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Thermal energy storage with tunnels in different subsurface conditions

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The widespread use of the underground and global climate change impact the urban subsurface temperature. Changes in the subsurface environment can affect the performance of underground thermal energy storage systems, especially when convection may characterize such systems in view of augmented thermal losses. This work focuses on tunnels equipped with ground heat exchangers, typically called energy tunnels, to serve as seasonal, medium-temperature underground thermal energy storage systems (UTES). Besides their structural purpose, energy tunnels can be used to inject, store and extract heat from the ground by means of a heat carrier fluid circulating through an integrated pipe system embedded within them. By storing thermal energy during periods of overproduction and utilizing it during high-demand periods, energy tunnels help reduce reliance on non-renewable energy sources without the need of additional infrastructure.

Specifically, this work addresses the storage performance of energy tunnels in different subsurface environmental conditions influenced by convection through 3-D thermo-hydraulic finite element simulations validated against full-scale experimental data. The results of this study are described in detail by Schaufelberger et al. [4].

The focus of the study lies on the influence of convection heat transfer driven by groundwater flows and airflows, whose properties may be altered by rising temperature in urban areas due to subsurface urban heat islands. The rationale behind this work is that Rotta Loria [3] recently highlighted promising storage efficiencies of up to 70% for energy tunnels characterized by favourable subsurface conditions for storage applications (i.e., lacking convection heat transfer). However, knowledge about the performance of energy tunnels in the presence of convection heat transfer has remained limited to date, representing a barrier for the practical implementation of such systems.

Simulations are run with the software COMSOL Multiphysics® [2]. 30 cycles of a seasonal, medium-temperature storage system are simulated by considering an infinitely long tunnel, composed of 1.4-m-wide lining rings (thermally activated over their complete length), and the surrounding ground, drawing from the geometry of the case study reported by Barla et al. [1]. One cycle corresponds to a 6 months heat injection interval with a fluid inlet temperature of 57.3°C, followed by another 6 months of energy extraction with a fluid inlet temperature of 17.3°C, which corresponds to a flow characterized by a temperature equal to the initial ground temperature. A Cauchy boundary condition applied on the interior lining represents heat exchange with tunnel air, with the convective heat transfer coefficient h_c (positively correlated with airflow velocity) and the air temperature T_A as input parameters. Three distinct parametric studies investigate the influence of: (1) groundwater velocity u, (2) air convection heat transfer coefficient h_c and temperature T_A, and (3) thickness t_{ins} and thermal conductivity λ_{ins} of an insulation layer on the storage performance. Thermal losses Q_{loss} and storage efficiency η are computed to characterize and compare the resulting performance for each set of parameters.

When considering a subsurface environment without convection heat transfer, a storage efficiency of about $\eta = 60\%$ is reached for the considered case study. This evidence results from slightly different geothermal parameters between the present work and the previous case study considered by Rotta Loria [3].

Meanwhile, complementary results obtained in this work show that energy storage via tunnels is advisable only when limited groundwater flow and airflows are present at sites, otherwise pronounced heat losses are induced by convection heat transfer.

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Thermal losses Q_{loss} are increasing nonlinearly with the applied convection heat transfer coefficient h_c, and thus with increasing airflow velocity (Figure 1(a)). Moreover, an increase in underground temperatures, which may result from subsurface heat islands, has a positive impact on the storage performance of tunnels. Higher average tunnel air temperatures (T_{A1}, T_{A2}, T_{A3}) allow an augmentation in extractable thermal energy Q_{ext} thanks to direct harvesting of heat from the tunnel air (Figure 1(a)). At the same time, a lower amount of injected heat Q_{inj} can be achieved during the storage interval due to a lower temperature gradient between carrier fluid and tunnel environment. As a result, thermal losses Q_{loss} are reduced in case of warmer tunnel air, leading to a significant increase in efficiency η (Figure 1(b)). In case of higher air temperatures, the increase in storage efficiency is more significant over the first couple of storage cycles compared to lower temperatures. Nonetheless, even for high air temperatures, the efficiency drops when it comes to an increase in airflow velocity that may be induced by ventilation and train movements (Figure 1(b)). This effect can be reduced with help of an insulation on the inside of the tunnel lining, increasing the overall thermal resistance.

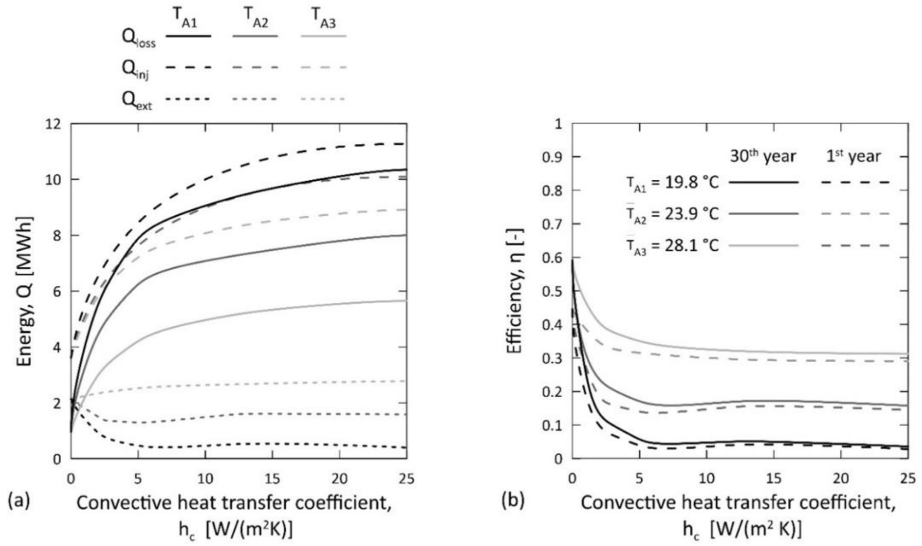

Figure 1: Influence of tunnel air convection and temperature on: (a) injected and extracted thermal energy Q_{inj}, Q_{ext} and heat losses Q_{loss}; (b) storage efficiency η (spline smoothing interpolation between obtained data points).

This study aimed to identify impacts of changes in subsurface environments on the thermal energy storage performance of underground tunnels used as heat exchangers. The findings indicate a positive influence of subsurface temperature rises on the thermal energy storage performance of underground tunnels. Meanwhile, the findings indicate a generally detrimental role played by convection heat transfer for the performance of such systems. Based on the result of this work, it is concluded that underground environments with limited convection or significant thermal insulation are necessary to ensure satisfactory thermal energy storage performance of energy tunnel systems.

Contributor statement

Annik Schaufelberger: Conceptualization, Data curation, Methodology, Software, Validation, Formal analysis, Visualization, Writing – original draft. Lyesse Laloui: Supervision, Writing – review & editing. Alessandro F. Rotta Loria: Conceptualization, Methodology, Supervision, Project administration, Writing – review & editing.

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