Applied Thermal Engineering 91 (2015) 687–693

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

# Numerical modeling and optimization of an insulation system for underground thermal energy storage

Hyunwoo Kim [a,*], Dohyun Park [a], Eui-Seob Park [a], Hyung-Mok Kim [b]

[a] Korea Institute of Geoscience and Mineral Resources (KIGAM), Daejeon 305-350, South Korea
[b] Energy & Mineral Resources Engineering, Sejong University, Seoul 143-747, South Korea

## HIGHLIGHTS

- Numerical analysis and design optimization of thermal insulation system for UTES.
- Temperature-dependent properties of insulation and other materials were applied.
- Component arrangement affected the performance of the insulation system.
- Optimal system consisted of inner & outer mineral wools, a steel liner and a lining.
- Regular emptying of the caverns slowed the temperature increase in the rock mass.

## ARTICLE INFO

*Article history:*
Received 7 June 2015
Accepted 26 August 2015
Available online 2 September 2015

*Keywords:*
Heat transfer analysis
Multilayer thermal insulation
Mineral wool
Temperature-dependent material properties
Optimization

## ABSTRACT

Underground thermal energy storage (TES) systems require an insulation system to control the heat flux from the TES system into the surrounding rock mass to minimize the adverse effects of the high-temperature storage media on the underground environment. In this study, numerical simulations were performed to investigate the temperature distribution and heat transfer in the insulation system and to determine the optimal design for the TES system. The performance of the mineral wool chosen as an insulation material is gradually degraded as its temperature is increased; thus, the temperature-dependent properties of component materials were applied to prevent the overestimation of the insulation performance. We demonstrated that the component arrangement could affect the performance of the insulation system under transient heat transfer conditions; thus, we compared three types of insulation systems according to the location of the mineral wool layer. An insulation system composed of an inner mineral wool layer, a steel liner, an outer mineral wool layer, and a concrete lining was proposed as the optimal system under the conditions given in this study. We showed that regular emptying of the storage caverns for a long time interval in periods of low energy demand would slow down the temperature increase in the surrounding rock mass, and we proposed that the operation schedule including idle time could also be an alternative to reduce the thickness of the mineral wool layers.

## 1. Introduction

The governments of many countries have promoted policies that encourage efforts to develop renewable energy sources and diversify the range of energy sources, endeavoring to improve energy efficiency and demand management [1]. However, output power fluctuations of renewable energy sources, such as wind power and solar power, may be a major obstacle to stable operation of the electrical grid. Thus, large-scale energy storage systems (ESSs) have been proposed to assist in the integration of this fluctuating energy into the grid. Pumped hydroelectric energy storage (PHES) is the largest and most mature form of ESS, but it is believed that suitable locations for new PHES construction are very limited [2]. Therefore, a system for storing and utilizing compressed air in underground caverns has been considered to be a viable alternative.

Compressed air energy storage (CAES) systems, the first of which was built at Huntorf in Germany in 1978, store electrical energy in the form of compressed air during times of low electricity demand. At times of peak load, the compressed air is drawn from

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[*] Corresponding author. Underground Space Department, Geologic Environment Division, KIGAM, Daejeon 305-350, South Korea. Tel.: +82 42 868 3243; fax: +82 42 868 3416.

*E-mail address:* hyunwoo.kim@kigam.re.kr (H. Kim).

http://dx.doi.org/10.1016/j.applthermaleng.2015.08.070
1359-4311/

**Nomenclature**

| | |
|---|---|
| CAES | compressed air energy storage |
| ESS | energy storage system |
| PHES | pumped hydroelectric energy storage |
| TES | thermal energy storage |
| $C_v$ | specific heat (J/kg-K) |
| $C_c$ | specific heat of concrete (J/kg-K) |
| $\mathbf{k}^T$ | thermal conductivity tensor (W/m-K) |
| $K_c$ | thermal conductivity of concrete (W/m-K) |
| $M_T$ | material constant (m$^3$-K/J) |
| $\mathbf{q}^T$ | heat-flux vector (W/m$^2$) |
| $q_v^T$ | heat source intensity (W/m$^3$) |
| $T$ | temperature (K) |
| $t$ | time (s) |
| $\beta_v$ | material constant (J/m$^3$) |
| $\varepsilon$ | volumetric strain (−) |
| $\zeta_T$ | heat stored per unit volume (J/m$^3$) |
| $\rho$ | mass density (kg/m$^3$) |
| $\rho_c$ | mass density of concrete (kg/m$^3$) |

the underground caverns and then heated and expanded in a gas turbine to drive a generator [3]. However, the use of fuel in the expansion process lowers the efficiency of the CAES systems, and it makes their operation costs heavily dependent on fuel price changes [4]. An adiabatic CAES system has been proposed to overcome these drawbacks, where, as shown in Fig. 1, high-temperature heat is stored via a compression process (blue line) and supplied to raise the temperature of the released air without a gas combustor prior to expansion (red line) [5]. These thermal energy storage (TES) facilities can be constructed underground for safety and space utilization, and an insulation system is required to reduce environmental impacts as well as to increase the storage efficiency. That is, the heat flux from the TES system into the surrounding rock mass should be controlled to minimize the adverse effects of the high-temperature TES system on the underground environment.

