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A study on performance of a liquid air energy storage system with packed bed units

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HIGHLIGHTS

- Thermodynamic analysis is presented for a LAES system combined with packed bed units.
- The LAES system round-trip efficiency is in the range 50–62%.
- Cold box inlet temperature and discharge pressure have significant influence on system performance.
- LAES system has smaller air storage volume and higher ASED compared with A-CAES system.

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ABSTRACT

Energy storage is a key technology required to manage intermittent or variable renewable energy, such as wind or solar energy. In this paper a concept of an energy storage based on liquid air energy storage (LAES) with packed bed units is introduced. First, the system thermodynamic performance of a typical cycle is investigated and temperature distribution in cold boxes is discussed. Then, the effects of inlet temperature of cold boxes, charge and discharge pressures on thermal behaviors of LAES system are analyzed, as well as the system round-trip efficiency. Finally, an overall comparison between this LAES system and an adiabatic compressed air energy storage (A-CAES) system is conducted. The system could achieve a round-trip efficiency in the range 50–62% depending on the values of process conditions. The system round-trip efficiency decreases with the increase of cold box inlet temperature, and increases with the rise of charge and discharge pressures. Although the round-trip efficiency of the present LAES system is a bit lower than the A-CAES system, however, the air storage volume decreases and the air storage energy density (ASED) increases remarkably for the same operational conditions. The main conclusions draw from this work is beneficial for future LAES development in particular the combination with the packed bed units and the fit with the requirements for large-scale energy storage.

1. Introduction

Recently, a lot of power production based on fossil fuels is gradually replaced by the renewable energy, such as solar energy and wind energy [1]. The renewable energy can be used in the existing grid large-scale by energy storage technology. It generates electricity for the demand of electricity power, and transform into the storable form of energy when the instantaneous demand is lower than the instantaneous production

Admittedly, pumped storage (PHS) and compressed air energy storage (CAES) can be run in the hundred MW class large-scale commercial systems [2–5]. However, it is difficult to realize the specific geographical condition to build large reservoirs for large scale storage of pumped storage. Conventional CAES system also needs a large volume of the storage reservoir, so large-scale cavities which are formed by salt, hard rock and porous rock are typically required for the CAES storage reservoir [6,7]. Above ground storage equipment can also be used to store compressed air but it needs high investment costs. Underwater CAES is also being developed [8], but this requires suitable water depths.

The liquid air energy storage system (LAES) is a new type of energy storage technology which has several advantages: high energy storage density & capacity, no geographical constraints, no pollution of the environment and long useful life [9]. Compared to the CAES system, LAES system stores air as a cryogenic liquid phase with higher energy density so that the volume of the reservoir is reduced. It does not need a

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Nomenclature

ASED	air storage energy density (kJ/m^3)
D	PBTES diameter (m)
H	PBTES height (m)
OSED	occupied space energy density (kJ/m^3)
R_g	gas constant (J/kg K)
T	temperature (K)
T_{st}	storage temperature of A-CAES system (K)
V	volume (m^3)
V_{CASV}	liquid air storage volume (m^3)
V_{LASV}	compressed air storage volume (m^3)
$V_{Methanol}$	storage volume of methanol (m^3)
V_{OS}	volume of occupied space (m^3)
$V_{Propane}$	storage volume of propane (m^3)
V_{SV}	storage volume (m^3)
W	power (kW)
Y	liquid yield
c_p	specific heat (J/kg K)
d_p	diameter of particle (m)
h	heat transfer coefficient (W/m^2 K)
he	enthalpy (J/kg)
m	mass flow rate (kg/s)
k	polytropic index
p	pressure (Pa)
p_{s0}	charge pressure of A-CAES system (Pa)
p_{s1}	discharge pressure of A-CAES system (Pa)
t	time (h)
u	velocity (m/s)

Greek symbols

ε	porosity
π	ratio
ρ	density (kg/m^3)
λ	thermal conductivity (W/m K)
η	efficiency

Subscripts

a	air
ay	liquefied air
c	compressor
ct	cryogenic turbine
cht	charge time
dcht	discharge time
in	inlet
i	index for compression stage
j	index for expansion stage
out	outlet
pol	polytropic
s	solid
t	turbine
w	wall

high-pressure vessel for air storage, requiring instead a well-insulated container at atmospheric pressure.

The first LAES pilot plant (350 kW/2.5 MWh) was developed in Scotland by the UK Company Highview Power Storage and was donated to the University of Birmingham in 2015, as shown in Fig. 1. The response time of this LAES system is about 2.5 min, much faster than CAES system of 8–12 min. The reported round-trip efficiency of this system is ~50%, which is slightly lower than the CAES system [10]. It has potential application prospects in the field of intermittent renewable energy storage and distributed energy supply. A larger prototype plant (5 MW/15 MWh) is under construction in the UK [11].

The first concept of LAES goes back to 1977 when Smith [12] proposed a thermodynamic cycle and reported an energy recovery efficiency of 72%. Since then, a few studies on the operating parameters, economy and overall round-trip efficiency of LAES plants are were published.

Chino and Araki [13] presented an air liquefaction plant with a high round-trip efficiency in excess of 70%. This high figure is attributed to the recovery of cold exergy from the liquefied air, which is stored in a storage medium (small pebbles) and later used in the liquefaction section. Ameel et al. [14] performed a thermodynamic analysis of energy storage based on a liquid air Rankine cycle. In this case, a round-trip efficiency of 43.3% was achieved which is quite low when compared to a CAES system, but the energy density is about 20 times larger than CAES. They also demonstrated that the combined cycle (Linde refrigeration and Rankine cycle) has a high efficiency and that isothermal compression and expansion are critical to achieving good storage efficiency and distinctly high energy density. Li et al. [15] proposed a new LAES system by integrating nuclear power plant and cryogenic energy storage technology. Thermodynamic analyses were carried out and the results showed that the system efficiency is over 70% due to the elevated topping temperature in the superheating process. Similar to the Chino and Araki's work, the round-trip efficiencies of these two LAES systems are both higher than 70%, which is close to the pumped hydro storage technology and shows a potential prospect of industrialization. Kantharaj et al. [16–18] analyzed a hybrid energy storage system involving compressed air and liquid air with a roundtrip efficiency of 53%. The thermodynamic analysis and economic analysis of this system are investigated which can serve as a guideline for the detailed design of a hybrid CAES-LAES plant. Guizzi et al. [19] performed a thermodynamic analysis of a LAES system. The results showed that a round-trip efficiency in the range of 54–55% can be achieved in a stand-alone configuration based on both cold and heat storage. They also pointed out that the cryogenic turbine is the most critical component of the liquefaction section whose adiabatic efficiency of at least 70% is required to reach the round-trip efficiency target. Morgan et al. [20] proposed a LAES system and then presented a pilot scale demonstration project to prove the LAES concept. Analysis showed that the net round-trip efficiency of up to 60% can be predicted by recycling and storing thermal energy between the charge and discharge processes. Most recently, She et al. [21] analyzed the amount of heat of compression stored in the air liquefaction, and found that ~20–40% of the stored heat was excess and cannot be used in the power recovery of the previous LAES. Based on this new finding, a

Fig. 1. The first LAES pilot plant (350 kW/2.5 MWh).