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Thermodynamic analysis of a novel energy storage system with carbon dioxide as working fluid

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ABSTRACT

Recently, energy storage system (ESS) with carbon dioxide (CO_2) as working fluid has been proposed as a new method to deal with the application restrictions of Compressed Air Energy Storage (CAES) technology, such as dependence on geological formations and low energy storage density. A novel ESS named as Compressed CO_2 Energy Storage (CCES) based on transcritical CO_2 Brayton cycle is presented in this paper. The working principle of CCES system is introduced and thermodynamic model is established to assess the system performance. Parametric analysis is carried out to study the effect of some key parameters on system performance. Results show that the increase of turbine efficiency is more favorable for system optimization and the effect of minimum pressures on system performance is more significant compared with maximum pressures. A simple comparison of CCES system, liquid CO_2 system and Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) system is conducted. It is shown that the system efficiency of CCES is lower than that of AA-CAES system but 4.05% higher than that of liquid CO_2 system, while the energy density of CCES system is 2.8 times the value of AA-CAES system, which makes CCES a novel ESS with potential application.

1. Introduction

Renewable energy has been a hot topic in the field of energy utilization because of its environment-friendly behavior and sustainability [1]. Nevertheless the instability and unpredictability of renewable energy present trouble for renewable energy efficient utilization and energy storage system (ESS) is regarded as one method to the variability problem of renewable-energy resources [2]. There are various types of storage methods and electrical energy can be stored in form of different kind of energies: mechanical, electro-chemical, electromagnetic, thermal [3]. As for ESSs related to mechanical energy, Compressed Air Energy Storage (CAES) is a promising ESS on the basis of gas turbine technology [4]. It can use excess power to compress air and store them in a storage chamber during low demand periods, while compressed air is drawn from the chamber and heated in a combustor and finally expanded through turbines to produce electricity during peak load hours [5]. CAES has been proved to be a reliable energy storage technology [6].

However, the dependence of CAES system on fossil fuels as well as geography restricts the development of CAES technology to some extent [7]. Thus it is necessary to optimize current CAES system for better applications. In an optimized CAES system, Thermal Energy Storage (TES) technology is adopted to replace combustor to eliminate the need for fossil fuels [8]. Heat-of-compression is stored in TES during energy storage process and reused to heat compressed air to increase work output during energy recovery process. This optimized CAES system is named Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) system, in which the use of fossil fuels is avoided [9].

One significant feature of CAES system is its dependence on geological formations such as salt, hard rock, and porous rock. Although the long-term outlook for CAES technology looks favorable, the geology is regarded as a negative factor [10]. In order to overcome this drawback, Liquid Air Energy Storage (LAES) system is developed [11]. Liquid air, whose density is much higher than that of gaseous air, is used to store energy to increase energy density of system [12]. With the help of artificial storage tanks, LAES system has no geographical restriction [13]. However, some scholars think the requirement of LAES system for insulation measures is strict as the critical temperature of air is so low, otherwise heat loss in LAES may affect system stability and safety. Meanwhile the cryogenic air

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Nomenclature

h	enthalpy (kJ kg^{-1})
m	mass flow rate (kg s^{-1})
p	pressure (bar)
s	entropy (kJ kg^{-1} K^{-1})
t	time (s)
Ex	exergy flow (kW)
E_D	exergy destruction rate (kW)
Q	heat transfer rate (kW)
T	temperature (K)
V	volume (m^3)
W	power (kW)

Greek symbol

η	efficiency
ρ	density (kg m^{-3})

Abbreviations

AA-CAES	Advanced Adiabatic Compressed Air Energy Storage
CAES	Compressed Air Energy Storage
CCES	Compressed Carbon-dioxide Energy Storage
CES	Cold energy storage
CR	cooler
ESS	Energy storage system
HEX	Heat exchanger
HST	High-pressure storage tank
LAES	Liquid Air Energy Storage
LST	Liquid storage tank
ORC	Organic Rankine cycle
RTE	Round-trip efficiency
TEES	Thermo-electric Energy Storage
TES	Thermal energy storage

Subscripts

1,2 …,9	state point
c	compressor
e	expander
es	energy storage
er	energy recovery
max	maximum
min	minimum
s	isentropic
t	turbine
CES	cold energy storage
CR	cooler
E	energy
HST	high-pressure storage tank
LST	liquid storage tank
TES	thermal energy storage

can also make system components become brittle [14]. So there is still room for improvement in CAES technology.

