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BOILING IN A VERTICAL FRACTURE

Robert J. DuTeaux

Stanford University
Dept. of Petroleum Engineering
Stanford, **CA,** 94305-2220
duteaux@stanford.edu

ABSTRACT

An experimental study of boiling in an artificial fracture has been conducted with the goal of understanding the propagation of a thermal front in a fracture where the liquid injectate flashes to steam. Laboratory work is illustrated, a background of liquid-vapor phase transition is described, and a strategy for modeling boiling in a discrete fracture with an impermeable matrix is being developed. This strategy involves the development of empirical functions relating heat flux on an impermeable surface to its excess temperature with experiments being conducted at Stanford. If functions that quantify a two-phase coefficient for thermal convection can be developed, a numerical model which balances the heat conduction from an impermeable rock with the advecting fluid enthalpy could be constructed. This modeling approach is derived from literature on multiphase heat exchange in tubes and on surfaces, and may ultimately be useful for the analysis of the propagation of a thermal front in fractured media.

INTRODUCTION

Fluid injected into geothermal reservoirs travels across a length scale defined by the separation between wells and on a time scale described by the residence time and arrival of an injected tracer at a production well. The characteristic time and length scales for heat transfer in a fractured reservoir with an impermeable matrix are coupled by the relatively small thermal diffusivity of rock. If the time required for heat to diffuse to the midpoint between flowing fractures is less than the tracer residence time, a relatively uniform thermal front will propagate through a fractured network outward from the injection well. If, however, the time required for thermal diffusion between fractures is much greater than the tracer residence time, colder fluid will "finger" down the fracture surfaces toward a production well leaving great quantities of energy in place. The rate of propagation of a thermal front outward from an injection well is a strongly depends on these characteristic time and length dimensions.

Several significant works analyzing heat transfer and the propagation of a thermal front for single and multiphase flow in fractured media have been published (for example see Gringarten, Witherspoon, and Ohnishi, 1975, Bodvarsson, and Tsang, 1982, Pruess, 1983). These studies accurately reveal the important relationships between flow rates, thermal diffusion times, and characteristic length dimensions, however, the thermal front associated with fluid boiling in an impermeable rock matrix with discrete fractures remains a relatively unexplored topic of research.

LABORATORY EXPERIMENTS

The experimental apparatus illustrated in Figure 1 was constructed to measure the temperatures of heat exchanged between an impermeable core and water tlowing upward and boiling in the concentric annulus surrounding the core. The annulus between these two large diameter glass tubes creates an artificial fracture about 1.0 mm wide. In reality the core is a 135 mm diameter glass cylinder, closed at the bottom to hold sand that has been heated to a temperature of about 150°C. Water flows on the outside of the glass core, not in the sand. The sand only provides a medium with a conductivity and heat capacity whose order of magnitude is comparable to real rock.

The glass provides an impermeable surface, but unfortunately, does not have a roughness a fractured surface, so a thin film of roughened Teflon was applied to the outside of the cylinder in recent experiments to provide sites for the nucleation of bubbles. With the Teflon on the outside of the core the annulus width was much less than 1 mm.

The apparatus is about ***0.6*** meters tall with thermocouples attached to the inside and outside of the core. Heat flux sensors were also attached to the outside of the core. Another concentric cylinder surrounds the artificial fracture aperture *to* insulate radial heat flow by applying a vacuum. In a typical experiment, water is injected near atmospheric pressure from the bottom at a slow rate, so that (without boiling) it would take a few minutes to reach the top.

