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Impacts of convection on high-temperature aquifer thermal energy storage

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Seasonal subsurface heat storage is increasingly used in order to overcome the temporal disparities between heat production from renewable sources like solar thermal installations or from industrial surplus heat and the heat demand for building climatisation or hot water supply. In this context, high-temperature aquifer thermal energy storage (ATES) is a technology to efficiently store and retrieve large amounts of heat using groundwater wells in an aquifer to inject or withdraw hot or cold water. Depending on the local hydrogeology and temperature amplitudes during high-temperature ATES, density differences between the injected hot water and the ambient groundwater may induce significant convective flow components in the groundwater flow field. As a consequence, stored heat may accumulate at the top of the storage aquifer which reduces the heat recovery efficiency of the ATES system. Also, an accumulation of heat at the aquifer top will induce increased emissions of heat to overlying formations with potential impacts on groundwater quality outside of the storage.
This work investigates the impacts of convective heat transport on the storage efficiency of a hypothetical high-temperature ATES system for seasonal heat storage as well as heat emissions to neighboring formations by numerical scenario simulations. The coupled groundwater flow and heat transport code OpenGeoSys is used to simulate a medium scale ATES system operating in a sandy aquifer of 20 m thickness with an average groundwater temperature of 10°C and confining aquicludes at top and bottom. Seasonal heat storage by a well doublet (i.e. one fully screened "hot" and "cold" well, respectively) is simulated over a period of 10 years with biannual injection / withdrawal cycles at pumping rates of 15 m^3/h and for different scenarios of the temperature of the injected water (20, 35, 60 and 90 °C).
Simulation results show, that for the simulated system significant convective heat transport sets in when injection temperatures exceed 35°C. Convection results in an accumulation of heat below the upper confining layer. The consequential increase of the heat plume contact area with this formation results in increased conductive heat transfer. Also, thermal gradients between the heat plume and the ambient groundwater increase with injection temperature, which increases heat conduction within the aquifer. Both effects reduce the thermal recovery of the ATES system. At the end of the 10th injection / withdrawal cycle the efficiency of thermal recovery thus reaches about 76 % for the 20°C scenario, 74% for 35°C, 71 % for 60°C and 66 % for the 90 °C scenario.
Sensitivity analysis indicates that permeability in horizontal and vertical directions are controlling factors for the extent of convective heat displacement. Also, heat plume dimensions are influenced by permeability, and to a lesser extent by heat capacity and porosity of the aquifer. The planning of high-temperature ATES at a specific site hence requires a careful investigation of hydraulic and heat transport properties.

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