Energy Conversion and Management 135 (2017) 394–401

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Modelling and analysis of a novel compressed air energy storage system for trigeneration based on electrical energy peak load shifting

Song Lv [a], Wei He [b,*], Aifeng Zhang [b], Guiqiang Li [a], Bingqing Luo [a], Xianghua Liu [b]

[a] Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230026, China
[b] Department of Building Environment and Equipment, Hefei University of Technology, Hefei 230009, China

ARTICLE INFO

Article history:
Received 31 October 2016
Received in revised form 8 December 2016
Accepted 29 December 2016

Keywords:
Compressed air energy storage system
Electricity storage
Building cooling heating power
Thermodynamic analysis
Economical analysis
Off-peak cooling

ABSTRACT

The compressed air energy storage (CAES) has made great contribution to both electricity and renewable energy. In the pursuit of reduced energy consumption and relieving power utility pressure effectively, a novel trigeneration system based on CAES for cooling, heating and electricity generation by electrical energy peak load shifting is proposed in this paper. The cooling power is generated by the direct expansion of compressed air, and the heating power is recovered in the process of compression and storage. Based on the working principle of the typical CAES, the theoretical analysis of the thermodynamic system models are established and the characteristics of the system are analyzed. A novel method used to evaluate energy and economic performance is proposed. A case study is conducted, and the economic-social and technical feasibility of the proposed system are discussed. The results show that the trigeneration system works efficiently at relatively low pressure, and the efficiency is expected to reach about 76.3% when air is compressed and released by 15 bar. The annual monetary cost saving annually is about 53.9%. Moreover, general considerations about the proposed system are also presented.

1. Introduction

With the rapid development of industry and the improvement of people living standards, energy and electricity consumption has risen sharply in recent years [1]. And due to the increasing occurrence of hot weather, drought and other types of natural disasters, the supply of electricity and energy is strained with the prominent shortages in certain regions and seasons. Thus, government of most countries have given their attention and support to develop the renewable energy or strengthen energy management and conservation [2–5]. Price volatility of electricity is a good regulation for energy management and has been practiced in the vast areas of the world. It makes great contribution to smooth out energy demand through peak shaving and valley filling. Moreover, it is a good chance for energy storage system to obtain economic benefits [6,7]. Therefore, energy storage is being identified as one of the solution to energy instability and shortages due to its efficiency and cost-effectiveness [8–10]. The Compressed Air Energy Storage (CAES) is considered as one of the most important and popular energy storage systems because it is technically feasible and economically attractive for load management in comparison with other energy storage systems [11–14]. The storage system has many advantages and applications, i.e., high reliability, flexibility, long life, low cost, high energy-capacity, relatively low operation and maintenance costs [14,15].

The traditional CAES is often used to generate electricity based on gas turbine technology [16]. During low-demand periods, electricity from base load plants or renewable energy is stored into a chamber or an underground reservoir, and the energy is converted into internal energy of compressed air. When there is demand of electricity, the compressed air is drawn from the storage chamber, and then mixed with fuel and expanded through turbine to drive a generator for the electricity power [17]. Nevertheless, most of the studies [3,8,12,18–22] on the CAES focus on the compressed air without considering and utilizing the energy loss in the compression process. Furthermore, the use of expansion work of the compressed air is getting more attention such as compressed air energy storage power station and pneumatic car, but the cooling power and cold air generated by the expansion process is ignored although it has been demonstrated in the inverted Brayton cycle [23]. However, the cooling technologies on the market mainly include ventilation, mechanical refrigeration and/or evaporative cooling. But these cooling technologies cannot completely meet the needs of large-scale public buildings. Limited by climate and geographical conditions, evaporative cooling cannot meet the requirements of high occasions in the vast areas of China. The

* Corresponding author.
E-mail address: hwei@hfut.edu.cn (W. He).

http://dx.doi.org/10.1016/j.enconman.2016.12.089
0196-8904/

Nomenclature

c_p	heat capacity of air, kJ/(kg K)
E_{in}	electrical power consumed by the compressor, J
E_{out}	energy output by the compressed air, J
m	element quality
n	the polytrophic factor
P_h	ultimate pressure after compress, Pa
p	compressed pressure of the air, Pa
p_0	atmospheric pressure, Pa
Q	heat recover from the compression, J
Q_c	cooling capacity of the venting air from the expansion, J
$Q_{cooling}$	cooling capacity after expansion, J
Q_h	heat recovered from the system, J
R	the universal gas constant
T_0	atmospheric temperature, K
V_h	ultimate volume after compress, m^3
W_c	work of the energy storage process, J
W_e	work of turbine expander, J

