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Analysis on heat transfer and heat loss characteristics of rock cavern thermal energy storage

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ABSTRACT

The present study is aimed at demonstrating the feasibility of the rock cavern, compared with the above-ground tank, for the storage of large-scale high-temperature thermal energy by quantitatively evaluating the heat transfer inside the storage tank and the heat loss characteristics of the surrounding environment. As a conceptual model, we consider a thermal energy storage (TES) system coupled with an adiabatic compressed air energy storage plant (A-CAES), which utilizes loosely packed bed of rocks as heat storage medium and stores heat of up to 685 °C. The specifications of the TES model, such as the mass flow rate of the heat transfer material and the storage volume, were determined through the analysis of the heat transfer in the packed bed, using a quasi-one-dimensional two-phase numerical model developed in this study. In this procedure, the inlet and outlet fluid temperatures and the thermal energy rates to be stored or extracted were examined over 200 consecutive daily cycles to ensure the TES met the requirements for the power generation of the A-CAES plant. Then, with the determined specifications of the TES, a comparative study on the heat loss characteristics of the rock cavern-type TES and above-ground-type TES systems was performed by simulating the operations on a daily basis for a period of 10 years using a three-dimensional numerical model. The comparison results indicated that the amount of cumulative heat loss in the rock cavern-type TES system over the operation period was far smaller than that in the above-ground-type TES system because of the surrounding rock heating and the consequent reduction in the thermal gradient between the surrounding rock and the storage medium. In terms of long-term operation, the rate of heat loss from the rock cavern-type TES system exhibited less-sensitive and less-dependent behaviors with respect to the insulator performance than that of the above-ground-type TES system.

1. Introduction

The importance of the development and management of renewable energy is increasingly recognized, as promoted by the global environmental crisis and the electric power shortage. Efficient utilization of renewable energy sources requires reliable methods of storing energy because of the intermittent characteristics of renewable energy sources. The technology of thermal energy storage (TES) can store thermal resources, such as solar energy, geothermal energy and industrial waste heat, without converting the thermal resource into different forms of energy, thus enabling the stored energy to be used for heating and cooling applications in addition to power generation when required. TES can improve the overall efficiency and flexibility of energy systems and help balance energy demand and supply.

Rock cavern thermal energy storage (CTES) is one of the underground thermal energy storage (UTES) technologies that makes use of a cavern as a thermal energy storage tank. Contrary to aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES), which use the underground environment as a storage medium, CTES is technically feasible even under poor geological conditions and can be customized for various purposes and storage temperatures. Moreover, the increasing needs for large-scale high-temperature TES for industrial purposes can make CTES superior to above-ground-type TES system. Underground spaces can offer a viable and economical alternative for large-scale storage because the surrounding rock can function as a heat insulator due to its low thermal conductivity (Park et al., 2013). Compared with above-ground-type TES system, in which heat loss characteristics are influenced by variable climatic factors, the underground space is hardly sensitive to the weather and climate. However, currently, there are limited applications of CTES because of the high investment costs and the environmental impacts. An exception is the Lyckebo rock cavern used for storing hot water of 40–90 °C for a heating system in Sweden, which has been operated since 1983 (SKANSKA, 1983). In terms of the CTES for high temperatures above 100 °C, few studies on the storage concepts and options are found in the literature.

There are numerous challenges facing large-scale high-temperature CTES technology such as the estimation and control of the thermal, hydrological and mechanical behaviors of rock mass and storage caverns,

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the design of the storage cavern ensuring the structure safety and storage efficiency and the selection of suitable storage site. The thermally induced environmental impact such as temperature change in surface water and groundwater and the corresponding effect on vegetation is also an important issue. In addition, considering that technologies of above-ground type TES has been commercially available in concentrating solar power (CSP) plants, it is essential to quantitatively present the benefit of using cavern type TES versus using above-ground type TES, as well as to find the reliable solutions to the above-mentioned technical problems.

The present study is aimed at evaluating the heat transfer and the storage efficiency of large-scale high-temperature CTES, and then demonstrating the feasibility of large-scale rock cavern type TES versus above-ground-type TES system. The first step for the analysis was to set up a conceptual model for large-scale high-temperature thermal energy storage systems; we considered a thermal energy storage system coupled with an adiabatic compressed air energy storage (A-CAES) plant that utilized loosely packed bed of rocks as heat storage materials and stored thermal energy of up to 685 °C. Based on the energy analysis for A-CAES system in the literature (Kim et al., 2012) and the heat transfer analysis for the packed-bed TES system using a theoretical solution developed by Schumann (1929), we determined the storage volume and the mass flow rate of heat transfer fluid (HTF) to ensure that TES system could fulfill the required capacity of the A-CAES plant. Next, as a part of the feasibility assessment of large-scale high-temperature CTES, the operations of rock cavern-type and above-ground-type TES systems were simulated for a period of ten years, and the heat loss characteristics through the storage walls were analyzed and quantitatively compared with one another using a three-dimensional numerical model.

