A Temperature-Profile Method for Estimating Flow Processes in Geologic Heat Pipes

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RESEARCH OBJECTIVES

Above-boiling temperature conditions, as encountered, for example, in geothermal reservoirs and in geologic repositories for the storage of heat-producing nuclear wastes, may give rise to strongly altered liquid and gas flow processes. Evaluating the magnitude of such flux alterations is a challenging task, because the direct *in situ* measurement of such quantities is virtually impossible. Thermally induced fluxes can be particularly strong in geologic heat pipes, where vaporization and subsequent condensation of pore water creates a continuous recirculation at significant rates. The energy transported with these fluxes generates characteristic features in temperature profiles. We have developed a temperature-gradient method that uses these characteristic features to derive the flux perturbation occurring in geologic heat pipes. Since field measurements of temperature are relatively simple and accurate in subsurface systems, our method can offer fast and reliable first-order estimates of heat pipe fluxes.

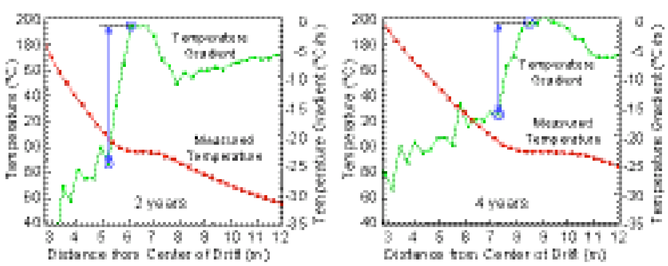

Figure 1. Temperature profiles measured in Borehole 137 of the Drift Scale Test at Yucca Mountain, at 2 years and 4 years of heating. Plot shows measured temperature at sensor location and average gradient between adjacent sensors. The blue arrow depicts the gradient difference at the boiling end of the heat pipe. The estimated liquid fluxes are 470 mm/yr at 2 years and 340 mm/yr at 4 years.

APPROACH

The detailed theoretical framework for the temperature-gradient method is presented in Birkholzer (2005a,b). In essence, differences between the temperature gradients measured at both sides of the boiling end of a heat pipe are used to estimate the amount of energy available to vaporize water (Figure 1). For stationary heat pipes, the estimated energy is directly proportional to the liquid reflux in the heat pipe. For transient heat pipes, some fraction of the supplied energy is used to change the temperature and to boil the resident pore water of downstream regions encountered when the heat pipe moves out from the heat source. Application of the method requires temperature profile data with sufficient resolution in time and space, knowledge of thermal properties, and a general idea of the geometry of heat transfer conditions. The starting point of each application is a thorough analysis of the measured temperature profiles. A valuable practice for identifying heat pipes and determining gradient differences is to calculate the gradients between two adjacent sensors and to plot these together with the temperature profile (Figure 1).

ACCOMPLISHMENTS

The proposed method was tested in comparison with various one-dimensional and two-dimensional example cases in porous and fractured media, for which model simulations were conducted to provide simulated temperature and flux results. The temperature results were fed as “measured data” input to the temperature-gradient method. It turned out that the fluxes estimated from applying the temperature-gradient method to these “measured data” were in excellent agreement with the simulated fluxes, demonstrating that the temperature-gradient method works in principle. In a second step, a temperature-profile analysis was performed with measured data from a large-scale *in situ* heater test at Yucca Mountain, demonstrating the general feasibility of the method in field situations. Fluxes were estimated for selected boreholes drilled from the heated tunnel in a vertical direction into the surrounding rock. All boreholes showed clearly detectable heat-pipe signatures, as evident from strong temperature-gradient changes and extended constant-temperature plateaus. The maximum fluxes estimated from the temperature-gradient method were as high as 470 mm/yr—much larger than site ambient percolation.

SIGNIFICANCE OF FINDINGS

The proposed temperature-gradient method offers a promising approach for quantifying liquid and gas flow processes in complex thermal-hydrological settings. The flux estimates obtained for the large-scale heater test at Yucca Mountain provide an additional piece of evidence for calibrating and validating numerical simulation models for predicting future thermal-hydrological conditions at Yucca Mountain.

RELATED PUBLICATIONS

Birkholzer, J., A temperature-profile method for estimating flow processes in geologic heat pipes. Journal of Contaminant Hydrology (submitted), 2005a. Berkeley Lab Report LBNL-56716.

ACKNOWLEDGMENTS

This work was supported by the Director, Office of Civilian Radioactive Waste Management, U.S. Department of Energy, through Memorandum Purchase Order EA9013MC5X between Bechtel SAIC Company, LLC, and the Ernest Orlando Lawrence Berkeley National Laboratory (Berkeley Lab). The support is provided to Berkeley Lab through the U.S. Department of Energy Contract No. DE-AC03-76SF00098.