Greek symbols

δ	efficiency of the heat exchanger
ε_C	coefficient of electrical chiller
ε_H	coefficient of heat pump
η_a	energy efficiency of the system
η_C	cooling efficiency of the system
$\eta_{C,s}$	adiabatic efficiency of the compressor
η_T	adiabatic efficiency of the air turbine
κ	the adiabatic index of air
π	rate of pressure rise
τ	decrease of the temperature

mechanical refrigeration could satisfy any requirement of indoor temperature. However, it causes a heavy load of electricity. What is more, initial investment and operating costs of mechanical refrigeration are relatively high, especially at the working hours when the demand for electricity in cities dramatically goes up during the peak time. Electricity shortage in summer has become a major problem in many areas [24]. Thus, ice storage air-conditioning has been considered to be a good way for saving the electric power in summer. It has been used in the electrical power load shifting and air conditioning application. However, they are hard to popularize because of their inherent shortcomings, such as low efficiency, low COP, complex structure and high initial cost. Thus, it is imperative to find an approach to solve these problems of cooling and ventilation with low cost and good performance. Actually, the CAES provide a good chance to solve the problem due to its unique properties. Wang et al. [25] proposed a new refrigeration system based on compressed air energy storage (CAES). It utilizes the expansion work of the compressed air and serves as a compression device for a vapor compression refrigeration cycle to get relative bigger cooling capacity. Kim and Favrat [26] presents a micro-CAES and air cycle heating and cooling system. The energy and exergy analyses of the micro-CAES system were conducted, as well as some innovative ideas for achieving high efficiency of these systems were put forward. They have made good use of the cooling power produced by the expansion of the compressed air and demonstrated the feasibility of their inventions from the technological economy and the technology. However, these systems above also have disadvantages such as low energy usage ratio, the characteristic and function of the product are also often single. Furthermore, Li et al. [23] put forward a trigeneration system associate with the CAES driven by extra energy or waste heat that refer to the cooling power generated by direct expansion of compressed air. Wu et al. [27] carried out the thermo-dynamic analysis and experimental investigation of tri-generation based on CAES and pneumatic motor. Facci et al. [28] proposed a trigenerative compressed air storage based on the concept of a CAES and the relevant thermodynamic analysis are carried out. And low-temperature air that expands in the expanders is used directly for space cooling. The results demonstrates that CAES may have a potential as a distributed system that combines extra energy storage with heat and cooling energy production. Yao et al. [29] proposed a CCHP system combined with small-scale CAES and gas engine. The gas engine is employed in the CCHP system to generate power and preheat the high-pressure air coming from the air storage vessel. Therefore, the proposed CCHP system could increase the output power of the CCHP system and realize the energy cascade utilization.

From the above analysis, it can be found that though some new concepts about CAES systems to make use of cooling capacity were proposed, and some works already discussed the applicability of CAES for trigeneration purposes [23,25–29], there are still some deficiencies:

(1) Some application restricted by geographical and renewable energy resource conditions, so it can be constructed only in a place where space and resource conditions are met.
(2) The use of natural resources like for the CAES is relatively difficult in metropolises. It causes complex structure and high initial investment for the system.
(3) The applicability of CAES for trigeneration has been mainly focused on very large scale systems and much less attention has been paid to micro-one or residential purposes.
(4) The heat of compression and storage, the power output by the turbine and the by-product of air cooling has not been made full use of in one case. And the sharing components for heating, cooling and electricity production based on the need aren't seldom discussed.
(5) The operating costs of the application of CAES for trigeneration is seldom analyzed because of the use of renewable energy and waste heat.

To address these problems, a novel compressed air energy storage system for trigeneration is furtherly proposed in this paper. During the charge period, excess electricity is used to compress air at off-peak time; the energy is then stored in an air storage vessel. During peak-hours, air compressed from the off-peak hours is released to generate electricity, cooling and heating power depending on the user's need. Whenever the customer needs cooling power, compressed air is released to the turbine, and cooling power could be generated by direct expansion. At the same time, a generator is connected with a clutch to the expander to produce electricity. Moreover, a system with thermal energy collector is designed to capture and recover the heat of the compressed air. In this paper, the thermodynamic model of the proposed system is developed. Thermodynamic and economic analysis are performed to investigate the feasibility and performance of the system. And some relevant parameters are evaluated and discussed. In addition, a comprehensive efficiency and economic indicators are defined to evaluate the proposed system. And then a case study on a typical five star hotel located in Shanghai, China is taken for an