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Experimental and numerical investigation of heat transfer from a high temperature borehole heat exchanger under saturated and unsaturated conditions

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The performance of borehole heat exchangers (BHE) for borehole thermal energy storage may be deteriorated by the occurrence of permeable water-bearing intermediate layers in the subsurface due to convective flow and heat transport especially at high storage temperatures. Under partly saturated conditions, e.g. in the shallow unsaturated zone, low water contents will reduce the storage capacity as well as the heat transfer rate as compared to fully saturated conditions. This study combines experimental work and numerical simulations in order to quantify these effects on the performance of high temperature BHEs under fully and partly saturated conditions.

A laboratory scale analogue of a coaxial BHE in a water saturated sand medium is constructed in a cylindrical storage cell of 1.2 m height and 1.4 m³ volume. Four short-term heat storage experiments in a temperature range from 30 to 90°C were carried out with six days of continuous heat injection at constant temperature (30, 50, 70, or 90°C), followed by 3 to 4 days of heat extraction, respectively. Temperatures and water contents were continuously monitored on a grid of 68 thermocouples and 20 SMT100 moisture sensors. The water level was then lowered to 0.2 m above the bottom of the system and the experiments were repeated under partly saturated conditions.

Under saturated conditions the observed temperatures in the 30°C experiment show an almost radial distribution with a maximum along the BHE, while for higher injection temperatures an increasing thermal stratification and tilted temperature fronts are observed, which clearly point at an increasing convective impact on heat transport. These results are corroborated by the model simulations, which show an increase of the mean vertical flow velocity from 0.1 to 0.6 m/d between 30 and 90°C due to convection. Additional simulations for purely conductive conditions generally showed lower steady state BHE heat transfer rates during the charging process. This allowed a quantification of the contribution of convection to overall heat transfer, which increases from 5.7% at 30°C to about 38% at 90°C during the charging process. During discharging, however, the thermal stratification due to convection reduces heat transfer rates by up to -38% at 90°C.

Under partly saturated conditions, heat is mainly stored in the direct vicinity of the BHE and the measured temperatures show a radial evolution with no stratification or indications for convection. This points out a conduction dominated heat transport. A decrease of heat transfer

rates by about 40% (30°C) to 50% (90°C) is observed in comparison to saturated conditions, which is due to decreased thermal conductivities and heat capacities of the unsaturated porous sand. No indications for significant moisture transport in the gas phase were observed during the experiments.

These results suggest, that high permeable saturated interlayers may severely deteriorate the efficiency of borehole thermal energy storage and increase heat loss and thus environmental impacts, while for unsaturated layers a general reduction of storage rates and capacities must be expected.