Toward High Thermal-Hydraulic Performance Of Heat Exchangers For Water-Gravel Thermal Energy Storage

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Abstract

Seasonal thermal energy storage systems are key enablers of future low-carbon and flexible energy infrastructures. Among the different storage technologies, water-gravel thermal energy storage (WGTES) offers a robust, cost-effective, and environmentally sustainable solution for large-scale heat storage. However, the performance of such systems is highly dependent on the layout and operation of the charging and discharging heat exchangers, which govern both thermal efficiency and hydraulic effort.

This study presents a simulation-driven methodology for the optimal planning and layout of heat exchangers used for charging and discharging in a WGTES consisting of three neighboring storage units at IN-Campus demo-site of INTERSTORES project. With the support of COMSOL Multiphysics®, a detailed numerical model of the water-gravel domain is developed, focusing on the thermal and hydraulic interaction between the heat exchangers and the porous gravel matrix.

The modeling framework integrates the Conjugate Heat Transfer, Porous Media Flow and Pipe Flow modules to capture heat transport and pressure dynamics in the heat exchangers. The heat exchanger sub-model is validated against experimental data from literature, confirming the model's reliability in replicating thermal profiles, pressure drops, and stratification dynamics during both charging and discharging cycles. This validation step establishes a trust in the model and forms the basis for further parametric analysis.

Subsequently, the study explores a wide range of heat exchanger configurations, varying in geometry, number of heat exchange levels, orientation, and spatial positioning within the storage units. Additionally, different boundary conditions for flow and temperature are examined to represent realistic operating scenarios.

The key performance indicator (KPI) used for performance assessment is the thermal-to-hydraulic ratio, defined as the fraction of thermal energy successfully discharged (or charged) to the corresponding pumping work required. This KPI effectively balances the thermal performance (i.e., temperature levels reached in the WGTES) against the pressure losses induced by the heat exchanger design, offering a complete measure for optimization.

Simulation results reveal strong dependencies between heat exchanger layout and storage efficiency. Multi-level configurations, strategic orientation relative to flow direction, and heat exchanger geometries are found to play a significant role in stratification and hydraulic losses. Moreover, operating conditions such as flow rate and inlet temperature critically affect the thermal-hydraulic behavior of the system.

This work demonstrates the power of multiphysics modeling in achieving a performance-optimized design of thermal storage systems, where heat exchanger layout is critical to realizing the full potential of WGTES. The developed simulation framework not only supports the design of the current system but also provides a transferable tool for future applications in large-scale seasonal storage planning.