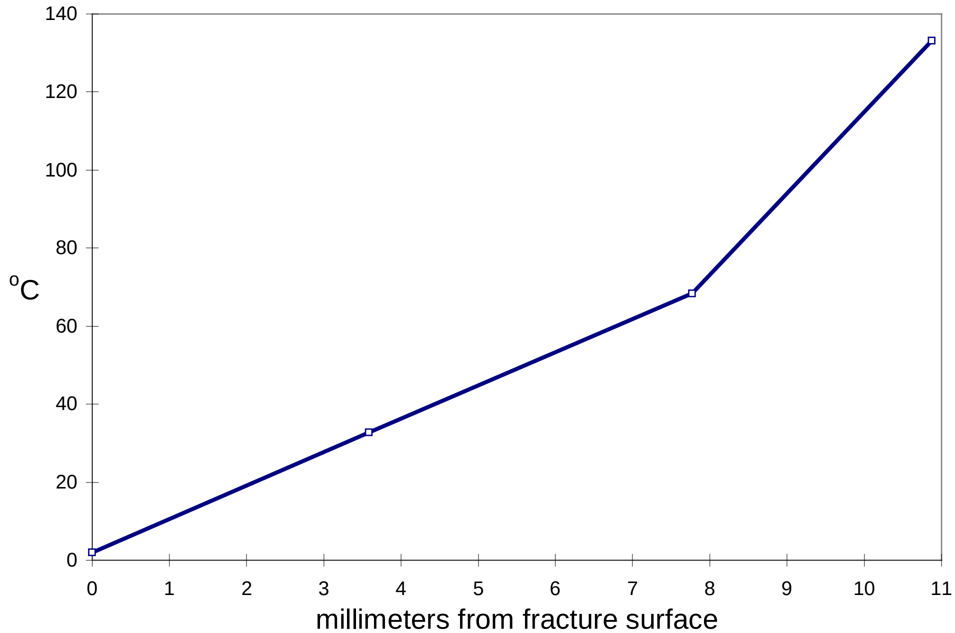

Figure 2.2: Steady state temperature distribution with ice water injection.

Data from the high temperature boiling flow experiment are shown in Figure 2.3. The arithmetic averages of temperatures from two steady states with water injected at 60 ml/min and 15 ml/min are displayed. The most remarkable observation made during this experiment was that the measured temperatures did not vary significantly when the fracture aperture and pump rates were changed. With volumetric flow rates from 15 to 60 ml/min, with apertures of either 0.102 mm or 0.889 mm, and vapor fractions that varied from less than 10 % to more than 50%, the measured temperatures never differed by more than a few degrees Centigrade, well less than the uncertainties associated with those measurements.

As noted earlier, the heat flux sensor read a continuous maximum after the apparatus was heated, so the heat flux was calculated indirectly from the temperature gradient and an assumed thermal conductivity. Assuming the overall thermal conductivity of 0.92 W/m-K measured from the ice water experiment, a calculated heat flux of about 18600 W/m^2 was observed to be practically independent of flow velocity and vapor fraction. Vapor fractions, however, never greatly exceeded about 50%.

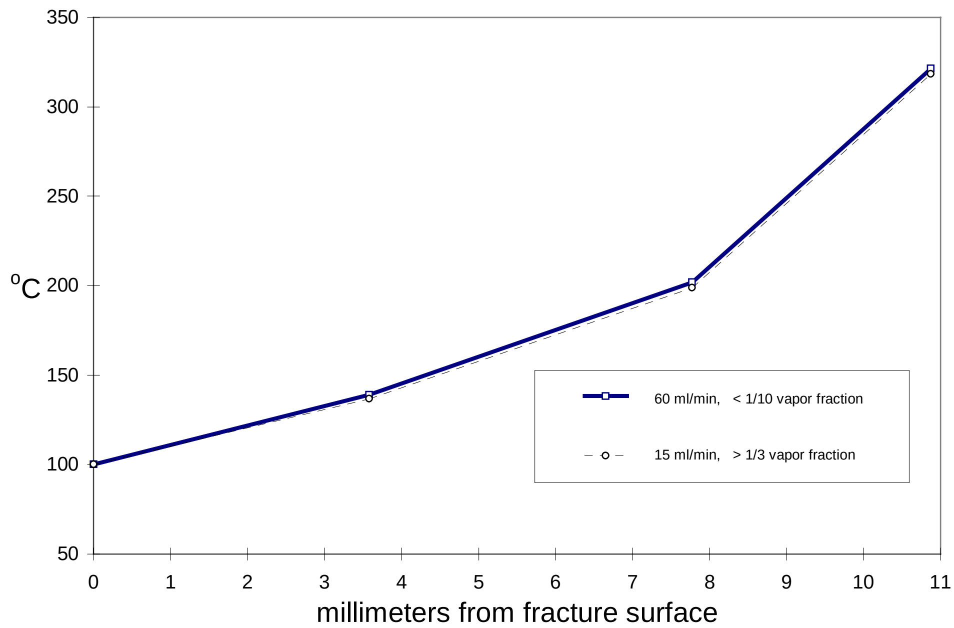

Figure 2.3: Steady state temperature distribution during injection / boiling flow.

It was also notable that the two-phase flow could not be described as steady. It was largely axisymmetric, however, a rapid pulsed expansion of vapor in the fracture with a slower return to a greater liquid fraction was observed, especially with the smaller aperture fracture, and at lower flow rates. With a uniform flow rate from the pump, this rapidly pulsed vapor expansion has been difficult to explain.