Recently, the idea that using carbon dioxide (CO_2) to replace air as working fluid of ESSs has been proposed [15]. On one hand, CO_2 has appropriate properties and characteristics. The critical temperature as well as critical pressure of CO_2 is higher than that of air, which means it is susceptible to being liquid state or supercritical state [16]. On the other hand, thermodynamic cycles with CO_2 as working fluid are mature and novel ESSs are expected to be developed based on various thermodynamic cycles [17]. Based on this idea, one novel CO_2-based-ESS named as Thermo-electric Energy Storage (TEES) has been proposed [18]. TEES system can be regarded as the combination of heat pump cycle and heat engine cycle. Electrical energy is converted into thermal energy through heat pump cycle during energy storage process and the stored energy is converted back into electrical energy through heat engine cycle during energy recovery process. Related research demonstrated the pilot system efficiency was 51% and pointed out the attractive capital cost as well as site independent nature of TEES system [19].

Some scholars have made further research on system performance of TEES system. Morandin et al. [20] carried out configuration optimization and parametric sensitivity analysis of TEES system to improve system performance, and they also investigated thermoeconomic optimization of TEES system [21]. A novel isothermal TEES system was proposed by Kim et al. [22] based on the initial TEES system model, and they analyzed operating parameters for a better system performance. Baik et al. [23] analyzed heat exchange process in TEES system and evaluated the effect of storage temperature in thermal reservoirs on system efficiency.

Subsequently, another novel ESS based on liquid CO_2 storage and supercritical cycle was proposed by Wang et al. [14]. Considering the high density of liquid CO_2, artificial storage tanks were used to store liquid CO_2 in this system, which avoided the need for underground storage. Besides, in order to take full advantage of the waste heat, a set of organic Rankine cycle (ORC) system was made use of to increase power output. It was shown that the system efficiency could reach 56.64% and energy density was 36.12 kWh m^{-3}. Subsequently they carried out system optimization and analyzed the effect of several key parameters on system performance [24].

Generally speaking, there are only two CO_2-based-ESSs (TEES system and liquid CO_2 storage system) in the world up to now and related research focuses on theoretical design, analysis and optimization. According to current research, CO_2-based-ESS offers potential for cost and efficiency improvements at favorable locations. Besides, research on supercritical CO_2 Brayton cycle has verified the compactness of key components such as turbomachinery and heat exchanger, which signifies the application flexibility of system with CO_2 as working fluid [25].

For present CO_2-based-ESSs, the low efficiency problem (<60%) is still unresolved. Considering that research on novel CO_2-based-ESSs is at the preliminary stage, there is room for novel ESSs with better performance. In this paper, a novel CO_2-based-ESS based on transcritical CO_2 Brayton cycle is proposed. Because its working principle is similar to that of CAES system, this system is named as Compressed CO_2 Energy Storage (CCES). Then the thermodynamic model of this system is developed and parametric analysis is conducted to analyze the effect of several operating parameters on system performance. Related results provide a foundation for further optimization of this novel ESS.

This paper is organized as follows: section 2 presents a general description of CCES system. The thermodynamic model of CCES system is established in section 3. Section 4 shows the working performance of CCES system and carries out parametric analysis. Finally, conclusions are drawn in section 5.

2. System description

On the basis of the working principle of CAES system as well as