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Results of the Single Heater Test at Yucca Mountain, Nevada

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Introduction

The Yucca Mountain Project conducted a Single Heater Test (SHT) in the Exploratory Studies Facility at Yucca Mountain. During the nine month-long heating phase, approximately 4 m³ of in situ, fractured, 92% saturated, welded tuff was heated to temperatures above 100°C by a 5 m long, 3.8 kW, horizontal, line heater. In this paper, the thermal data collected during the test (Sandia National Laboratories, 1997) are compared to three numerical simulations (Sobolik et al., 1996) in order to gain insight into the coupled thermal-hydrologic processes. All three numerical simulations rely on the Equivalent Continuum Model (ECM) for reasons of computational efficiency. The ECM assumes that the matrix and the fractures are in thermodynamic equilibrium which allows the thermal and hydrologic properties of the matrix and the fractures to be combined into single, bulk values. The three numerical simulations differ only in their bulk permeabilities (5.2×10^{-12} , 5.0×10^{-15} and 4×10^{-18} m²) and are referred to as the High, Low and Matrix Permeability Models, respectively. In the Matrix Permeability Model, the system behaves as an unfractured porous medium with the properties of the rock matrix.

Results

Figure 1 illustrates the measured and predicted temperatures as a function of time for a temperature gage located 41 cm away from the heater in the vertical plane perpendicular to the heater at its midpoint. Figure 2 illustrates the measured and predicted temperatures after 70 days

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of heating, as a function of radial distance from the heater, in the vertical plane perpendicular to the heater at its midpoint. The Low and High Permeability Models show significant isothermal regions or temperature inflections near the boiling point of water which reflect energy consumption by the water vaporization process. The data and the Matrix Permeability Model do not exhibit these temperature signatures. As the temperature in the Matrix Permeability Model rises past 96°C, minute amounts of water vaporize but cannot escape from the pore space, resulting in a dramatic increase in pore pressure. This very effectively inhibits further evaporation of the pore water so the liquid saturation remains very near ambient levels, even up to temperatures of 160°C.

Although the Matrix Permeability Model yields the best match between the measured and calculated temperatures in Figures 1 and 2, it is unlikely to accurately reflect reality, primarily because it does not predict a dry-out zone around the heater. In Figure 3, the amount by which the temperature of the gages in the interior of the SHT block increased during the last 3 months of the 9 month test is plotted as a function of the temperature measured 6 months into the test. The temperatures recorded by gages whose temperature 6 months into the test were less than 100°C increased by about 3°C, while the temperatures of gages whose temperature 6 months into the test exceeded 100°C rose by up to 8°C. This behavior reflects formation of a dry-out zone around the heater since drying the rock reduces both its heat capacity and thermal conductivity. The Low and High Permeability Models predict the formation of a dry-out zone and more rapid warming of the rock in the dry-out zone. The Matrix Permeability Model predicts neither since water vaporization is strongly inhibited in the model by the low permeability.

Discussion

The poor match between the simulations and the data likely result from the assumptions upon which the ECM is based. In the ECM, the bulk permeability and bulk capillary suction in the models more closely resemble those of the matrix until such time as the liquid saturation approaches unity. As a result, the flow of liquid water in the models is strongly inhibited until near total saturation is achieved. When the rock temperature exceeds the boiling point of water, vapor forms and flows radially away from the heater in response to the pore pressure gradient. Once past the boiling point isotherm it condenses, but then the resulting liquid water cannot readily flow very far because complete saturation is only rarely achieved in the SHT models. As the boiling point isotherm progressively moves radially outward, the water revaporizes and moves radially outward until it recondenses. This process, called refluxing, is repeated ad infinitum.

The magnitude of the isothermal regions and temperature inflections in the Low and High Permeability Models is likely exaggerated due to the assumptions of the ECM. Consider a cylindrical surface whose axis coincides with the axis of the heater. In the ECM, when the temperature of this surface reaches the boiling point, all the water that originally filled the pores of the cylindrical volume enclosed by the cylindrical surface is filling the pores just outside the surface of the cylinder. Throughout the time period required to vaporize water, virtually all the thermal energy entering the rock is consumed by the vaporization process, and very little is devoted to raising the temperature of the rock. If, once the vapor condensed, it did so in a material with the permeability of the fractures, the resulting condensate could drain out of the system under the influence of gravity, thereby reducing the amount of liquid water that would have to be vaporized as the boiling point isotherm expanded. In this case, the isothermal time periods and annular regions would still exist because the water that was originally in the pores still

needs to be vaporized, but their magnitudes might be greatly reduced due to the reduction in the amount of water subject to refluxing.

Future Work

As an alternative to the ECM, a Dual Permeability Model (DKM) will be implemented. To relax the assumption of capillary pressure equilibrium between the matrix and the fractures, DKMs have two coupled model domains: one for the matrix and one for the fractures. This will permit water to drain away from the condensate zone through a material with the properties of the fractures, thereby reducing the amount of water in the condensate zone subject to refluxing. This will allow the models to predict a dry-out zone while reducing the magnitude of the isothermal regions and temperature inflections to levels which more closely match the measured data.

References

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Figure 1 - Temperature-time history for a temperature gage located 41 cm from the heater.

Figure 2 - Radial temperature distribution in the vertical plane that intersects the heater at its midpoint, after 9 months of heating.

Figure 3 - Amount by which the temperature increased during the last 3 months of the test, as a function of the temperature measured 6 months into the test.

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