2.5 DISCUSSION

When compared with the results of the previous experiments involving transient flow through a narrow glass channel, the data show a significant difference between the heat transfer characteristics of nonporous and porous surfaces. This might be expected, however, even the tiny pores of Geysers core show sufficient permeability for the boiling process to occur just beneath the fracture surface, rather that at the surface, which causes the heat flux to the surface to be only moderately affected by the flow rate and flow regime in the fracture. This means that the heat advected at the surface of a fracture is not as highly coupled to the flow regime as the boiling heat flux in channels of nonporous materials.

There are uncertainties in the measured temperatures and other derived quantities due to some aspects of how the apparatus was constructed. For example, since the rock disks were cut, ground flat and mated, the pore space and permeability at the junctions of the disks were likely to be much greater than the intrinsic porosity and permeability of the rock. Also, small channels were cut in the rock for the placement of thermocouples, which also created regions of permeability orders of magnitude greater than the natural rock matrix. Since temperatures recorded at symmetric locations the same distance from the fracture surface showed differences of as much as 16 percent, fluid might have unintentionally circulated around the locations of some of the thermocouples and not others.

The thermal conductivity calculated from the temperatures and heat flux in the ice water experiment is notably lower than most measurements of conductivity in Geysers rocks (Walters and Combs, 1991). Since the thermocouples had been checked and calibrated, it would be advisable to check the heat flux sensor by measuring the heat flux and temperature gradient across a well characterized material. Also, thermal conductivity is often a moderate function of temperature, and in a wetted porous rock would change with the liquid-vapor fraction in the pore space. During the boiling experiment the temperature in part of the rock exceeded 300 ^oC. Dependent upon the size of the pores, this may have been sufficient to vaporize much of the liquid in the pores at these high temperatures (Udell 1982). During the high temperature experiment in the apparatus as it was assembled, there may have been thermal contact resistances between the rock disks due to the vaporization of liquid water on those surfaces.

However, if the conductivity of top two rock disks remained consistent, (although it may be a function of temperature), there should have been a nearly linear temperature gradient through this section of rock to the fracture surface. Since this is not seen in Figure 2.3, an extrapolation of the linear trend from the middle rock disk to 100 ^oC might indicate the depth within the rock that liquid is circulating, vaporizing, and returning to the flow in the fracture. This idea is illustrated in Figure 2.4, where the arrow indicates the location where boiling within the rock alters the temperature gradient to the fracture surface.

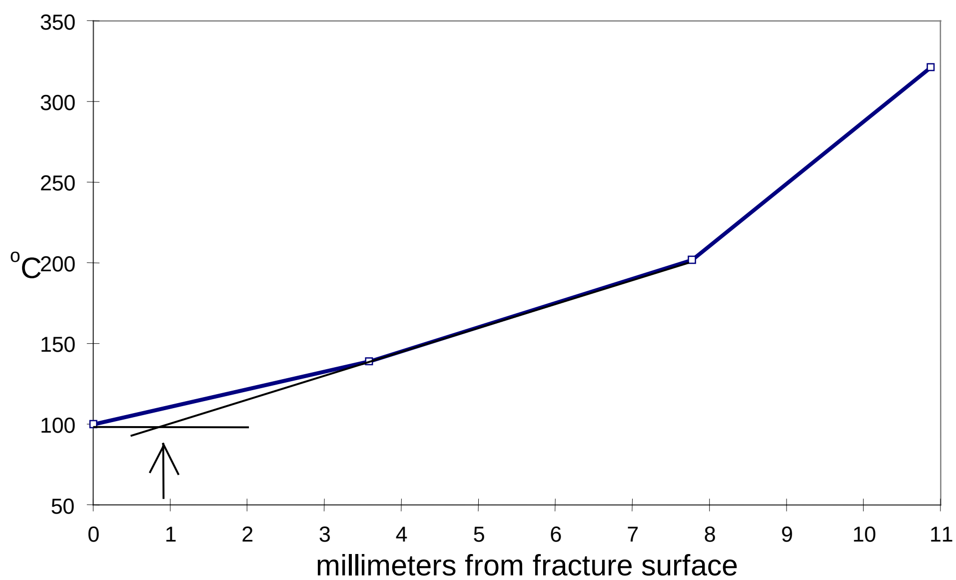

Figure 2.4: Extrapolated temperature gradient assuming uniform conductivity.

One conclusion that can be drawn from this concept is that boiling in a fracture is not strictly a surface phenomenon even in very low porosity and low permeability rock, but that the porosity plays an important role in reducing the coupling between the heat flux and the liquid/vapor ratio of the flow in the fracture. This is notably unlike the boiling heat transfer coefficient in tubes and channels of nonporous material, which are relatively strongly coupled to the liquid-vapor fraction (Carey, 1992).

2.6 FUTURE RESEARCH

Although a final report on this research will be written before the end of the coming quarter, an attempt to duplicate this experiment with glass disks rather than rock disks has been planned to further analyze the difference between boiling on porous and nonporous surfaces. There have been many questions raised, and a new strategy for modeling advective heat transfer in fractured rock has been suggested. Rather than applying a dual porosity model to forecast the position of a thermal front in a fractured reservoir, this research has been working toward modeling fractures as discrete features by analyzing and quantifying a boiling heat transfer coefficient to couple the rock matrix to the thermal transport in fractures. If this approach is deemed promising, further research may follow.

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