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Research Paper

Performance optimization of adiabatic compressed air energy storage with ejector technology

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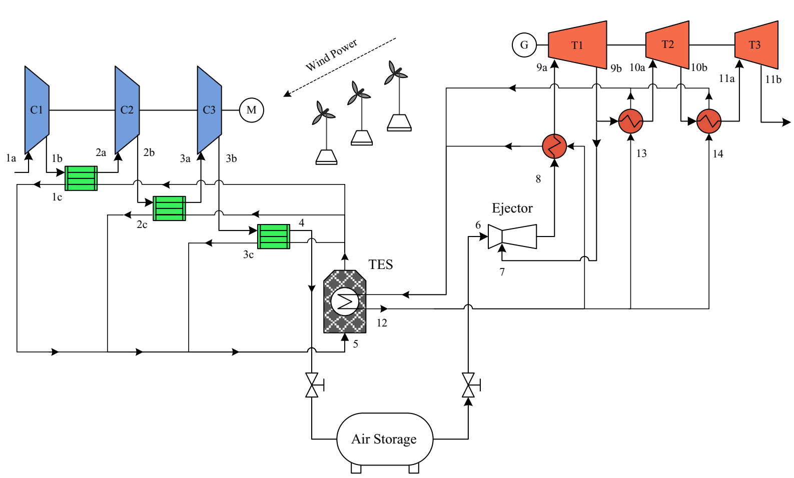
HIGHLIGHTS

- CAES technology can improve electricity quality of wind power and solar power.
- Adiabatic CAES technology has the advantage of zero natural gas consumption.
- Ejector was integrated to adiabatic CAES system to recover pressure reducing loss.
- Application of ejector achieved an efficiency increase of 3.41% for adiabatic CAES.
- Energy conversion efficiency of the optimized adiabatic CAES reached 65.36%.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, the performances of two adiabatic compressed air energy storage systems were determined. In system 1#, compressed air was reduced directly from 6.40 MPa to 2.50 MPa. In system 2#, compressed air was first reduced to 5.00 MPa and was later adjusted to 2.50 MPa by an ejector under an ejecting coefficient of 0.45. The mass flow of turbine 1# increased by 45%, and its power output capacity increased from 3.80 MW to 5.51 MW. The energy conversion efficiency of system 2# increased to 65.36% from 61.95% for system 1#. The application of the ejector improved the efficiency by 3.41%.

1. Introduction

Wind power has been developed on a large scale worldwide. The installed capacity of wind power around the world reached 194.69 GW, of which the USA occupied 40.18 GW and China occupied 42.29 GW in 2010 [1]. With the rapid increase in wind power installed capacity, the difficulty in introducing wind power to the electricity grid became a serious issue due to its disadvantage in electricity quality. The instability of the wind velocity causes fluctuations of the wind power output. To compensate for the fluctuating property of renewable power, electricity storage technologies are becoming increasingly necessary. The fluctuating renewable electricity can be stored during off-peak times and is then released as firm peak load electricity.

Electricity storage technologies generally include battery energy storage [2,3], super capacitor storage [4,5], flywheels [6,7],

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superconducting magnetic energy storage [8], pumped-hydro storage [9] and compressed air energy storage [10,11]. Among these electricity storage technologies, only pumped-hydro storage and compressed air energy storage (CAES) have the potential for large-scale utilization with a capacity over 100 MW. Compared to pumped-hydro storage, CAES can be applied in arid region. There are two different types of CAES systems: diabatic and adiabatic. For the diabatic CAES plant, additional natural gas is consumed to maintain the operation of the CAES plant. There are two commercial diabatic CAES plants around the world. One was built in 1978 in Huntorf, Germany, with an electricity storage capacity of 60 MW and an electricity output capacity of 290 MW [12]. The other diabatic CAES plant was built in McIntosh, United States, with an energy storage capacity of 50 MW and an output capacity of 110 MW [13,14]. The existing diabatic CAES plants suggested an energy conversion efficiency of 54%.

The adiabatic CAES stores the thermal energy after compression in a thermal energy storage (TES) unit, and then the compressed air can be heated by heat transfer out of the TES during the discharging process. The addition of natural gas in an adiabatic CAES can be neglected. The generally accepted energy efficiency of adiabatic CAES plants was approximately 70% [15,16]. The performance of adiabatic CAES was calculated by Jubeh, who noted that the efficiency of adiabatic CAES systems reached 72.5% [11]. However, some literature also reported efficiencies of lower than 70%. The results from Hartmann showed that the efficiency of adiabatic CAES varied between 52% and 62% [17]. He also showed that the high value efficiency of 70% was only reached for the ideal configuration with high temperature thermal storage (>600 °C). The pressure ratio and temperature of TES are important parameters that affect the efficiency of adiabatic CAES systems. However, the pressure reducing loss from the compressed air storage volume to the turbine inlet is also important. Taking the Huntorf CAES plant as an example, the air storage pressure was 7.0 MPa in the air storage volume, while the inlet pressure of the turbine was lower than 4.3 MPa.