The purpose of this study is to find the optimal design of the insulation system by comparing the thermal insulation performance of the systems with different arrangement of components. Numerical simulation method, which can simulate transient heat transfer processes, is a useful and reliable tool for the analysis of heat transfer in multilayer insulation, so numerical studies for design optimization of thermal insulation systems can be found in the fields of building insulation and aerospace engineering [6–10].

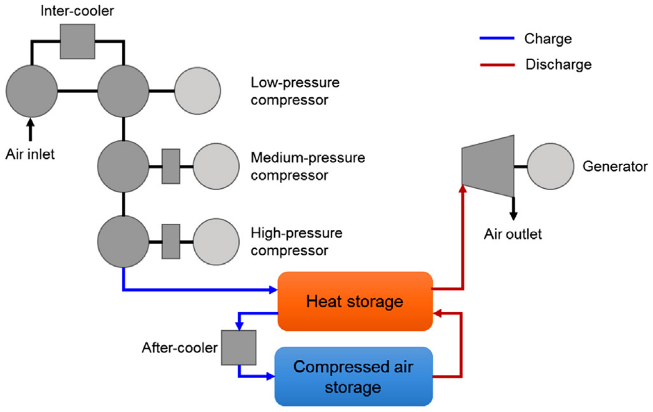

**Fig. 1.** A possible technical concept for an advanced adiabatic CAES system [5].

In this study, an insulation material for the TES system was chosen first, and the heat transfer through an insulation system between thermal storage media and a surrounding rock mass was analyzed using a two-dimensional finite difference code, *FLAC* [11]. A model with temperature-dependent properties, where the heat transfer characteristic of the selected insulation material (mineral wool) and others were changed according to their temperature, was used to investigate the effects of both thickness of the insulation material and the repetitive thermal charging–discharging process on the insulation performance. As a result, the optimal design of the insulation system for maintaining the rock mass temperature below 100 °C was proposed based on the numerical simulation results. In addition, it was examined how much the increase in rock mass temperature could be suppressed by emptying the TES system at regular intervals and, thus, to what extent the thickness of the insulation material could be reduced without exceeding the permissible temperature.

## 2. Selection of insulation material

When selecting an insulation material, not for aboveground structures but for rough and harsh underground environments, it is desirable to compare various materials in terms of durability, perforation robustness, water resistance, and site adaptation, as well as thermal insulation performance [12]. There exist currently many traditional thermal insulation materials, for example, mineral wool, expanded polystyrene, extruded polystyrene, cellulose, cork and polyurethane, as shown in Table 1. Furthermore, state-of-the-art and possible future materials are being developed and tested for thinner and high-performance insulation systems.

Among the state-of-the-art insulation materials, vacuum insulation panels and gas-filled panels have low applicability, and aerosol has drawbacks such as high production costs and low tensile strength [13]. In the traditional insulation materials, polyurethane has low thermal conductivity, but very toxic hydrogen cyanide and isocyanates are released when it is burned [12]. Cellulose and the cork have relatively high thermal conductivity of 40–50 mW/m-K. The other three materials have similar thermal conductivity, and their thermal performance is not seriously affected by cutting or perforating the insulation materials. Among them, mineral wool is mass-produced in various types of boards, rolls, and filling materials in South Korea, and, moreover, it can be produced in customized shapes considering construction conditions. Consequently, mineral wool was selected as the insulation material for the TES system in this study.

## 3. Numerical modeling of the insulation system

### 3.1. Heat transfer analysis

Heat transfer analysis was performed using a finite difference code, *FLAC* [11], and it was assumed that the heat was transferred by conduction through an insulation system consisting of mineral wool, steel liner, and concrete lining. The variables involved in heat conduction are the temperature and the heat flux, which are related through the energy-balance equation and transport law derived from Fourier's law of heat conduction.

The differential expression of the energy balance has the form

$$-\nabla\cdot\mathbf{q}^T + q_v^T = \frac{\partial \zeta_T}{\partial t} \qquad (1)$$