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Thermodynamic analytical solution and exergy analysis for supercritical compressed air energy storage system

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HIGHLIGHTS

- A concise analytical solution for SC-CAES system was presented for the first time.
- The analytical solution is universal for SC-CAES and other similar CAES systems.
- A method of sectional treatment and Taylor expansion was carried out.
- Exergy analysis for SC-CAES system with its analytical model was conducted.

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ABSTRACT

An analytical solution for a novel Compressed Air Energy Storage (CAES) system, Supercritical Compressed Air Energy Storage (SC-CAES) system, was conducted in this paper. The analytical solution can explore the evolution and its reason of roundtrip efficiency varying with system key parameters in depth, while it can also reveal the coupling mechanism of different sections of the system. On that basis, the model of exergy destruction for each part was obtained, and the exergy destruction can be easily calculated. Furthermore, the analytical solution has the character of universality due to the deduced method of sectional treatment, hence it can be extended to other similar CAES systems. Lastly, a sensitivity analysis and an exergy analysis were conducted for SC-CAES system. It is found and proved that the system efficiency varies linearly with isentropic efficiencies of compressor and expander, temperature difference of intercooler and reheater, pressure loss of intercooler and reheater. Meanwhile, the main factors of the varying tendency of total exergy destruction with different parameters are revealed.

1. Introduction

Electrical energy storage has become a worldwide concern in research and development because it plays an important supporting role in the areas of renewable energy power generation, off-peak electricity utilization, distributed energy system, microgrid, smart grid, and energy internet. The main power energy storage technologies include pumped hydroelectric storage (PHS), compressed air energy storage (CAES), thermal energy storage (TES), superconducting magnetic energy storage (SEMS), flywheel, capacitor/supercapacitor, lithium-ion (Li-ion) battery, flow battery energy storage (FBES), sodium–sulfur (NaS) battery, and lead–acid battery [1–3]. Among these technologies, compressed air energy storage (CAES) system is considered as one of the most promising energy storage technologies because of its advantages: deployable at large scale, low initial and O&M costs, high efficiency, environmental friendliness, and long lifetime [1–6].

In conventional CAES systems, the air is compressed by the compressor using electricity and stored in a cavern during energy charge period. Thus the electricity is converted into internal energy and pressure energy of the stored air. During energy discharge period, the high pressure air in the cavern is released and mixed with fuel, and burned to generate high-pressure high-temperature gas, which then drives the expander to produce power. Conventional CAES has the disadvantages of relying on fossil fuel and large chambers, low efficiency and low energy density, limiting its development and large scale application [7–9]. Targeting this problem, a novel CAES, supercritical compressed air energy storage (SC-CAES) system, was proposed by our team in 2009. This system eliminates the relying on fossil fuel and large chamber simultaneously with a high roundtrip efficiency (around 67%) and high energy density (around 3.4×10^5 kJ/m^3) [10,11].

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At present, there is much research focus on the thermodynamic characteristics of CAES [12–18], in which the methodologies adopted can be summarized into numerical method and analytical method. The former obtains the solution by the method of interpolation, iteration, etc., which is an approximate solution. It is suitable for the condition that the object cannot be expressed as an explicit function of independent variables. The analytical method expresses the object with an explicit function of independent variables, thus it can be calculated directly if the independent variables are substituted into the explicit function, which is convenient and precise under its assumptions.

It is difficult to express the thermodynamic characteristics of CAES analytically because of strong coupling relationships among different processes of CAES system. Research on system thermodynamic characteristics is mostly based on numerical methods with business software or self-programming [12,13,16,17,19,20]. The thermodynamic characteristics of CAES systems are revealed in Refs. [12,13] by numerical method. Barbour et al. conducted an exergy analysis on an adiabatic CAES (A-CAES) with packed bed storing heat, and found that the compressor and expander take the largest exergy destruction [12]. Sciacovelli et al. studied the off-design performance of an A-CAES system by numerical method, the results indicated that a roundtrip efficiency exceeding 70% can be achieved when thermal energy storage (TES) efficiency rises above 90% [13]. The thermodynamic characteristics and off-design performance can be calculated and analysed by numerical method, however, it is difficult to thoroughly explore the coupling relationships of system processes and parameters, as are the internal reasons of the system characteristics.

