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Comparison of compressed air energy storage process in aquifers and caverns based on the Huntorf CAES plant

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HIGHLIGHTS

- A wellbore-reservoir coupled model is developed based on Huntorf CAES plant.
- Performance of CAESA can be similar to or even better than CAESC.
- The temperature of CAESA shows a smooth variation due to large grain specific heat.
- The impact of initial gas bubble volume on the storage efficiency is not significant.
- Boundary permeability of the reservoir can significantly affect total storage efficiency.

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ABSTRACT

CAESA (compressed air energy storage in aquifers) attracts more and more attention as the increase need of large scale energy storage. The compassion of CAESA and CAESC (compressed air energy storage in caverns) can help on understanding the performance of CAESA, since there is no on running CAESA project. In order to investigate the detail thermodynamic process, integrated wellbore-reservoir (cavern or aquifer) simulations of CAES (compressed air energy storage) are carried out based on parameters of the Huntorf CAES plant. Reasonable matches between monitored data and simulated results are obtained for the Huntorf cavern systems in the wellbore and cavern regions. In this study, the hydrodynamic and thermodynamic behaviors of CAES in cavern and aquifer systems are investigated, such as pressure and temperature distribution and variation in both the wellbore and cavern regions of the CAES systems. Performances of CAESA are investigated with numerical models and compared with the performances of CAESC. The comparisons of CAESC and CAESA indicate that the pressure variation in CAESA shows a wider variation range than that in CAESC, while the temperature shows a smooth variation due to the large grain specific heat of the grains in the porous media. The simulation results confirm that the CAES can be achieved in aquifers, and further that the performance of energy storage in aquifers can be similar to or better than CAESC, if the aquifers have appropriate reservoir properties, which means the gas bubble can be well developed in an aquifer with such properties and the aquifer should have closed or semi-closed boundaries. The impacts of gas-bubble volume, formation permeability, and aquifer boundary permeability on storage efficiency are investigated and the simulation results indicate that the increase of gas bubble volume and permeability can improve the efficiency, but the effect is not significant. The gas bubble boundary permeability has a small effect on the energy efficiency of the sustainable daily cycle but can significantly affect total sustainable cycle times. The analysis of thermodynamic behaviors in CAESA suggests that more attention should be paid to the heat storage, reservoir properties and two-phase flow processes.

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1. Introduction

Large-scale energy storage is receiving increasing attention with the rapid growth in the use of intermittent renewable energy

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Nomenclature

A	wellbore cross-sectional area (m^2)	P	pressure (Pa)
C_0	shape factor	S	saturation
$\mathbf{g}$	acceleration of gravity vector (m/s^2)	t	time (s)
$\mathbf{F}$	Darcy flux vector (kg m^2/s)	U	internal energy (J/kg)
H	specific enthalpy (J/kg)	z	Z-coordinate (m)
k_1	storage space permeability	β	phase index
k_2	storage space boundary permeability	ρ	density (kg/m^3)
M	mass or energy accumulation term (kg/m^3, J/m^3)	μ	dynamic viscosity (Pa s)
NK	number of components	u_G, u_L	phase velocity of gas and liquid in the well (m/s)
NPH	number of phases	u_m, ud	velocity of mixture and drift in the well (m/s)

sources. Among the energy storage options, CAES (compressed air energy storage) is believed to be attractive due to its cost-effective at large temporal scales (from several hours to days) and at a hundreds-of-MW power scale [1–3].

Historically, the caverns (salt rock or hard rock) have been applied to develop CAES projects [4], such as the first commercial CAES plant in Huntorf, German [5,6]. The thermodynamic behaviors of CAESC (compressed air energy storage in caverns) have been studied by many researchers [1,7–13]. Kushnir et al. [7] discussed the solutions for air temperature and pressure variations in the cavern and conducted sensitivity analyses to identify the dominant parameters that affect the storage temperature and pressure fluctuations. Raju and Khaitan [8] used a heat transfer coefficient between the cavern wall and the air to represent the heat loss. A report [9] by Princeton Environmental Institute has summarized the theory, resources, and applications of CAES for wind power. The economic and environment aspects of CAESC have been studied in literatures [14–16]. CAES have been considered to combine with other technologies to improve the efficiency, such as thermal storage [17–19], phase change (like liquid air) [20,21], and adiabatic method [18,22,23].

