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Calculation of Thermal Conductivity of Unsaturated Porous Media Based on Microscopic Fluid Distribution

by

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INTRODUCTION

The emplacement of the heat-generating high-level radioactive waste underground will elevate the temperature field, cause a redistribution of the *in situ* water, affect container corrosion process, and alter geochemical transport of the radionuclides. It is argued that the advective heat transfer is negligible and much of the heat transfer is expected to be conduction dominated (Roglans-Ribas and Spinard, 1989; Buscheck and Nitao, 1992). For many far-field temperature prediction, this assumption is expected to be valid, especially when the liquid flow is negligible (Buscheck and Nitao, 1992). Hence, calculations are expected to be sensitive to thermal properties.

The principal factor influencing thermal properties of rock units at Yucca Mountain have been reported to be the degree of liquid saturation. The work of O'Neal et al. (1984) indicates that a significant volume of the surrounding host rock may reach high temperature (>100°C), which will enhance the rock dryout. When the rock is dry, the rock thermal conductivity can be much lower than saturated rock due to air having a much lower thermal conductivity than water.

Due to the broad variation in rock types, saturation, temperature, and other environmental conditions, measurement of thermal properties is often expensive and time consuming. In addition, difficuties associated with preventing heat losses cause error in the measured data. Therefore, predictive models based on easily measurable input parameters such as porosity and the conductivities of constituent components are desirable. In the literature, the relationship between thermal conductivity and saturation has been assumed to be representable through either a linear or a square-root function. In this paper, a method is presented to predict thermal conductivity at various fluid saturations while taking into account the pore structure that embody the relevant physics of the most general and universal properties of the assemblages.

DESCRIPTION OF ACTUAL WORK

The effect of fluid saturation on the thermal conductivity was studied by using a thin-section which was photographed, digitized, converted to a gray scale image, and finally to a binary image selecting an appropriate threshold. Water and air distribution in the digitized porous medium was generated based on the equilibrium distribution principle which ensures the minimization of interface energy (Mohanty, 1993). The minimum interfacial free energy represented equilibrium distribution of fluids or fluid phases. The nature of fluid distribution was verified first by creating a single capillary tube whose radius was increased step-wise from the left edge to the center of the rock matrix and then was gradually decreased from the center to the right edge. The partial saturation images thus obtained were used to obtain the thermal conductivity of partially saturated rocks. A solid conductivity of 8.3736 W/m-K (conductivity of quartz) was used in the calculation. The wetting phase (water) and the nonwetting phase (air) fluids have conductivity contrast with grain exceeding 10, and 230, respectively.

RESULTS

A typical fluid saturated generated numerically, is shown in Figure 1. The variation of effective conductivity with fluid saturation in two dimensions is shown in Fig. 2. At smaller saturations, the wetting phase occupies the narrow gaps in between the grains. As the fluid saturation is increased, the wetting phase gradually occupies the central regions of larger pores. The effective conductivity increases, though nonlinearly, with the increase in water saturation. A slight jump is observed near 40% water saturation. Similar behavior is observed as we approach lower values starting from 100% water saturation. This implies that a percolation-like phenomenon is taking place in the neighborhood of 40% water saturation. This corresponds to

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water making its own connecting path in addition to aiding the rock matrix to conduct more heat. It also implies that the relationship between multiphase fluid saturation and conductivity is not monotonic as has been predicted by the empirical models presented in the past.

CONCLUSIONS

To study the thermal conductivity of porous media as a function of saturation, a realistic numerical representation of the structure of the porous medium is essential. A realistic representation of the distribution of fluids is also necessary since the fluids significantly influence the macroscopic properties of interest. As most of the heat transfer takes place through grain-to-grain contact, the degree of intergrain contact and the fluid around the grain contacts (*i.e.* the wetting fluid) influences the heat conduction. This study suggests that the effect of fluid saturation on the overall thermal conductivity is not monotonous as believed in the past. Even if all phases have a finite conductivity, the effective conductivity shows a percolation like behavior with respect to the fluid saturation.

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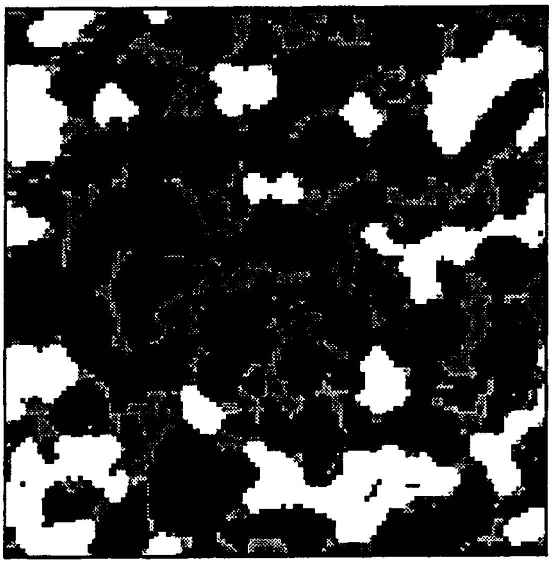

Figure 1: Simulated fluids distribution in a thin section of Berea sandstone constructed of 128x128 pixels. Black region represents grains, white region water (saturation = 0.4), and the gray region air. Two dimensional porosity = 0.34%.

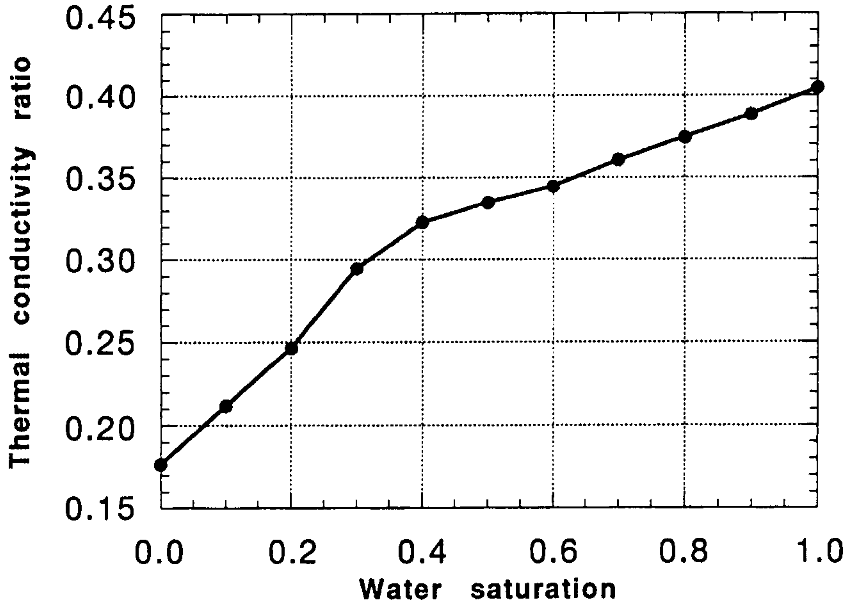

Figure 2. Calculated thermal conductivity from the thin section of Berea sandstone with air and water as saturating fluids. 2-D porosity = 0.3474.