Some research has obtained the analytical solutions of some CAES systems. Yang at al. achieved the analytical expressions of system efficiency and heat storage of a thermal-compressed air energy storage system [14]. Zhang at al. attained the analytical expressions of system efficiency, heat storage and heat returned of an A-CAES under different chamber models [15]. However, these analytical solutions are all based on special conditions, such as the chamber at a fixed pressure or a fixed temperature [14,21], an indirect thermal energy storage of two tanks or a simple heat storage model was adopted [15,21], or the charge and discharge process are all operated under design condition (or only some parameters are all under design condition) [15,22], etc. These analytical solutions can't show the effects of key parameters on system performance explicitly because the key parameters are coupled in different items but not detached.

System efficiency is always an item of evaluation indexes in economic analysis of energy storage systems because system efficiency indicates the energy recovery rate. The key indexes include net benefit [23,24], annualized replacement costs [25], component cost [26], etc. Obtaining thermodynamic analytical solution is beneficial for the calculation and analysis of system economy. The effects of key system parameters on system economy, and the coupling relationship of the key parameters are clearly shown by substituting thermodynamic analytical solution into the economic evaluation indexes. In this way the key points can be found out quickly when the economic evaluation index is the optimization objective.

The system flow of SC-CAES system is complex. The coupling relationships of system processes, and parameters cannot be explored thoroughly with numerical method. Therefore a concise analytical model of the SC-CAES system was established in this paper, through which, the influence of key parameters on system efficiency can be revealed conveniently. In turn, the coupling relationships of different system processes can be revealed. The concise analytical model is also beneficial to economic analysis and thus development of an economic analytical model.

The analysis methods of the thermal performance for CAES system include energy analysis method based on the first law of thermodynamics [15,19,27] and exergy analysis method based on the second law of thermodynamics [12,28–31]. The exergy analysis method focuses not only on the change of energy quantity but also on the change of exergy quality compared with the energy analysis method that only focuses on the change of energy quantity. Furthermore, exergy analysis can provide more detailed information about the system. For example, Osterle et al. [22] compared the energy analysis method and exergy analysis method in analysing the CAES system and found the result of the exergy analysis to be more meaningful. Then exergy analysis is important for SC-CAES system.

The analytical solution of exergy destruction in each part can be easily obtained on the basis of the concise analytical model in this paper. By obtaining the variation of the exergy destruction with key parameters and finding out the main components and parameters affecting total exergy destruction variation, the analytical solution of exergy destruction is benefical to system exergy analysis and optimization. Thus the exergy analysis is conducted in this paper.

The work can be used as a reference for designing and optimizing of the SC-CAES system and other similar CAES systems.

2. System flow

The schematic illustration of a SC-CAES system is shown in Fig. 1. During energy charge period, atmospheric air is compressed to supercritical state by the compressors, while the compression heat is recovered by water cycling from a cold tank. This heated water is stored in a hot tank. The supercritical air is cooled to liquid state by the stored cold energy in the cold storage/heat exchanger and then expanded to atmospheric pressure by the valve or liquid expander. Then part of the air is liquefied to liquid state, and the other is changed into gas state. The liquid air is stored in the cryogenic storage tank for energy storage, while the gaseous air is piped to cold storage/heat exchanger to release cold. During the energy discharge period, the stored liquid air is pumped to supercritical pressure by the cryopump, then piped to the cold storage/heat exchanger and heated to atmospheric temperature, while the cold energy of the liquid air is released and stored in the cold storage/heat exchanger. The high-pressure air out of the cold storage/heat exchanger absorbs compression heat which has been stored in the circulation water during energy charge period, the cooled circulation water is cooled again in cooler 2 to near atmospheric temperature and stored in the cold tank. The heated high-pressure air is expanded in the expanders to produce power.

In Fig. 1, for convenience, the left side of red dashed line A is called Compression and Expansion (CE) section, while the right side is called Cold Storage and Liquefaction (CSL) section.

3. System thermodynamic model

3.1. Analytical model of system efficiency

For a higher system efficiency and a more simple system flow, generally, the compressors are set to be having the same compression ratio, and the expanders are set to be having the same expansion ratio [21]. Hence, a SC-CAES system with the same compression ratio for all compressors and the same expansion ratio for all expanders is studied in this paper. There are N compressors and M expanders, and the size of M and N is determined by whether the compression heat can meet the requirement of reheat because the compression heat is not enough (the hot water is not enough) when N is much smaller than M.