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Modelling heat and moisture transport in the ANDRA/SKB temperature buffer test

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Abstract

The present paper regards heat and moisture transport in the barrier of the temperature buffer test (TBT) large-scale experiment. TBT includes two individually powered 1500 W heaters, vertically positioned on top of each other in a KBS-3 type disposal pit with 0.5 m of compacted MX80 bentonite in between. The experiment is run at high temperatures and with controlled hydraulic boundary conditions. This, and an extensive instrumentation of the barriers, makes the TBT experiment particularly suited for modelling and for testing and evaluation of different modelling approaches. This is in particular true for the two horizontal sections at the heater mid-height levels, where radial arrays of densely spaced thermocouples allow for accurate direct monitoring of the temperature development and for monitoring of the saturation development with indirect interpretation methods. Examples of early predictions, given by a number of modelling teams using different codes and different approaches, are presented in the paper. Comparisons are made between different sets of modelling results and measurements.

Keywords: Bentonite; Barrier; Saturation; Heat flux; Vapour; Sand; Heater

1. Introduction

For ANDRA as well as for other organizations responsible for the development of concepts for geological disposal of nuclear waste, there is an interest in improving the understanding of the Thermo-Hydro-Mechanical properties and behaviour of bentonite-based buffer materials during the water saturation process, in particular in the high temperature range above 100 °C. To meet the need for experimental data, a large-scale field test, the temperature buffer test (TBT) has been designed and set-up in crystalline rock at 420 m depth below ground surface at the Äspö Hard Rock Laboratory in Southeast Sweden (Fig. 1). The test, which is jointly operated by ANDRA and SKB, the Swedish Nuclear Fuel and Waste Management, is in operation since March 2003.

The response of the barrier materials to high temperatures and to high temperature gradients is the main concern. One aspect of this is the question whether the bentonite will endure a period of hot and possibly dry conditions without loosing its sealing properties because of chemical and mineralogical alterations. This question will have to be addressed when the experiment is dismantled and samples can be examined. The questions addressed here regard transport of heat and moisture and whether the conceptual models commonly used for describing mass and heat transport in unsaturated porous media are

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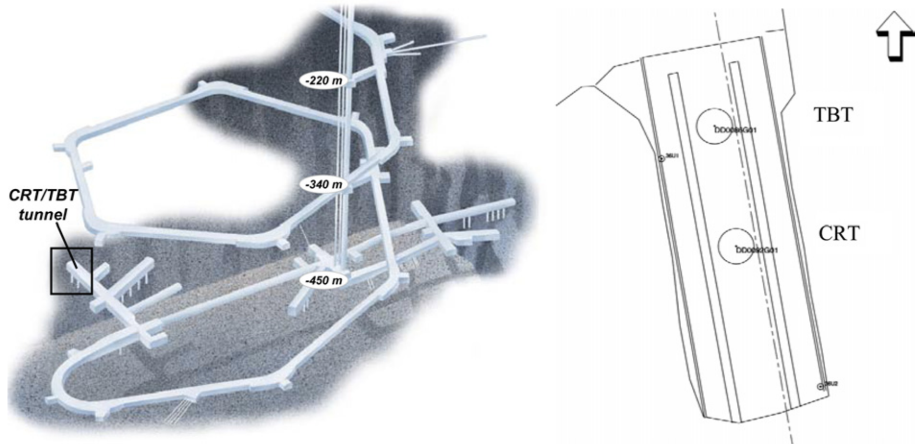

Fig. 1. Left: test region (CRT/TBT tunnel) at 420 m depth at Äspö HRL. Right: The CRT/TBT tunnel with the deposition hole used for TBT positioned about 6 m from the canister retrieval test (CRT).

reasonably valid and relevant also for systems at high temperatures.

2. Test design and test running conditions

Fig. 2 shows the design of the experiment. Two heaters, each 3 m long, 0.6 m in diameter and generating 1500 W of thermal power, are stacked on top of each other within a bentonite buffer inside a vertical deposition hole, 8 m deep and 1.8 m in diameter. Ring-shaped blocks of highly compacted MX80 bentonite are in direct contact with the lower heater, while there is a 0.2 m sand-shield between the upper heater and the surrounding bentonite. Cylinder-shaped blocks of bentonite are placed below, between and above the heaters. An anchored plug seals the hole and confines the experiment mechanically in the vertical direction. To allow for control of the hydraulic boundary, a sand filter is installed in the 50 mm slot between the bentonite buffer and the rock wall. Water is supplied to the sand filter through injection points at two different levels, whereas the supply from the surrounding granite is assumed to be small. The upper part of the slot is sealed with bentonite pellets. Temperatures, relative humidities, total stresses, pore pressures, water inflow and forces taken up by the plug anchoring cables are monitored continuously, logged hourly and reported monthly (Sandén and Börgesson, 2002).

The THM processes in the TBT may potentially be disturbed or influenced by the nearby canister retrieval test (CRT). Fig. 3 shows an estimate of the temperature contribution from CRT at experiment mid-height. For the TBT periphery, the effect of the neighbour experiment is that the background temperature is elevated by about 8° above the natural one. For the expected duration of the test, this condition will not change much. The combined effect of the cool tunnel floor and the CRT heat load complicates the heat transfer conditions, but is not judged to compromise the validity of the conclusions that will be drawn after completion of the experiment.

3. Heat and mass transfer at heater mid-height

The design of the experiment with dense arrays of temperature sensors along radial scan-lines allows for close monitoring of the heat and moisture conditions at mid-height of the two heaters. Here the transport conditions are almost purely radial and the slope of temperature curves can be used to calculate the thermal conductivity λ using the steady-state heat flux expression:

$$\lambda = \frac{Q}{2 \cdot \pi \cdot (T_r - T_{r+\mathrm{d}r})} \cdot \ln\left(\frac{r + \mathrm{d}r}{r}\right), \tag{1}$$

where T_r and $T_{r+\mathrm{d}r}$ are the temperatures at points at radial distances r and $r + \mathrm{d}r$, respectively, and Q is the power per unit length of a long linear heat source. Figs. 4 and 5 show the results at the Ring 10 and Ring 4 levels, respectively (cf. Fig. 1). The 20-day temperature curve may have been influenced by the step-by-step increase of the heat output after start, and cannot be used here to estimate the thermal conductivity quantitatively. The heater power, 1500 W, gives a nominal unit length heat of 500 W/m. Here Q was set at 440 W/m for both heaters to account for the shape of the heaters and for their finite length (Hökmark and Fälth, 2003a). In reality, the effective radial flux will not be constant and the same for both heaters: as the transport conditions change over time there will also be a small and varying vertical heat flow between the two heaters.

Around the upper heater (Fig. 4), there was no major change of the heat transfer properties in the bentonite over time. However, there was a slow increase in sand-shield thermal conductivity. In particular close to the rock wall, the calculated conductivities were higher than would be expected considering data obtained in lab-scale experiments (cf. Fig. 6). This is probably an effect of the radial heat flux approximation made in Eq. (1). The heat flux vector has a non-zero axial component which means that the radial heat flux corresponds to a smaller effective value of Q.

In the lower part of the experiment (Fig. 5), there was an early and fast decrease in thermal conductivity in a 0.15 m