Though CAESC has a number of advantages, the disadvantage of CAESC is obvious. The two existing commercial grid-scale CAES facilities were constructed in salt-dome formations that exist only in certain kinds of geologic specific regions, not generally available in proximity to either renewable energy sources or to be the demand [24]. This geographical limitation on siting of CAES plants does not apply if aquifers (deep porous media systems) are used as the compressed air storage reservoir, which is analogous to the natural gas storage in aquifers carried out extensively in the U.S [2].

The feasibility of compressed air energy storage in aquifers (CAESA) was demonstrated through numerical simulations in previous studies, e.g. Oldenburg and Pan [25,26], Guo et al. [27] and Jarvis [28]. The pressure variations for CAESA were investigated by Kushnir et al. [10] through analytical solutions under assumption of ideal gas bubble. In addition, field tests had also been reported by Allen et al. [29], proving that the aquifers can be used as the compressed air storage reservoir for CAES. Some projects are in the planning or design process, such as the CAES plant located at Columbia Hills [30]. The first proposed IEP (Iowa Energy Park) CAESA project has been ceased for economic reasons with a smaller scale than planned [31,32]. The influence of permeability on CAESA have been addressed by analytical analysis and numerical simulations [27,33,34], which indicate that the permeability can significantly affect the energy storage scale and efficiency. One of the advantage of CAESA is the lower cost than CAESC. The cost of production of a CAES plant in porous media (aquifer) is about 0.11 $/kW h, while the cost in salt rock is about 2 $/kW h [4,9,14,35].

While there are no real commercial projects of CAESA that can provide detailed information on the thermodynamics behaviors, one important method to understand the process of CAESA is the comparison. Oldenburg and Pan [25] discussed the theoretical differences between CAES in caverns and in porous media (aquifers or depleted reservoirs). In short, Oldenburg and Pan [25] found that energy storage in CAESA occurs dominantly over regions of variable pressure (pressure gradient) associated with flow resistance caused by permeability rather than the single pressure value which can be easily evaluated in an open cavern. Sanchez et al. [4] carried out numerical simulations based on field and laboratory information of an actual site in Iowa to confirm that the site of IEP project is not suitable for a CAESA plant.

However, little attention has been devoted to the detail process comparison of CAESC and CAESA. The design of CAESA project is complex with a number of factors that have to be considered [33,36]. For example, one important aspect during design of CAESA is the impact of wellbore. The injection and production of compressed air involve the use of a wellbore, which is not explicitly included in the system described above [4,8,31].

Many questions about the CAESC and CAESA remain and have not been thoroughly studied and documented in the literature.

1. How does the wellbore affect the performance of CAESC?
2. What is the difference between efficiency of CAESA and CAESC?
3. What is the influence of gas bubble volume, reservoir permeability and gas bubble boundary permeability on storage efficiency?

Accurate predictions about pressure and temperature in the wellbore and cavern throughout the operating cycle are necessary to understand the thermodynamic behaviors of the cavern and wellbore so as to achieve optimal operational efficiency [37]. An accurate and reliable model is needed for characterization and comparison of the thermodynamics processes, and assessment for the influence of reservoir properties.

In order to investigate the detail thermodynamic processes, we have developed and validated an integrated wellbore-reservoir (cavern or aquifer) model based on the parameters of the Huntorf CAES plant. The pressure, temperature and energy variations in both the wellbore and storage reservoir (cavern or aquifer) are discussed and compared with an aim to understand the common and different thermodynamic behaviors. The results can provide helpful information for the design of CAESA projects.

2. Model development

2.1. Model setup

2.1.1. Conceptual model

The conceptual model is developed using the parameters of the Huntorf CAES plant, shown schematically in Fig. 1. There are two

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