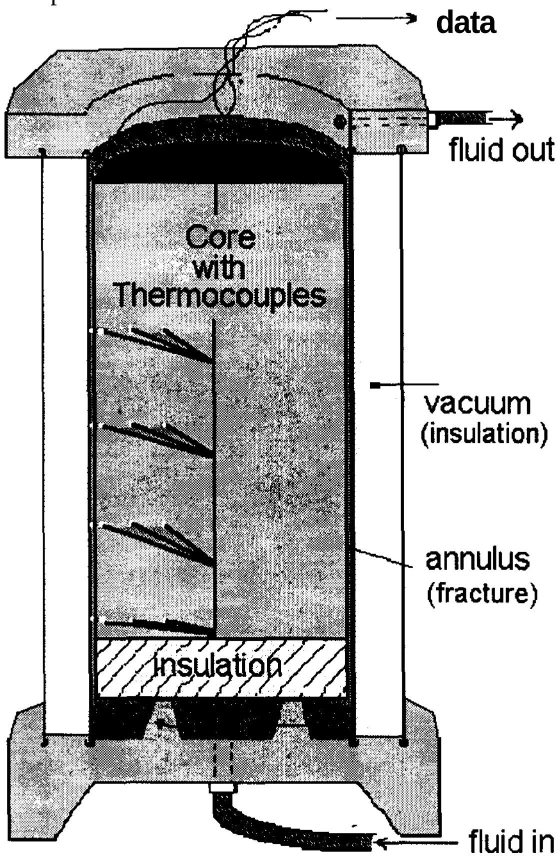

Fig. 1. ***Illustration of experimental apparatus.***

Initially it was difficult to place thermocouples in the fluid annulus, therefore temperature measurements inside and on the surface of the heated core were recorded. Figure **2** shows the decline in temperature of a point on the surface of the fracture (the outer surface of the glass tube). The plot shows how the temperature changed quickly during the initial contact with fluid past the thermocouple position. Cyclic temperature fluctuations appear just after fluid contact with the thermocouple position, then a fairly rapid temperature decline occurs as water boiled at that location.

The two-phase zone quickly grew to the full height of the apparatus during an experiment. With a larger aperture fracture (without the Teflon coating) the two-phase seemed to be smaller, so it is likely that the aperture has a strong influence on the extent of the two-phase region. Only a much larger apparatus, however, could confirm this.

Figure **2** also shows some irregular temperature inflections as boiling proceeds until boiling stopped at just above the saturation temperature. These step-like inflections have been identified in other previous experiments but have not been interpreted.

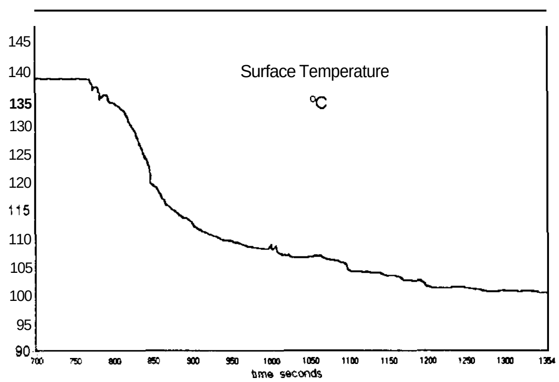

Fig. 2. Surface temperature decline during boiling.

Figure **3** plots the heat flux measured at two vertical locations separated by 5 cm on the core. The instantaneous maximum heat flux occurred when fluid first reached each location and then declined as boiling proceeds. The maximum of the measured heat flux was about 6000 W/m^2, but this lasted only a few seconds. Due to surface roughness differences, it is unknown if this heat flux is close to the magnitude of the heat flux that would be observed with real impermeable rock at the same excess temperature.

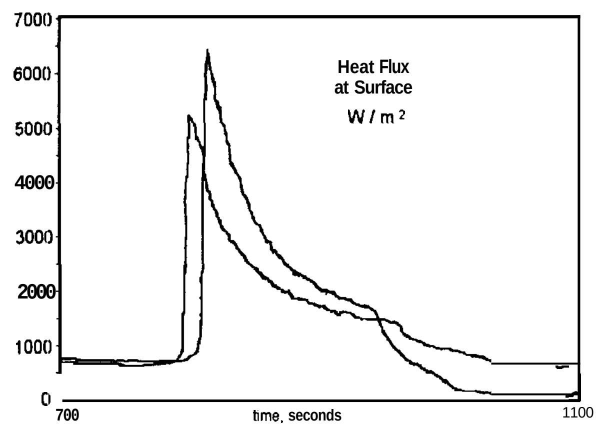

Fig. 3. Heat flux measurements during boiling.

A relative few experiments have been conducted to date and the data obtained has been limited. Many difficulties have been resolved and operation in the near future should provide the information needed for comparison to the work of others and for comparison to numerical simulation.