Ejectors were widely used in the refrigeration area to recover the pressure reducing loss [18]. Huang et al. [19] predicted the ejector performance with critical-mode and verified the analytical results with experiments using 11 ejectors and R141b as the working fluid. El-Dessouky et al. [20] developed semi-empirical models for designing ejectors and gave the entrainment ratio as a function of the expansion ratio and the pressures of the entrained vapor, motive steam and compressed vapor. In this paper, the pressure adjustment method with ejector was integrated into an adiabatic CAES system, and its positive influence on adiabatic CAES performance was discussed.

2. Theoretical analysis of compressed air energy storage

Adiabatic compressed air energy storage system (AA-CAES) generally consists of an air compression module, a thermal energy storage module, an air storage module and an electricity releasing module. A schematic diagram of AA-CAES is given in Fig. 1. The theoretical analysis methods and basic description of the ejector device are given in this section.

2.1. Air compression module

The temperature of the compressed air during the compression process was calculated using the polytropic relation between temperature and pressure. The polytropic index n for the polytropic compression process was set to $n = 1.46$. The specific heat capacity at constant pressure for air was set to $c_p = 1.005$ kJ/kg k. Moreover, the consumed compression power for each stage of the compressor was calculated as the difference in enthalpy.

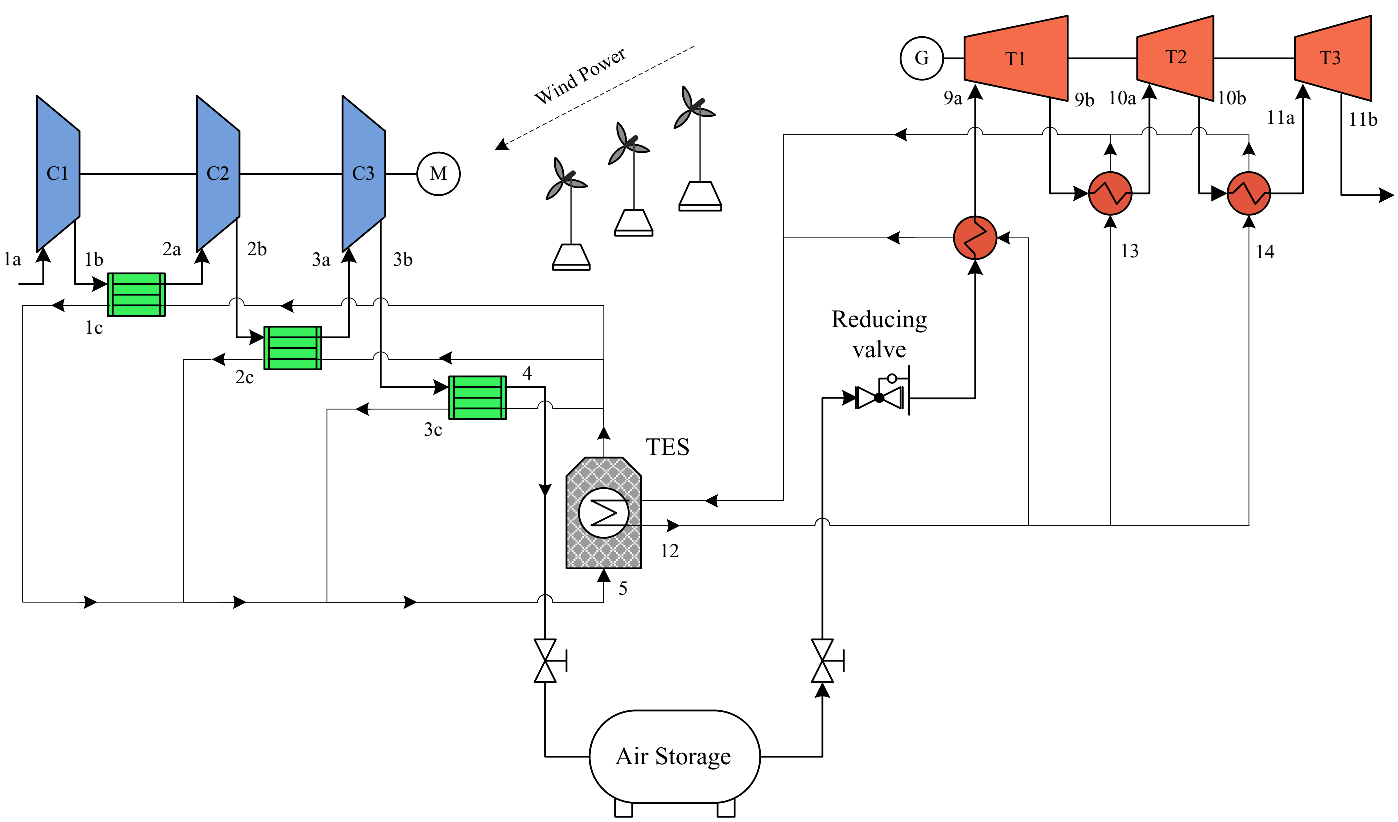

Fig. 1. Schematic diagram of adiabatic CAES.