Energy Conversion and Management 108 (2016) 566–578

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A comparative research of two adiabatic compressed air energy storage systems

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ARTICLE INFO

Article history:
Received 8 September 2015
Accepted 23 November 2015
Available online 9 December 2015

Keywords:
Adiabatic compressed air energy storage
Conventional A-CAES system
Modified A-CAES system
Energy analysis
Exergy analysis

ABSTRACT

Adiabatic compressed air energy storage (A-CAES) is regarded as a promising emission-free technology to facilitate the renewable energy integration, when a large amount of renewable energy is abandoned due to the difficulty of integrating fluctuating renewable energy into electricity grid systems all over the world. However, the temperature of discharged air from low pressure turbine is still high in the conventional A-CAES system and a considerable amount of energy is lost. So a modified A-CAES system is proposed to solve this problem in this paper. The proposed modified A-CAES system can simultaneously provide mechanical energy, heating energy and cooling power. This paper aims to make a comparative research of the two A-CAES systems from the technological point of view. The thermodynamic analyses including energy analysis and exergy analysis are evaluated by using steady-state mathematical models and thermodynamic laws. The results show that total exergy efficiency of the modified A-CAES system can be improved nearly 3% compared to the conventional A-CAES system in spite of lower round trip efficiency. Meanwhile, a parametric analysis is also carried out to evaluate the effects of several key parameters on the system performance of the two A-CAES systems.

1. Introduction

Energy has been a key element to the development of a country. It can be divided into two categories: non-renewable energy and renewable energy sources. In the past decades, worldwide demand for energy is rapidly increasing, which has resulted in a rapid decline of non-renewable energy resources such as coal, natural gas, oil and nuclear fuel. Moreover, this has led to high-priced energy, global warming and local pollution [1,2]. So finding alternative energy and developing renewable energy have become much more important and impendent than any time in history.

As a result, wind power generation and solar photovoltaic generation have shown a robust growth trend worldwide these years. The global installed generation capacity of wind power and solar photovoltaic reached 369 GW and 177 GW at the end of 2014, respectively [3,4]. So using renewable energy resources seems to be a promising option. However, there are still some serious concerns about these renewable energy resources and their implementation, e.g. (1) lower power density, (2) intermittent nature in power production, (3) largely depending upon local site and (4) unpredictable weather conditions [5–7]. These limitations make it difficult to deliver power output from renewable energy with an instant match to the electricity demand. Therefore, in order to make these renewable energy resources to be completely reliable as primary sources of energy, energy storage is a crucial factor [8,9].

Energy storage of a power system can be defined as any installation or method, which can be used to store the energy generated in the power system. The stored energy can be used again when it is necessary [10–12]. There are a number of benefits associated with the introduction of energy storage system (ESS) in the built environment. ESS can contribute to increasing power systems' efficiencies, as they can effectively manage the surplus electricity generation from renewable energy technologies, which would otherwise be wasted. In this way, ESS helps to maximize the value and the contribution of intermittent renewables [12]. In addition, ESS has long been considered as a crucial mechanism for ensuring power system stability and reliability, because ESS can address the fluctuations in consumption and generation by providing the necessary flexibility [1]. Furthermore, ESS can contribute to the increase of energy security and quality of supply, by sustaining frequency and voltage at the required levels. For example, electricity storage options could deal with the occurring voltage sags in case of a power failure, ensuring reliability of supply [9,13].

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http://dx.doi.org/10.1016/j.enconman.2015.11.049
0196-8904/

Nomenclature

Symbols	
T	temperature, K
$\dot{Q}$	heat flow rate, kW
h	specific enthalpy, kJ/kg
s	specific entropy, kJ/kg K
$\dot{W}$	work input rate, kW
$\dot{m}$	mass flow rate, kg/s
W	work, kW
$\dot{E}x$	exergy flow rate, kW
ex	specific exergy flow, kJ/kg
Acronyms	
CAES	compressed air energy storage
A-CAES	adiabatic compressed air energy storage
TES	thermal energy storage
ESS	energy storage system
LC	low pressure compressor
HC	high pressure compressor
HT	high pressure turbine
LT	low pressure turbine
PM	pneumatic motor
IC	inter-cooler
AC	after-cooler
PH	pre-heater
IH	inter-heater
SV	air storage vessel
P1	pump 1
P2	pump 2
TV	throttling valve
HA	heat accumulator
Greek letters	
π	pressure ratio
η	isentropic efficiency
λ	ratio of specific heats
Subscripts	
i	inlet
o	outlet
d	destruction
c	compression process
ec	expansion process of the conventional system
em	expansion process of the modified system
0	ambient conditions
1–12	state points of charge process
13–22	state points of discharge process in the modified system
13s–27s	state points of discharge process in the conventional system

