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An iterative method for evaluating air leakage from unlined compressed air energy storage (CAES) caverns

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Evaluating sealing capacity against the air leakage from unlined underground caverns for compressed air energy storage (CAES), a large-scale energy storage technology, is usually costly and time consuming. This paper presents an iterative method that can quickly estimate the air leakage rate of an unlined CAES cavern with adequate accuracy and requires fewer parameters than numerical simulations. The field tests of a pilot cavern in Japan and the NK1 cavern of the Huntorf plant as well as some numerical simulations were used as case studies to verify the proposed method. In these verifications, the proposed method achieved satisfactory results in terms of air leakage and cavern pressure. A sensitivity analysis was also conducted to examine the dependence of the air leakage from an unlined CAES cavern on the cavern characteristics and operating conditions. The most influential parameters were rock permeability, cavern radius, and the mass rate of injected air. Rock permeability should be smaller than 2.5×10^{-19} m^2 to achieve a daily leakage percentage of less than 1% for a dry CAES cavern under pressure between 5 and 8 MPa. Moreover, a large cavern radius and a large mass rate of injected air could decrease a daily leakage percentage.

1. Introduction

A major disadvantage of renewable energy is its intermittent nature during supply. Renewable energy may either exceed the electricity demand or be insufficient. As a promising large-scale energy storage technology that can overcome the intermittency problem of renewable energy supply, compressed air energy storage (CAES) has received increasing research attention [1,2]. CAES uses surplus renewable energy to compress and conventionally store air in unlined underground rock caverns. When the renewable energy cannot meet the electricity demand, high pressure air is withdrawn from the caverns and then injected into a turbine to generate electricity [3]. In this manner, CAES mitigates the fluctuation of renewable energy and helps produce reliable and stable power. Only two commercial CAES plants are currently in operation, namely, the 290 MW plant (later up-rated to 321 MW) in Huntorf, Germany that was built in 1978, and the 110 MW plant in McIntosh, Alabama, United States that was commissioned in 1991 [4].

Adequate sealing capacity against air leakage is one of the most critical requirements for a suitable cavern for CAES [5]. Allen et al. [6] pointed out that a 2% per day air leakage rate would result in an additional annual levelized compression power cost in excess of $1 million. However, examining whether a cavern fulfills such requirement is difficult. Cavern temperature and pressure increase during air injection yet decrease during air storage and withdrawal. These temperature and pressure variations induce air leakage, which in turn affects the variations. Therefore, the evaluation of CAES caverns involves a complicated thermo-hydro (TH) coupling process.

The air leakage from potential caverns for CAES can be evaluated in several ways, among which carrying out an in-situ field test is the most reliable yet costly evaluation method. This test can obtain the real air leakage rates of candidate caverns that are subjected to temperature and pressure variations [6–11]. However, performing a field test on a most likely candidate cavern that is selected through several preliminary inexpensive studies presents a more

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realistic evaluation method. In addition, although some physical model tests have been performed [12,13] to investigate the mechanical responses of CAES caverns, none of them have considered air leakage.

A numerical simulation presents another useful evaluation method. Only a few simulations have considered air leakage compared with those exclusively investigate the mechanical stability of CAES caverns [14–16]. Kim et al. [17] and Rutqvist et al. [5] conducted pioneering simulations to investigate the feasibility of lined rock caverns (LRCs) for CAES based on the TOUGH-FLAC simulator. Bauer et al. [18] analyzed the air leakage from a hypothetical CAES facility using an effective continuum two-phase flow model. Zhuang et al. [19] conducted a coupled THM modeling of non-isothermal gas flow to investigate the air loss and mechanical responses of a CAES cavern. Zhou et al. [20] conducted a simulation to evaluate the feasibility of rubber seal applications in CAES caverns. However, performing a detailed numerical simulation is time consuming, given that building an exact numerical model and selecting appropriate rock parameters require expertise.

