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# Heat transfer and mechanical stability analyses to determine the aspect ratio of rock caverns for thermal energy storage

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**Abstract**

Thermal stratification in solar thermal storages is used to improve the efficiency of solar heating systems because a high degree of thermal stratification in the storages increases the thermal performance of the systems. It has been demonstrated that better thermal stratification can be achieved by increasing the aspect ratio (height-to-width ratio) of the heat storage containers. However, a high-aspect-ratio design may lead to mechanical (structural) instability of the storage space because of its tall, narrow shape. Therefore, heat storage containers should be designed to provide good thermal performance, while considering the mechanical stability of the storage space. This is an important issue in the design of thermal energy storage (TES) spaces, particularly the underground rock caverns used for TES, because the stability of rock caverns depends largely on geomechanical factors, such as rock properties and in-situ stresses. To address this issue, we present a numerical approach for determining the aspect ratio of underground TES caverns that considers both thermal performance and mechanical stability. This approach is based on a thermal performance evaluation in terms of thermal stratification using heat transfer analysis and a mechanical stability assessment that calculates the factor of safety using finite element analysis combined with a shear strength reduction (SSR) method. The applicability of our approach is demonstrated in the preliminary design of a silo-shaped rock cavern used to store hot water for district heating. The results of the numerical analyses under various design conditions are presented and discussed in detail, and we propose an aspect ratio for the rock cavern.


*Keywords:* Cavern thermal energy storage; Aspect ratio; Thermal stratification; Computational fluid dynamics

## 1. Introduction

Thermal energy storage (TES) is a technology that stores thermal energy by heating or cooling a storage medium. The stored energy can then be used later based on customer demand, not only availability. TES systems can help balance energy demand and supply on a daily, weekly, and even seasonal basis; therefore, TES can improve the overall efficiency of energy systems. The conversion and storage of various renewable resources in the form of thermal energy can also help increase the share of renewables in the energy mix (the distribution of energy consumption from different sources). Underground TES using rock caverns, known as cavern thermal energy storage (CTES) is a viable option for large-scale TES utilization because underground spaces can provide safe and economical storage on a large scale. The surrounding rock can function as a heat insulator because it has low thermal conductivity. However, application is limited because of

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**Nomenclature**

| | |
|---|---|
| $AR$ | aspect ratio of rock cavern |
| $c$ | cohesion of rock (MPa) |
| $c_{trial}$ | cohesion of rock reduced for calculating factor of safety (MPa) |
| $FS$ | factor of safety of rock cavern |
| $h_c$ | convective heat transfer coefficient (W/m$^2$ K) |
| $K_0$ | initial stress ratio of rock |
| $R_{TS}$ | thermal stratification ratio |
| $SR$ | horizontal-to-vertical stress ratio of rock |
| $SRF$ | strength reduction factor used for calculating factor of safety |
| $T$ | temperature (K) |
| $z$ | vertical distance from a surface (m) |
| $\lambda$ | thermal conductivity of water (W/m K) |
| $\mu$ | viscosity of water (kg/m s) |
| $\rho$ | density of water (kg/m$^3$) |
| $\phi$ | internal friction angle of rock (°) |
| $\phi_{trial}$ | internal friction angle of rock reduced for calculating factor of safety (°) |

*Subscripts*

| | |
|---|---|
| $i$ | initial |
| $t$ | time |

the high investment costs. CTES can be more efficient for large-scale TES than aboveground storage, in which the heat loss to the surrounding area is largely influenced by the ambient air temperature and wind conditions. The need to ensure the mechanical stability of the heat storages imposes limitations on storing thermal energy on a large scale.

Hot-water storage systems represent a well-known technology for sensible heat storage. Large hot-water storage systems can be used for seasonal storage of solar thermal heat as part of district heating systems. In sensible heat storage systems, energy is stored or extracted by heating or cooling a liquid or a solid at temperatures that do not change the phase. A variety of mediums have been used in such systems. The choice of the medium used for TES depends on the temperature of the application. Water is most commonly used for temperatures below 100 °C because it is inexpensive, easy to handle, non-toxic, and a widely available and has a comparatively high specific heat (Ataer, 2006). It is well-established that the efficiency of TES systems using water is improved if the water in a heat storage is thermally stratified because the water can be selectively extracted at specific temperatures for the necessary uses.

Thermal stratification of the water in heat storages refers to the separation of the stored water into multiple layers with different temperatures and is created by the difference in density between hot and cold water. Hot water tends to accumulate at the top of a storage, while colder water is forced downward because cold water is denser than hot water. The loss or degradation of stratification in heat storages, i.e., destratification, occurs as a result of the following four mechanisms: (1) heat loss to the surroundings; (2) forced convection when charging or discharging thermal energy; (3) heat conduction between thermally stratified layers; and (4) natural convection due to the conduction of heat into the wall. These mechanisms are illustrated in Fig. 1.

The height-to-width ratio of a heat storage container, i.e., the aspect ratio, is a well-known factor that influences the thermal stratification in the storage container (Haller et al., 2009). Previous studies on aboveground storage tanks for hot water storage have demonstrated that better thermal stratification can be obtained by increasing the aspect ratio of the storage tanks; the effect was significant when the aspect ratio was less than 3 (Lavan and Thompson, 1977; Cotter and Charles, 1993; Matrawy et al., 1996; Ismail et al., 1997; Eames and Norton, 1998; Bouhdjar and Harhad, 2002). These previous studies mainly focused on evaluating the thermal performance of heat storage tanks based on numerical simulations and experiments. They suggested optimal aspect ratios for heat storage tanks in terms of only thermal stratification because these studies targeted small-scale storage tanks that did not require an assessment of mechanical stability in their design.

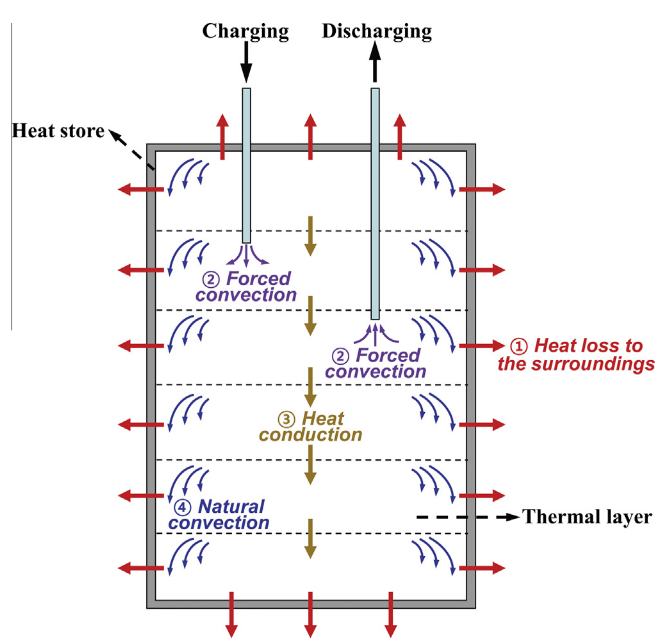


Fig. 1. Factors that influence thermal stratification.