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A simplified and unified analytical solution for temperature and pressure variations in compressed air energy storage caverns

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ABSTRACT

Temperature and pressure variations in compressed air energy storage (CAES) caverns are important factors that affect the overall performance of CAES systems. However, current air storage cavern models used in the thermodynamic analysis of CAES systems usually ignore the effect of heat exchange between cavern air and the surrounding environment and thus cannot accurately predict temperature and pressure variations. In this study, a diabatic analytical solution in a simple and unified form and that considers heat exchange is proposed for temperature and pressure variations in CAES caverns. The solution is derived on the basis of assumptions that the air density in the cavern can be represented by a constant average value and that the cavern wall temperature remains constant. The proposed solution is validated with the test data of the Huntorf plant trial test and the results calculated with other solutions. Moreover, the errors of the proposed solution caused by the assumptions are analyzed. Results show that in representative ranges, the errors have a significant positive correlation with the ratio of the injected to the initial cavern air mass and the difference between the injected air temperature and the initial air temperature. The errors also have an insignificant negative correlation with the rock thermal effusivity and the heat transfer coefficient. Finally, the condition under which the proposed solution is applicable with an error less than 20% is defined on the basis of the combination of the ratio of the injected to the initial cavern air mass and the difference between the injected air temperature and the initial air temperature. This simplified and unified solution can be a simple yet adequately accurate tool to be used in the thermodynamic analysis of CAES systems.

1. Introduction

Compressed air energy storage (CAES) is one of the most promising large-scale energy storage technologies that can overcome the problem of intermittency to make renewable energy sources stable and reliable. CAES is an approach in which excess power is used to compress air, which is then conventionally stored in an underground storage cavern during low-cost off-peak load periods. During peak load periods, the compressed air is released from the cavern and expands in a gas turbine with natural gas to produce electricity. Typically, the CAES efficiency is in the range of 66%–82% [1]. To date, two existing commercial CAES plants are in operation: the 290 MW plant (later up-rated to 321 MW) at Huntorf, Germany, built in1978 and the 110 MW plant in McIntosh, Alabama, USA, commissioned in 1991 [2].

Since the commission of Huntorf plant, the thermodynamic performance of CAES systems has been an emphasis of CAES research because it directly determines the techno-economic viability of CAES technology. However, the importance of the thermodynamic performance of air storage caverns is usually underestimated compared with those of other components, such as the compressor or turbine. In the thermodynamic analysis of CAES systems, the current treatments of air storage caverns can be generally divided into three groups: 1) those that directly ignore the effect of air storage caverns [3,4], 2) those that assume the temperature in the cavern is constant [5–7], 3) and those that assume the cavern is adiabatic [8,9]. In fact, the temperature and pressure in caverns continuously fluctuate with the heat exchange between cavern air and the surrounding environment during the operation of CAES plants. All of the three treatments of air storage

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Nomenclature

A_c	cavern wall surface area, m^2
c_p	constant pressure specific heat, J/(kg K)
c_v	constant volume specific heat, J/(kg K)
e_R	rock thermal effusivity, $(k_R\rho_R c_{pR})^{1/2}$, W s$^{1/2}$/(m^2 K)
h	specific enthalpy of air, J/kg
h_i	specific enthalpy of injected air, J/kg
h_c	heat transfer coefficient, W/(m^2 K)
k_R	thermal conductivity of rock, W/(m K)
$\dot{m}_i(t)$	function of injected air mass flow rate, kg/s
m_i	injected air mass flow rate during charging, kg/s
$\dot{m}_e(t)$	function of withdrawn air mass flow rate, kg/s
m_e	withdrawn air mass flow rate during discharging, kg/s
m_r	injected to initial cavern air mass ratio, $m_i t_1/(\rho_0 V)$, 1
ρ	air density in the cavern, kg/m^3
ρ_{av}	average air density in the cavern, kg/m^3
ρ_R	surrounding rock density, kg/m^3
p	air pressure in the cavern, Pa
$\dot{Q}$	convective heat transfer rate, W
R	specific air constant, J/(kg K)
R_w	cavern radius, m
t_i	i = 1,2,3,4, process duration time, s, see Fig. 1
T_0	initial air and rock temperature, °C
T_i	injected air temperature, °C
ΔT	difference between injected air temperature and initial air temperature, $T_i - T_0$, °C
T_R	rock temperature, °C
T_{RW}	cavern wall surface temperature, °C
u	specific internal energy of air, W
V	cavern volume, m^3
Z	air compressibility factor, 1