NUCLEATION AND EXCESS TEMPERATURE

Excess temperature, (ΔT_e), defined as $\Delta T_e = T_{surface} - T_{saturation}$, is required for the nucleation of bubbles in a boiling process. However, the surface tension of a fluid and the size distribution of small asperities (and their geometry) on a fracture surface influences the ΔT_e required for nucleation. For example, very smooth surfaces require large excess temperatures because the radii of curvature of bubbles begin infinitely small and require very large pressure differences between the vapor and the liquid to expand the bubbles. On rough surfaces, bubbles may expand more easily because they begin in the sharp crevices and expand with larger radii of curvature. This suggests that the boiling process begins with physical dynamics that are specific to the fluid and the fracture surface involved. Therefore, laboratory measurements derived from fluids and surfaces unlike geothermal fluids and real rocks may not provide accurate parameters for modeling real reservoir fractures.

Although no rigorous theory exists, it is generally accepted that departing bubbles promote the mixing of a superheated boundary layer with the bulk fluid, and the bulk fluid displaces the volume previously occupied by the bubble bringing cooler fluid into contact with the surface. Research has demonstrated that the heat flux during nucleate boiling is proportional to the nucleation site density as well as the excess temperature on a surface. Furthermore, flow regimes that depend upon fracture orientation, aperture, liquid-vapor fractions, and liquid-vapor mobility have great influences on the heat flux at a surface during boiling.

BACKGROUND ON BOILING

The small thermal diffusivity of rock restricts the quantity of heat that can quickly conduct to a fluid boiling at a fracture surface. This means that large temperature gradients (and transiently large heat fluxes) develop near boiling fractures, and two phase flow may transition from superheated steam to liquid water relatively quickly as heat is extracted from the rock near fracture surfaces.

Fluid properties, as well as rock properties, govern the advection of heat with a fluid in a boiling fracture. Surface tension (σ), the latent heat of vaporization (h_{fg}), viscosity (μ), flow velocity (u), fluid conductivity (k), the liquid and vapor phase heat capacities ($C_{p,liq/vap}$), and the density difference between the liquid and vapor (ρ_{liq}-ρ_{vap}), gravity g, and length dimension L, are fundamental parameters. In order to reduce the number of functional variables to a minimum these may be grouped into a smaller number of dimensionless groups. The common groups relevant for boiling include the Reynolds number ρ u L / μ (Re), the Prandtl number μ Cp / k (Pr), the Jakob number $C_p \Delta T_e / h_{fg}$ (Ja), and the Bond number $g(\rho_{liq}-\rho_{vap}) / \sigma$ (Bo). The Nusselt number h L / k (Nu), which characterizes the convection coefficient h, is considered a function of the above dimensionless parameters (Incropera and DeWitt, 1990), but may also be influence by additional factors in fractured rock. For example, in fractures capillary forces and relative permeability will affect the mobility of the vapor, so the fracture aperture may have a significant influence on how vapor nucleates, expands, and moves.

Internal flow heat transfer is commonly characterized by the Nusselt number, which can be viewed as a dimensionless convection coefficient and describes the temperature gradient at the surface-fluid contact. The convection coefficient is a factor of proportionality between the heat flux and the temperature difference in accordance with Newton's law of cooling $q'' = h(T_{surface} - T_{fluid})$. With boiling, the convection coefficient is a function of excess temperature, $h = q''/\Delta T_e$, and h can be 2 to 3 orders of magnitude larger for boiling than for single phase flow.

A commonly employed illustration of the relation between surface heat flux and ΔT_e is the boiling curve, shown in figure 4.

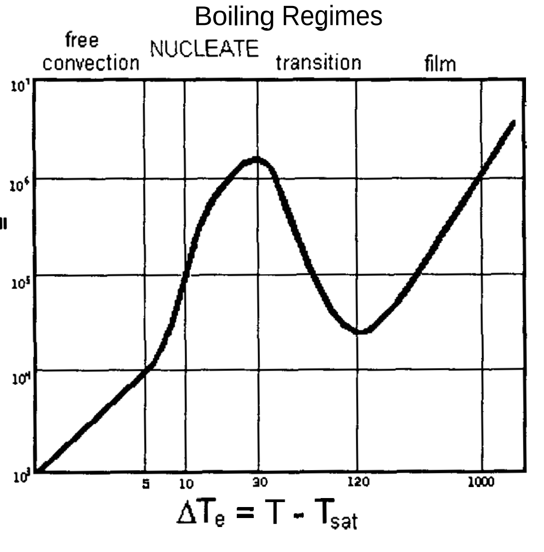

Fig. 4. ***Boiling curve for water at 1 atm.***

This curve is specific to a particular fluid-surface combination at a particular pressure, and it describes the boiling regimes labeled: Free convection, Nucleate, Transition, and Film boiling.