Deriving some analytical solutions is a less popular evaluation method. Kushnir et al. [21] developed an analytical solution to calculate the temperature and pressure variations during CAES operations. Based on that approach, Zhou et al. [22] derived an analytical solution for the mechanical responses that were induced by the temperature and pressure variations in a LRC. However, neither of these two solutions can estimate the air leakage from a CAES cavern. Kushnir et al. [23] also developed a model and its approximate analytical solution on the air flow within aquifer reservoirs for CAES. Although this model helps derive analytical solutions for the air leakage from caverns, the inner boundary condition of this solution must be modified to a pressure boundary condition. Furthermore, these three solutions require the solving of infinite series, infinite integrals, or determinants of non-elementary functions, which is not simpler than numerical simulations.

In the above methods, high computation accuracy entails high computation costs. In fact, there should be a tradeoff between accuracy and cost. In early study stages, such as a preliminary evaluation of large-scale areas to identify potential caverns for CAES, a less accurate but also less costly method is more effective. In this context, an iterative method was proposed to evaluate the air leakage from CAES caverns based on a simplified analytical solution for the temperature and pressure variations in CAES caverns [24]. The iteration process of the proposed method was analyzed, several field tests and simulations were then used as case studies to verify this method, and a sensitivity analysis was finally conducted to identify dominant parameters that could affect the air leakage from CAES caverns.

2. Iterative method for evaluating air leakage from CAES caverns

As described above, cavern temperature, cavern pressure, and air leakage are correlated with one another and can only be simultaneously solved via numerical computations [5,17,19]. We adopted an iterative method to semi-analytically solve this problem.

The basic idea of the iterative method lies in the use of the simplified solution proposed by Xia et al. [24] with which cavern temperature and pressure are calculated as initial values. These initial values are then inputted into the deliverability equation developed in the natural gas industry [25] to obtain the initial air leakage rate. Subsequently, the initial air leakage rate is employed in Xia's solution with modified coefficients to recalculate the cavern temperature and pressure. Such a method constructs an iteration loop for cavern temperature, pressure, and air leakage rate. When the acceptable error is reached, the iteration is stopped and the final results are obtained.

2.1. Calculation of cavern temperature and pressure

In a typical CAES operation cycle as shown in Fig. 1, temperature and pressure variations in CAES caverns were obtained using the simplified analytical solution derived by Xia et al. [24]. However, these obtained values were only used as initial values for subsequent iterations because Xia's solution did not take air leakage into account. To determine cavern temperature and pressure affected by air leakage, Xia's solution must be modified to Eqs. (1)–(5) whose detail derivations are outlined in Appendix. Note that cavern air density in Xia's original solution was calculated using Eq. (1) without air leakage term $m_l(t)$, which was not explicitly presented in reference [24].

$$\rho = \rho_0 + \frac{1}{V}\int_{\underline{t}_0}^{t}\left(m_i(t) + m_e(t) - m_l(t)\right)dt$$
$$= \begin{pmatrix} \rho_0 + \left[m_i(t-\underline{t}_0) - \int_{\underline{t}_0}^{t} m_l(t)dt\right]\Big/V & , \underline{t}_0 \le t \le \underline{t}_1(\text{ injection phase}) \\ \rho_0 + \left[m_i(\underline{t}_1-\underline{t}_0) - \int_{\underline{t}_0}^{t} m_l(t)dt\right]\Big/V & , \underline{t}_1 < t \le \underline{t}_2(\text{ first storage phase}) \\ \rho_0 + \left[m_i(\underline{t}_1-\underline{t}_0) + m_e(t-\underline{t}_2) - \int_{\underline{t}_0}^{t} m_l(t)dt\right]\Big/V & , \underline{t}_2 < t \le \underline{t}_3(\text{ withdrawal phase}) \\ \rho_0 + \left[m_i(\underline{t}_1-\underline{t}_0) + m_e(\underline{t}_3-\underline{t}_2) - \int_{\underline{t}_0}^{t} m_l(t)dt\right]\Big/V & , \underline{t}_3 < t \le \underline{t}_4(\text{ second storage phase}) \end{pmatrix} \tag{1}$$