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Experimental and numerical investigation of thermal convection in a water saturated porous medium induced by heat exchangers in high temperature borehole thermal energy storage

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Borehole thermal energy storage is a well-established technology for seasonal geological heat storage, where arrays of borehole heat exchangers (BHE) are installed in low permeability geological media dominated by conductive heat transfer. Increasing storage temperatures would increase storage capacities and rates and would thus allow for a better inclusion of BTES in the energy system. When using storage temperatures of up 90°C, however, highly permeable zones or intermediate layers may allow for thermally induced fluid migration and convective heat transport in the storage medium, which may increase heat losses from the storage and thus limit the thermal performance of the BTES system. Therefore, we present results from experimental work and subsequent numerical modelling aimed at quantifying thermally induced convection for a lab-scale BHE in a water saturated porous medium for a temperature range of 20°C to 70°C.

The experimental heat storage unit consists of a fully water saturated coarse sand within a cylindrical polypropylene barrel of 1.23 m height and 0.6 m radius and a vertical coaxial BHE, which is grouted by a thermally enhanced cement. The barrel is cooled from the outside using ventilators and laboratory air. A grid of 68 thermocouples is emplaced in the storage medium for monitoring the temperature distribution. For the stationary experiment, heat is transferred to the storage unit using a supply temperature of 70°C for 6 days until a steady state temperature distribution is achieved, followed by 3 days of heat recovery. The dynamic experiment begins with 3 days of heating with 70°C followed by 6 cycles of alternating heating at 70°C and cooling at approximately 18°C for 12 hours each.

The stationary experiment reveals a vertical temperature stratification, with temperatures increasing up to 48°C towards the top of the porous medium, as well as a horizontal temperature gradient along the top of the sand, while the lower part of the barrel and the outer wall remain at the laboratory temperature of approximately 18°C. This temperature distribution has stabilized after about 90 hours and represents a clear tilted thermal front, suggesting a significant contribution of induced thermal convection to the overall heat transport. The cyclic experiment shows a decrease of storage temperatures relative to the stationary experiment, with temperatures near to the BHE at the top of the porous lower by 2.5°C and 4.75°C, respectively, because the heating phase is not long enough to reach the stationary temperature distribution. This lower horizontal temperature gradient indicates a weakened thermal convection, however the thermal stratification is conserved. This shows that even under the cyclic loading conditions thermal convection may impair high temperature BTES operation and efficiency.

Numerical process simulation of coupled flow and heat transport accounting for variable density and the experimental boundary conditions reproduces the spatial and temporal temperature distribution of both experiments with good accuracy. This shows that induced thermal is causing the observed temperature distributions.