FLOW REGIMES

Free convection occurs before the nucleation of bubbles and extends into temperatures slightly above the saturation temperature. Vapor bubbles form in the nucleate region. The nucleate region of the boiling curve describes an increasing surface heat flux with ΔT_e until a the boiling heat flux reaches a maximum. The maximum occurs because the vapor covers an increasing fraction of the surface area and restricts heat flow due to its smaller thermal conductivity and heat capacity. In the Transition Regime vapor covers an increasing fraction of the total surface area and further reduces heat flux with ΔT_e. At the local minimum between the Transition and Film regimes vapor completely covers the surface. With increasing ΔT_e in the Film Regime q'' increases much more slowly than in the Nucleate Regime. (Notice the scale in the Film Regime).

In a vertical fracture the flow regimes may change along the height of the flow path. If subcooled water is injected at the base of a fracture, the flow will transition from free convection to nucleate boiling, then from bubbly flow to slug flow (where bubbles combine), and upward into a region of annular flow where a thin film of liquid evaporates into a predominantly vapor filled aperture. For a constant mass flow the velocity of multiphase flow increases significantly and liquid droplets may be entrained in the vapor flow. Still further upward along the fracture the fluid may become completely superheated.

Empirical studies of boiling quantify either the heat flux at the surface or the convection coefficient as functionally dependent upon the aforementioned parameters and the ΔT_e. One well known example of an empirical relation, valid in the nucleate boiling regime, was developed by Rohsenow in 1952, with $q'' = (\mu_{liq} h_{fg}) [g(\rho_{liq}-\rho_{vap})/\sigma]^{0.5}$ IC,,,, $\Delta T_e / (C_{s,f} h_{fg} Pr^n)\}^3$, where $C_{s,f}$ and n are characteristic of the surface and fluid to be determined by experimental data. Many similar empirical correlations have been developed in other researchers for each flow regime (Lung, Latsch, and Rampf, 1977) (Carey, 1992).

Such correlations that quantify a boiling convection coefficient have been based upon empirical studies of multiphase heat exchangers. Although quite useful in mechanical engineering applications, experimental studies with fractured impermeable rocks have not yet been conducted. Furthermore, many of these relations were developed with either unconfined surfaces, or tubes in with horizontal and vertical orientations for specific flow regimes. They lack the potentially important considerations for flow in rock fractures such as aperture variability and intermediate orientations. There is not even a distinct trend in the data for describing the pressure gradient in two phase flow (Carey, 1992). Clearly, further experimental work with geothermal rocks and fluids would be required to establish useful relationships for modeling a network of fractured impermeable rock.

FUTURE RESEARCH / MODELING

Because the extent of a liquid/vapor zone in a flowing fracture is likely to be a function of the aperture, saturation, inclination, and rock/fluid properties, it may be difficult to predict a flow regime based strictly upon excess temperature. A model formulation that employs an energy balance between the rock matrix and the fluid enthalpy must consider the liquid-vapor fraction as an indication of the flow regime. Fortunately many correlations have been developed in terms of this ratio for heat exchangers, and experiments with impermeable fractured rock may proceed under this guidance. Generally, the heat supplied from an impermeable matrix to a discrete fracture can be modeled by a discretization of the heat diffusion equation with the energy supplied to the fluid constrained by a convection boundary condition.

Experimental studies of boiling with real geothermal rocks has been planned. Investigations of the relation between heat flux as a function of excess surface temperature are being prepared with rock samples that allow a variable fracture aperture and orientation. If these laboratory studies affirm the general utility of a convection coefficient modeling approach, future efforts could proceed toward the construction of this kind of impermeable matrix discrete fracture geothermal model. Ultimately, such a model could provide insightful analyses of injection into two phase reservoirs.

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