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Exergy storage of compressed air in cavern and cavern volume estimation of the large-scale compressed air energy storage system

Wei He[a], Xing Luo[a], David Evans[b], Jonathan Busby[b], Seamus Garvey[c], Daniel Parkes[b], Jihong Wang[a,*]

[a] School of Engineering, University of Warwick, Coventry CV4 7AL, United Kingdom
[b] British Geological Survey, Keyworth, Nottingham NG12 5GG, United Kingdom
[c] Faculty of Mechanical Engineering, University of Nottingham, Nottingham NG7 2RD, United Kingdom

HIGHLIGHTS

- An estimating exergy storage method of cavern-based CAES is developed.
- Two cavern operational scenarios, isochoric and isobaric cavern, are studied.
- Air temperature variations in cavern significantly affect the exergy storage.
- Uncompensated isobaric cavern has high exergy storage per unit cavern volume.
- A case study of Hornsea gas storage indicated the potential of CAES in the UK.

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ABSTRACT

Accurate estimation of the energy storage capacity of a cavern with a defined storage volume and type is the very first step in planning and engineering a Compressed Air Energy Storage (CAES) plant. The challenges in obtaining a reliable estimation arise in the complexity associated with the thermodynamics of the internal air compression and expansion processes and the coupled heat transfer with surroundings. This study developed the methodology for estimating the exergy storage capacity with a known cavern volume, as well as the cavern volume required for a defined exergy storage capacity with different operation and heat transfer conditions.

The work started by developing the mathematical models of the thermodynamic responses of air in a cavern subject to cavern operation in isochoric uncompensated or isobaric compensated modes, and heat transfer conditions including isothermal, convective heat transfer (CHT) and adiabatic wall conditions. The simulated transient air pressure and temperature were verified with the operational data of the Huntorf CAES plant. The study of the Huntorf CAES cavern confirmed the importance of the heat transfer influence on the energy conversion performance. The increase of mass storage due to the reduced temperature variation leads to an enhanced total exergy storage of the cavern. According to our simulations, within the operating range of the Huntorf plant, 34.77% more exergy after the charging and 37.98% more exergy after throttling can be stored in the cavern with isothermal wall condition than those in the cavern with adiabatic wall condition. Also, the nearly isothermal behaviour and high operating pressure in the compensated isobaric cavern resulted in the high effectiveness of exergy storage per unit cavern volume. The required cavern volume of the assumed isobaric cavern operation can be reduced to only 35% of the current cavern volume at the Huntorf plant. Finally, cavern volumes for an operational gas storage facility were used to demonstrate the methodology in estimating the exergy storage capacity, which provided an initial assessment of the storage capacity in the UK.

1. Introduction

Energy storage is one of the key solutions needed to address the challenges to the power grid arising from the increasingly high renewable energy penetration [1]. Electrical energy storage provides a mechanism of decoupling the electricity generation from energy harvesting, and potentially compensating for the intermittence of power generation from renewable energy sources such as wind, solar, etc. Of

* Corresponding author.
E-mail address: Jihong.wang@warwick.ac.uk (J. Wang).

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Nomenclature

Symbols

$\dot{B}$	exergy variation, J/s
c_p	specific heat capacity, J/(K·kg)
h	specific enthalpy, J/kg
k	heat conductivity, W/(m·K)
$\dot{m}$	mass flow rate, kg/s
m	mass, kg
p	pressure, Pa
$\dot{Q}$	heat transfer flux, J/s
r	cavern radius
R	gas constant, J/(kg·K)
s	specific entropy, J/kg
T	temperature, K
u	specific internal energy, J/kg
V	volume, m^3
$\dot{W}_{CV}$	work flux, J/s
κ	heat capacity ratio
ρ	density, kg/m^3

Subscripts/superscripts

A	air
B	brine
C	cavern
in	inflow
out	outflow
o	reference state
W	cavern wall
s	salt

