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Probabilistic Simulation of High-Temperature Underground Thermal Energy Storage in Caverns

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ABSTRACT

The growing demand for seasonal heat storage in decarbonized energy systems requires scalable and efficient high-temperature underground thermal energy storage technologies. This study presents a comprehensive methodology for designing and numerically simulating representative scenarios of Cavern Thermal Energy Storage (CTES) systems in solid rock environments. Geological feasibility is evaluated using a probabilistic approach with geostatistical realizations to analyze the thermal-hydraulic-mechanical behavior of the surrounding host rock during operation. An integrated modeling framework applies the finite element method to optimize CTES design, storage volume, and operating modes for both pre-designed and re-engineered systems. Simulation results identify key geological and design parameters influencing long-term operational performance. Results show that optimized geometries can impact significantly thermal efficiency, while hydrogeological factors are critical for minimizing heat loss. The findings provide a foundation for refined planning of future CTES systems across different geological settings.

1 INTRODUCTION

Decarbonizing the heating and cooling sector is a critical step toward reducing global reliance on fossil fuels, as both industrial and residential energy demands remain heavily dependent on non-renewable sources (Monie and Åberg, 2023). Thermal energy storage offers a promising enhancement by enabling the flexible use of sustainably produced energy or waste heat, helping to cover peak demand and make use of low-cost surplus energy during periods of high consumption (European Commission, 1999). Among TES technologies, sensible storage is the most common and cost-effective approach (Koçak et al., 2020), particularly for large-scale underground thermal energy storage systems (Narula et al., 2020). These concepts, such as tank thermal energy storage (Bott et al., 2019), aquifer thermal energy storage (Fleuchaus et al., 2018), borehole thermal energy storage (Lanahan and Tabares-Velasco, 2017), pit thermal energy storage (Dahash et al., 2019), and cavern thermal energy storage (CTES) (Zelzer et al., 2023), offer significant potential, though their efficiency is strongly influenced by local geological conditions and proximity to district heating systems (Zhang et al., 2024). CTES systems, which operate with direct contact between water and the surrounding rock, benefit from stable thermal conditions and reduced long-term heat losses, making them particularly suitable for seasonal heat storage applications (Park et al., 2014b).

Despite their potential, the practical implementation of CTES currently faces several challenges. Key issues include geological uncertainty, heat losses, and the mechanical stability of the host rock. A detailed understanding of the thermal performance of the surrounding rock mass is essential, particularly regarding heat-up dynamics and long-term thermal stability, to ensure efficient and reliable operation. Also, geological discontinuities, like fractures, can have significant effects on efficiency of TES systems in solid rock. Moreover, systematic methodologies for assessing and optimizing CTES in solid rock, especially under coupled thermo-hydro-mechanical (THM) conditions, are currently not available. Addressing this gap is crucial for reducing investment risks and enabling scalable, efficient, and sustainable CTES deployment. The focus of this study is (i) the time-dependent heat distribution within the surrounding host rock, (ii) the comparison of pre-designed and re-engineered cavern designs, and (iii) the impact of discrete fracture networks (DFN) on heat transport. The objective of this work is to present a comprehensive modeling and simulation framework (under development) for the design, assessment, and optimization of CTES systems, explicitly accounting for geological variability and long-term storage performance. The integrated framework aims to support the practical implementation of CTES as a reliable and sustainable solution for large-scale underground thermal energy storage.

2 METHODS

The framework is being developed in COMSOL Multiphysics, which is a software developed for modelling and simulation using finite element method. The physics modules: heat transfer in solids and fluids and fracture flow were used to simulated fracture flow and heat transport. The software has been successfully applied in related studies (Bott et al., 2024; Tosatto et al., 2023).

The surrounding host rock is represented by using the finite element method to model the heat transport, groundwater flow, and other internal as well as environmental processes of different storage designs. Two different geometrical shapes are investigated, representing pre-designed (e.g., cylindrical) and re-engineered (e.g., cuboidal) CTES types, corresponding to existing and theoretical CTES configurations (Müller et al., 2025). Each cavern is placed at the center of a cubic model domain with a side length of 300 m of the surrounding host rock, ensuring no influence of boundary effects on the heating process during operation. For simplification, the charging and discharging process is assumed as a temperature boundary condition, whereby the operational temperature of the CTES varies between 60 °C and 90 °C, following a sinusoidal function over one year. This is based on the assumption of a high-temperature district heating network. The host rock initial temperature is set to 11 °C. To measure the temperature distribution after operational use, one measurement probe is located in 10 m distance to the envelope, orthogonal to the center of the cavern (Figure 1).