In general, ESS can be described as either electrical or thermal. Electrical energy storage includes a broad range of technologies, e.g. electrochemical energy storage system, electromagnetic energy storage system and mechanical energy storage system [11,14]. Compressed air energy storage (CAES) is a kind of mechanical energy storage system, and it is one of the most promising methods for electrical energy storage. This is due to its low capital cost, high reliability, high efficiency, high economic feasibility and environmental friendliness [15–17].

CAES is a hybrid mechanical energy storage system, comprising energy storage and conversion. Ambient air is compressed and conventionally stored in large underground caverns or artificial storage vessels (SV) with excess power during low-cost off-peak load periods. During peak load periods, the stored compressed air is released from the underground caverns or the artificial SVs, then expanded in a gas turbine with natural gas to produce electricity [16,18,19].

The main drawback of conventional CAES system is that it involves combusting fossil fuels via gas turbines, resulting in traditional non-renewable energy resources consumption and CO_2 emissions [1]. Therefore, the concept of Adiabatic Compressed Air Energy Storage (A-CAES) has been proposed [20–22]. The main difference between an A-CAES system and a conventional CAES system is the additional storage of the heat released during compression process in a separate heat storage reservoir [20]. When the A-CAES system is operated at the expansion mode, by integrating a Thermal Energy Storage (TES) system, the energy stored in the compressed air is converted into the electrical power without a combustion process involved. The significant benefit of an A-CAES system is zero emissions, assuming that the electricity for the compression process is also from zero carbon energy sources.

The idea of developing A-CAES systems reaches back to the 1980s [23–25], but no plant has been developed due to technological barriers. The interest for the development of A-CAES systems was reignited by the increasing fuel prices and the need to reduce CO_2 emissions [25].

In recent years, a lot of research works regarding A-CAES systems have been conducted. The energy efficiencies of one full charge and discharge cycle of several A-CAES configurations are analyzed with the help of an energy balance. The results show that the key element to improve the efficiencies of A-CAES systems is developing high temperature thermal storages and temperature resistant materials for compressors, and the highest efficiency is delivered by the two-stage A-CAES configuration [26]. Performance, the operating variables and some performance parameters of an A-CAES system are evaluated and discussed by Jubeh and Najjar [27]. The results show us that, compared with conventional CAES systems, the A-CAES system can offer relatively higher energy storage efficiency. The thermodynamic effects of air storage chamber model, thermal energy storage and heat exchanger on A-CAES systems have been conducted by Zhang et al. [28–30]. Zhao et al. have proposed a hybrid energy storage system based on A-CAES and flywheel energy storage system for wind power application [31,32]. Zhang et al. have made a thermodynamic analysis of energy conversion and transfer in a hybrid system consisting of wind turbine and A-CAES [33]. Based on A-CAES, a hybrid thermal-compressed air energy storage system for the integration of wind power has been proposed by Yang et al. [34]. Thermodynamic analysis of the hybrid system is also conducted. A plant layout for A-CAES aiming at lower thermal storage temperatures has been developed by Wolf and Budt [35]. The proposed plant concept shows better profitability due to fast cycling capabilities.

It is noticed that the temperature of discharged air in all the A-CAES systems mentioned above is still high and a considerable amount of thermal energy in the discharged air is lost [27,32]. In order to solve this problem, a modified A-CAES system is proposed in this paper. The temperature of discharged air in this system is lower than ambient temperature. This modified A-CAES system not only doesn't waste thermal energy, but also provides cooling power. Therefore, the proposed system can provide three kinds of energy resources: mechanical energy, heating energy and cooling power.