Acronyms

A-CAES	Adiabatic Compressed Air Energy storage
CAES	Compressed Air Energy Storage
CHT	Convective Heat Transfer
TES	Thermal Energy Storage

the existing commercialised bulk energy storage utilities (> 100 MW), Compressed Air Energy Storage (CAES) is a prominent technology. Currently, there are two diabatic utility-scale CAES plants in operation in the world. The first operational CAES plant, built in 1978, was the 290 MW (upgraded to 321 MW in 2006) Huntorf plant in Germany, using salt caverns solution-mined in a salt dome and currently operated by E.ON [2]. The second is the 110 MW plant with a rated energy capacity of 26 hours in McIntosh, Alabama. The Huntorf plant has two salt caverns, about 310,000 m^3, at a depth of 600 m, in which the pressure varies between 43 and 70 bar on a daily cycle [3]. The total usable volume of the McIntosh plant is approximately 19,000,000 cubic feet (about 538,000 m^3) and the salt cavern is at a depth of about 1500 feet (about 450 m) with the allowable pressure between 45 and 76 bar [4]. These two CAES systems have successfully operated for several decades. The Huntorf CAES plant has been reliably operated with excellent performance of 90% availability and 99% starting reliability [5]. The McIntosh CAES plant has maintained an average starting reliability between 91.2% and 92.1%, and an average running reliability of 96.8% and 99.5% for the discharge and charge periods, respectively [5]. In addition to diabatic CAES, adiabatic CAES (A-CAES) has been proposed in recent years to avoid using fossil fuels in the discharging of the energy storage process. Using thermal energy storage (TES), A-CAES collects and stores heat from the air compression process during the charge period, and reuses that heat instead of fossil fuels to raise the air discharge temperature at the expansion stage. Besides independence of fossil fuels, A-CAES is expected to have higher cycle efficiency than the conventional CAES plants [6–9]. In addition to conventional CAES and A-CAES, there are other CAES possibilities and innovations [10,11].

Large-scale CAES (> 100 MW) usually utilises underground reservoirs which are capable of storing compressed air effectively and economically. According to the classification in [12], porous rock reservoirs (aquifers or depleted gas reservoirs) and cavern reservoirs (caverns in salt formation and low-permeability hard rock) are appropriate. Of these options for air storage, Donader and Schneider pointed out that caverns are particularly suitable for flexible compressed air storage operation with high flow rates and frequent cycles [13], because caverns have one/serval large open space/spaces compared to porous rock which consists of a large number of pore spaces. Combined with the self-healing capacity of salt-rock and solubility of salt-rock in water, which leads to easy and economical excavation of storage cavern in deep salt rock formation, salt caverns are widely used in large-scale CAES plants. The two current commercial CAES facilities were both constructed in salt-dome, in which solution-mined caverns are used for compressed air storage. In addition, low-permeability hard rock formation also is potentially suitable for underground compressed air storage. This can be achieved by either unlined rock cavern using ground water pressure and drilled water curtain or lined rock cavern with a thin impermeable liner [14].

Therefore, for a cavern-based CAES system, the storage capacity of the compressed air in a cavern, and the identification of an appropriate cavern volume are crucial for accommodating the matched compressed air energy to deliver the designed rate of power and energy at the plant planning and design stage. The complexity of these estimations results from the time-dependent CAES system operation, dynamic internal air responses in the cavern, and the coupled thermal effects of surrounding rocks. To deal with the challenge, this study proposed a method to balance the complexity and accuracy of these estimations for the plant's planning and design. The novel estimation method is not only simple to carry out the early-stage preliminary design without excessive cost, but also comprehensive and accurate enough to consider all the associated factors. This study examines exergy flow based on the second law of thermodynamics, and evaluates the storage capacity of the compressed air in the cavern-based CAES system. Compared to "energy", which regards work and heat with equivalent contribution to balance the energy flow according to the first law of thermodynamics, exergy analysis focuses primarily on the maximum useful work and considers the exergy losses in the energy conversions. The exergetic analysis is valuable and it has been studied in applications with electricity output, such as the Organic Rankine cycle [15,16], the fuel cell [17], Combined Cycle Gas Turbine [18], and other power generation processes [19–21]. These investigations used exergetic analysis and accounted for the exergy losses and efficiencies. Thus, in this study, exergy storage capacity of the compressed air indicates the equivalent maximum work deliverable during the system discharging period.

Exergy storage capacity of a cavern was studied by Garvey et al and the capacity is evaluated solely in terms of the pressure variation of the air in the cavern [22]. However, compared to the identified significance of pressure variation in the cavern to determine the exergy storage capacity, air temperature variation is significantly underestimated. For capturing the unsteady heat transfer between the air and cavern wall, three wall conditions which approximate the heat flux between air and surrounding rock are considered: (1) the adiabatic boundary condition for the cavern wall in which heat flux is zero; (2) the isothermal boundary condition for the cavern wall in which heat flux is infinite with perfect conduction through surrounding rocks; and (3) the convective heat transfer (CHT) boundary condition for the cavern wall