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**Authors**
Kneafsey, T.
Pruess, K.

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# Vaporizing Flow in Hot Fractures: Observations from Laboratory Experiments

Timothy J. Kneafsey (TJKneafsey@lbl.gov)
Karsten Pruess (K_Pruess@lbl.gov)
Earth Sciences Division
Lawrence Berkeley National Laboratory
Berkeley, CA, 94720

Understanding water seepage in hot fractured rock is important in a number of fields including geothermal energy recovery and nuclear waste disposal. Heat-generating high-level nuclear waste packages which will be emplaced in the partially saturated fractured tuffs at the potential high-level nuclear waste repository at Yucca Mountain, Nevada, if it becomes a high-level nuclear waste repository, will cause significant impacts on moisture distribution and migration. Liquid water, which occupies anywhere from 30 to 100% of the porespace, will be vaporized as the temperature reaches the boiling temperature. Flowing primarily in fractures, the vapor will condense where it encounters cooler rock, generating mobile water. This water will flow under gravitational and capillary forces and may flow back to the vicinity of the emplaced waste where it may partially escape vaporization. Water flowing down (sub-) vertical fractures may migrate considerable distances through fractured rock that is at above-boiling temperatures; thus, flowing condensate may contact waste packages, and provide a pathway for the transport of water-soluble radionuclides downward to the saturated zone.

Thermally-driven flow processes induced by repository heat may be as important or even more important for repository performance than natural infiltration. For a nominal thermal loading of 57 kW/acre, vaporization may generate an average equivalent percolation flux from condensate of 23.1 mm/yr over 1,000 years, and 5.2 mm/yr over 10,000 years. These numbers are comparable to or larger than current estimates of net infiltration at Yucca Mountain. This condensate, which is generated in the immediate vicinity (meters) of the waste packages, will likely have a larger impact on waste package and repository performance than a similar amount of water introduced at the land surface.

Laboratory experiments have been conducted to visualize liquid flow in fracture models, transparent fracture replicas, rock-replica assemblies, saw-cut fractures made with Topopah Spring Tuff and glass, and a natural fracture in Topopah Spring Tuff. In these experiments, portions of the models were kept at above-boiling temperatures, while portions were kept at below-boiling temperatures. To facilitate many of these experiments, pentane, with a boiling temperature of 36.1$^{o}$C was used as the working fluid instead of water. Video recording and spatially resolved thermal monitoring were used in experiments to (1) investigate seepage and boiling phenomena in fracture models and replicas, (2) investigate seepage into a heated natural fracture at different flow rates, (3) quantify liquid flow in refluxing heat pipes in glass fracture models, and (4) examine the effect of fracture angle on flow, and finger and film penetration into the boiling region.

In fracture models and replicas, liquid flow was observed to occur in continuous and intermittent rivulets, and films. Rapid evaporation events were seen frequently in the experiments. These events occur when liquid superheats and spontaneously boils, generating large volumes of vapor quickly, and causing pressure pulses. These rapid evaporation events could potentially disturb capillary barrier conditions at fracture/drift intersections at the potential repository, possibly causing drop snap-off or water spray out of fractures. Continuous rivulet flow was seen at high liquid flow rates, intermittent rivulets occurred when liquid was added by flow or condensation to capillary-held liquid islands causing the gravitational force to exceed the stabilizing capillary force, and film flow along the fracture-wall faces was predominant under low-flow or wide aperture conditions.

Water at three flowrates (~1.35 $\mathrm{ml \cdot hr^{-1} cm^{-1}}$, ~0.68 $\mathrm{ml \cdot hr^{-1} cm^{-1}}$, and ~0.34 $\mathrm{ml \cdot hr^{-1} cm^{-1}}$) was introduced with three nonvolatile dyes into a heated natural fracture (~20 x 20 cm). The water penetrated the boiling region, with dye stains indicating that a wider finger was present at the highest flow rate used, and a narrower finger at the medium flow rate. In some locations, dye from the medium flow rate case was present outside the dye remaining from the high flow rate case, indicating flow-rate dependent flow paths. Flow did not penetrate deeply into the boiling region at the lowest flow rate used. Thermal gradients of several hundred degrees Centigrade per meter occurred in this experiment.

Liquid flow rates in glass fracture models were quantified by measuring heat flux from the models during refluxing, as well as in dry conditions. The heat transfer difference between these two cases was attributed to phase change (heat pipe), which was directly proportional to the liquid flow rate. Liquid flow rates were evaluated in two models that were similar except for aperture; one had a nominal 0.76 mm aperture and the other ranged from zero to several hundred microns. Contrary to what had been expected, a higher flow rate was observed in the smaller aperture fracture. This was explained by noting that in the wide aperture fracture, flow is restricted to films, whereas in the narrow fracture, flow occurs in thicker pendular or corner structures in addition to films.

Finger and film penetration into the boiling region was not well described by a simple model which accounts only for gravitational force. Reduction of the gravitational force by reducing the inclination of the fracture, while holding other parameters constant, was expected to reduce finger and film length, reduce the number of fingers, and increase finger width. In some cases, finger and film lengths exceeded the predicted lengths when the fracture inclination was reduced. These differences may be attributed to changes in fluid mechanics and aperture heterogeneity. Films on the hanging (top) wall penetrated deeper into the boiling zone than predicted, whereas the film on the foot (bottom) wall did not penetrate nearly as far. For the same liquid saturation, a film on one wall will carry twice the flow of equal films on two walls. Aperture heterogeneity affects the local saturation at a given capillary pressure, and thus is important in determining flow paths. At non-vertical angles, gravitational influence will cause liquid to be distributed differently in the aperture, affecting the flow path.

A simple physical model of sheet flow into a fracture exceeding the boiling temperature was developed, and measurements of finger penetration into the boiling region from several experiments were used in the simple model to estimate the rate of liquid flow. These liquid flow rates matched well with thermal techniques of quantifying liquid flow rates.

The laboratory experiments have revealed some surprising phenomena during vaporizing flows in hot rock fractures, which were neither expected nor easily explained on the basis of conventional continuum models for fluid flow and heat transfer. There is a strong interplay between heat transfer, gas and liquid flow processes, and phase change. Investigations are ongoing to determine behavior of non-isothermal flows in fractures on different space and time scales to bridge the gap to *in-situ* heater experiments at Yucca Mountain, and to gain an understanding of large-scale, long-term thermohydrologic effects in an actual nuclear waste repository.

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