Section 2 briefly introduces the A-CAES system and the packed-bed TES system, and Section 3 presents the procedure to set up the conceptual model for a large-scale high-temperature TES based on the analysis on the heat transfer in the storage tank. Section 4 discusses the numerical modeling of the heat loss characteristics, which is then followed by a few conclusions.

2. Conceptual model for large-scale high-temperature TES

2.1. TES connected to A-CAES

The basic idea of CAES (compressed air energy storage) technology is to transfer the surplus energy produced by permanently operated convectional power plants during base-load periods to peak load periods. CAES concept mainly consists of 1) compression train, 2) motor-generator, 3) gas turbine and 4) compressed air storage. During off-peak base-load periods, electrically driven compressors compress air into underground or above-ground storage system. Later, during peak load periods, the compressed air is released from the storage and expanded to power a gas turbine. Since the heat of compression is removed from air for the safe process and storage of the compressed air, additional injection of heat is required prior to the expansion. Unfortunately, conventional CAES system dumps the heat of compression into the atmosphere and requires the combustion of fuels in the expansion phase. A-CAES is an advanced concept seeking to overcome these drawbacks. A-CAES stores the heat occurring in the air compression stage and reuses the heat when expanding the compressed air for power generation, resulting in an increase of round-trip efficiency of the process. During the thermal charging mode, the heat is extracted from the compressed air being stored in the thermal energy storage tank, whereas the cooled air is transferred to the compressed air storage tank. During thermal discharging mode, the air is heated using the stored thermal energy and expanded through an air turbine for power generation. At present, no A-CAES plant is yet available commercially, but the project ADELE to construct the first A-CAES plant with a capacity of 200 MW by 2016 was launched in 2010 by RWE, General Electric, Zublin AG and German Aerospace Centre (DLR) in Germany (Steta, 2010). An above-ground container with a height of 40 m with beds of stones or ceramic molded bricks through which the hot air flows has been considered for thermal energy storage (RWE power, 2014).

In the present study, we assumed that the TES system storing thermal energy of 20–685 °C is operated with a daily cycle consisting of 6 h of charging, 6 h of idling, 6 h of discharging and 6 h of idling. Based on the research by Kim et al. (2012), the specifications of the TES system were determined to produce the electrical energy at a rate of 100 MW for 6 h a day. According to their energy and exergy analysis for an A-CAES system in single-stage compression configuration, if the air of 20 °C is adiabatically compressed up to 50 bar in single-stage compression configuration, then the outlet air temperature of the compressor is approximately 685 °C, as shown in Fig. 1. The production of electrical energy of 1.00 kWh requires thermal energy of 1.28 kWh from the TES, which indicates that thermal energy of 1.43 kWh should be stored into the TES assuming that the efficiency of TES is 90%, and the inlet and outlet temperatures of air are 685 °C and 622 °C, respectively. The detailed descriptions for the procedures to determine the operational parameters for TES are provided in Section 3.

2.2. Packed-bed thermal energy storage

Thermal energy storage systems can be divided into three types: 1) sensible heat storage that stores thermal energy by increasing the storage medium temperature, 2) latent heat storage that uses phase change materials (PCM) as a storage medium and 3) thermo-chemical storage that involves chemical reactions. Although the latent heat storage and thermo-chemical energy storage are more advanced than sensible heat storage from a technical viewpoint, they are mostly under development and demonstration. At present, the sensible heat storage systems are the only commercially feasible options (Michels and Pitz-Paal, 2007; Singh et al., 2010). In common types of sensible TES, the storage tank is filled with a thermal storage medium such as water, rocks, pebbles and sand. The energy is transported into and out of the tank by a heat transfer fluid (HTF). In some cases such as water storages, the storage medium is directly used as the HTF. Because of the low boiling point of water, the use of a packed bed of solid materials with heat transfer fluid is more widely considered for high- as well as low-temperature TES. The porous structure of packed beds can maximize heat transfer between fluid and storage media and minimize heat transport inside the storage media, which results in the stable thermal stratification and the efficient heat transfer in TES (Hänchen et al., 2011).

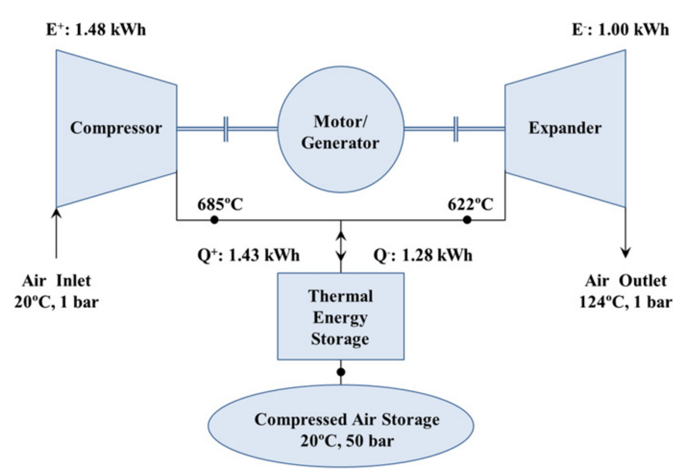

Fig. 1. Diagram of an A-CAES system in single-stage configuration for the production of 1 kWh (after Kim et al., 2012).