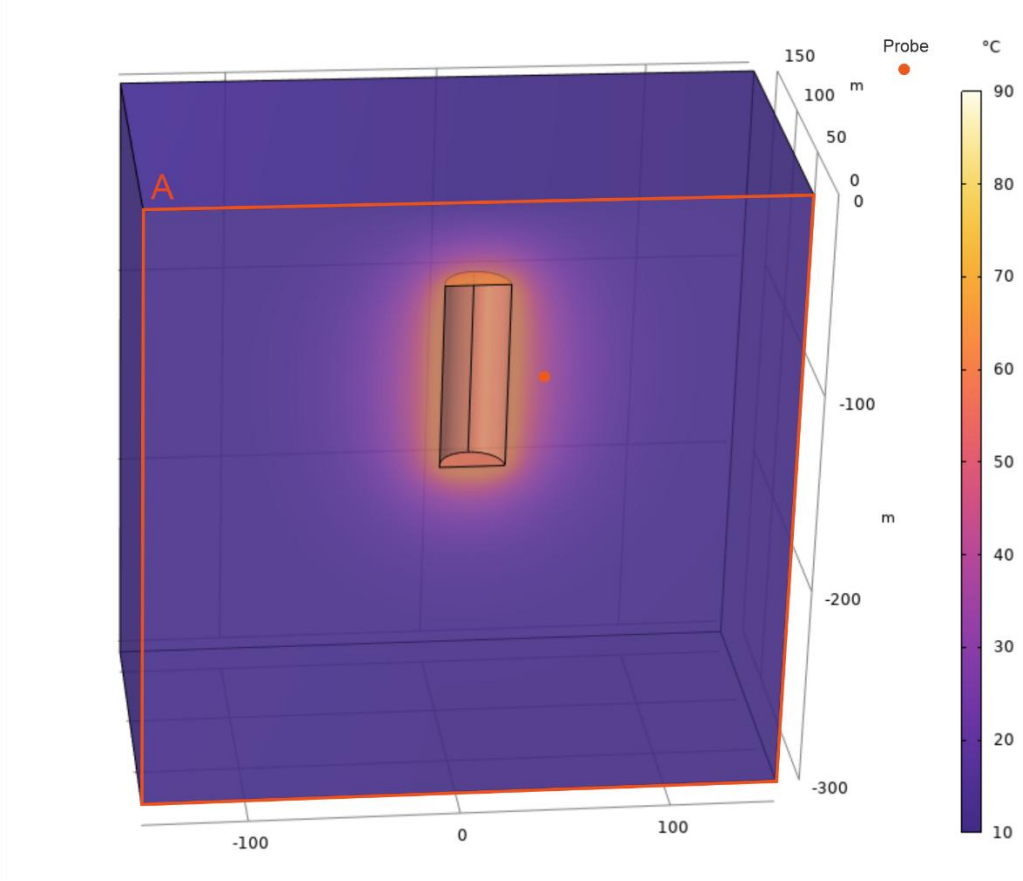


Figure 1. The temperature distribution of 30 years of operation. (A) Plane area for the 2D discrete fracture network model including the measurement probe.

Multiple analyzed discrete fracture networks (DFNs) were generated with the “2D discrete fracture network add-in” of COMSOL Multiphysics. This model is validated by comparison with analytical solutions for single-fracture heat transport and flow, as described in (Sun et al., 2017). To characterize the influence of different DFNs on heat transport during operation, a 2D model near the storage wall was developed to identify lateral heat transport behavior. Two joints of fractures (2 x 25) were generated with inclination angles of 30° and 110°. All used physical parameters are summarized in Table 1.

Table 1. Parameters used for the CTES operation simulations.