Subscripts

0	initial state
e	exit
i	inlet
R	rock

caverns do not correctly take the effect of heat exchange into account and thus cause certain errors in the thermodynamic analysis of CAES systems. A comparison between the results of current treatments and test data is also lacking to confirm the ability of these treatments to adequately predict the thermodynamic response of CAES caverns. Therefore, an accurate and reliable method to calculate the thermodynamic response of air storage caverns is needed to efficiently analyze the thermodynamic performance of CAES systems.

Currently, there are mainly two methods to calculate the thermodynamic response of CAES caverns [10]: 1) the adiabatic method adopting the adiabatic assumption and 2) the diabatic method taking into account the heat exchange between cavern air and the surrounding rock. As mentioned earlier, the adiabatic method [11] ignores the effect of heat exchange between cavern air and the surrounding rock and therefore calculates larger temperature and pressure variations than the real variations. On the contrary, the diabatic method considers heat exchange and can accurately predict the thermodynamic response of caverns; it therefore has attracted research attention. Tada and Yoshida [12,13] developed an analytical model based on a 2D laminar flow model on the cross-section of a horizontal circular CAES cavern. The model was solved by numerical computations coupled with conduction in the surrounding rock to obtain the spatial distribution of air temperature and pressure in the cavern. Raju and Khaitan [14] modeled the temperature and pressure variations in CAES caverns on the basis of the mass and energy conservation equations while assuming that the cavern wall temperature is constant. They proposed a variable model for the heat transfer coefficient and determined the parameters of this model by calibrating the model with the test data of Huntorf plant. Kim and Rutqvist [15,16] conducted a numerical analysis on the thermodynamic performance of a lined rock cavern of a CAES plant. The model was based on the TOUGH-FLAC simulator, and the interior of the air-filled cavern was explicitly represented by a single peripheral row of grid elements of highly porous, permeable, and mechanically soft material. Kushnir [17] constructed a model for temperature and pressure variations in CAES caverns on the basis of the mass and energy conservation equations, as well as the conduction equation of the surrounding rock. The operational data of Huntorf plant was compared with the calculated results to validate the model. Recently, Zhang [18] constructed four air storage chamber models and analyzed the effect of the air storage chamber model on the performance of advanced adiabatic CAES systems. However, Zhang's models either assumed the temperatures in the cavern are constant or that the cavern is adiabatic. The models may therefore be inappropriate for practical use.

Considering the diabatic method mentioned above can give good results, some scholars have already used this method in the thermodynamic analysis of CAES systems [19,20]. However, the diabatic method has the following disadvantage: it usually requires numerical calculations of differential equations, which considerably increase computational complexity, especially when the diabatic method is used in thermodynamic analysis to optimize the configuration of CAES systems or when the CAES system is integrated with district energy systems.

The diabatic analytical solution is an alternative approach that can accurately predict the thermodynamic response of CAES caverns and does not entail great computation complexity. Kushnir [17] proposed two analytical solutions for the temperature and pressure variations in CAES caverns: the average density approximate solution and the isothermal solution. Both of these two analytical solutions were derived on the basis of the mass and energy conservation equations, as well as the conduction equation of the surrounding rock. The average density approximate solution assumes that the air density in caverns varies little, so the air density can be represented by a constant average value that simplifies the mass conservation equation. With this simplification, the average density approximate solution was derived from the energy conservation and conduction equations through the Laplace transform. The average density approximate solution predicts temperature and pressure variations well, but it requires infinite integral operations that also increase computational complexity. As for the isothermal solution, it assumes that the temperature of the rock surrounding the cavern is constant and thus avoids solving the conduction equation of the surrounding rock. Then, the isothermal solution is derived from the energy and mass conservation equations. Although the isothermal solution has a simple form, it is technically justifiable only for perfectly conducting rocks and, more importantly, the resultant error is unknown when it is applied in practice. Moreover, both of the two solutions have different forms for different operation periods of CAES plants; these forms are not straightforward to understand and not convenient for practical use. In summary, although they can be used in the thermodynamic analysis of CAES systems, these two solutions have disadvantages.