Parameter	values	unit
Matrix density	2,700	kg m^{-3}
Matrix-specific heat capacity	1,000	J kg^{-1} K^{-1}
Matrix heat conductivity	3	W m^{-1} K^{-1}
Water density	1,000	kg m^{-3}
Water specific heat capacity	4,200	J kg^{-1} K^{-1}
Water viscosity	10^{-3}	Pa s
Fracture thickness	10^{-4}	m
Storage volume	60,000	m^3

3 RESULTS & DISCUSSION

3.1 Long-term heating up behavior

First, the impact of different CTES designs on geometry (Figure 2) is discussed. The simulation results show variations in the temperature levels at the observation point. After 10 years of operation, the pre-designed storage exhibits a lower temperature. In the case of the re-engineered cavern, the increased surface-to-volume ratio (re-engineered = 0.18; pre-designed = 0.15) results in a 10% higher temperature increase in the surrounding host rock, for same boundary conditions. Compared to the simulated tank thermal energy storage, for the unlined scenario in Tosatto et al. (2023), the measured temperature of the pre-designed cavern is quite lower.

Both, re-engineered and pre-designed geometries, show reduced temperature increases after 10 years of operation, which can be attributed to the progressive heating of the surrounding host rock. This observation is consistent with the findings of analyzed data from pre-engineered CTES (Sagebrand et al., 2024). The results further indicate that ca. 66% of the total heating occurs within the first 10 years of operation. Therefore, the importance of adopting a long-term perspective in the development of CTES is emphasized to establish techno-economic planning guidelines under realistic operational conditions.

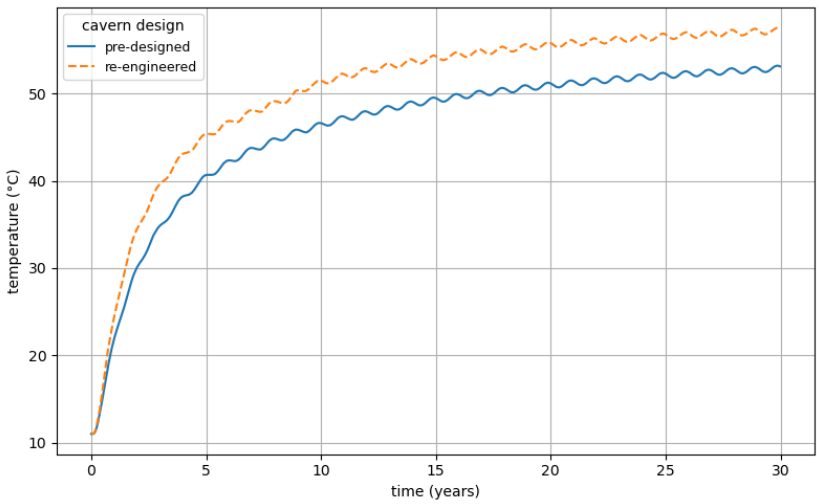


Figure 2: Temperature of the surrounding bedrock for pre-designed and re-engineered CTES designs.

3.2 Effect of the discrete fracture network

Based on the findings of Sagebrand et al. (2024), fractures can have a significant impact on heat loss due to enhanced connectivity to groundwater or advective heat transport processes occurring during storage operation. Previous studies (Messerklinger et al., 2024; Park et al., 2014a) on CTES have generally assumed homogeneous host rock conditions and did not account for the influence of geological discontinuities. However, no existing study has fully captured the coupled THM processes in the context of CTES. Nevertheless, probabilistic approaches, like Chen et al. (2024), can be used for effective determination effects of stochastically generated DFN. This enables the opportunity to take the high uncertainty of various fracture parameters (e.g. inclination, length, aperture) into account, without knowing their exact parametrization.

4 CONCLUSIONS

Seasonal thermal energy storage plays a crucial role in the decarbonization of heating and cooling. This study investigates the long-term thermal transport processes in the subsurface for different cavern designs in the context of seasonal thermal energy storage. The findings highlight that cavern design, even at equal storage volumes, has a significant impact on the surrounding host rock, and, vice versa, on heat losses. Furthermore, preliminary results indicate that fracture networks account for a considerable portion of the heat losses in cavern thermal energy storage systems. To ensure effective site selection, the underlying storage processes must be well understood, and appropriate host rock formations must be identified. Therefore, to enable a robust and application-oriented integration of cavern thermal energy storage systems, it is essential to analyze various scenarios involving different storage and host rock conditions.

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