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Thermodynamic analysis of a novel tri-generation system based on compressed air energy storage and pneumatic motor

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Based on CAES (compressed air energy storage) and PM (pneumatic motor), a novel tri-generation system (heat energy, mechanical energy and cooling power) is proposed in this paper. Both the cheap electricity generated at night and the excess power from undelivered renewable energy due to instability, can be stored as compressed air and hot water by the proposed system. When energy is in great demand, the compressed air stored in this system is released to drive PM to generate mechanical power. The discharged air from PM can be further utilized as valuable cooling power. Compared to conventional CAES systems, the biggest characteristic of the proposed system is that the discharged air usually abandoned is used as cooling power. In order to study the performances of this system, a thermodynamic analysis and an experimental investigation are carried out. The thermodynamic model is validated by the experimental data. Using the validated thermodynamic model, the mechanical energy output, cooling capacity and temperature of discharged air, as well as the efficiency of the system are analyzed. The theoretical analysis indicates that the additional application of discharged air can improve total energy efficiency by 20–30%. Therefore, this system is very worthy of consideration and being popularized.

1. Introduction

The global demand for energy is rising fast, which leads to a rapid consumption of traditional fossil fuel resources and a serious issue concerning of global environmental pollution [1]. To address issues related to fossil fuel consumption, renewable energy resources, such as wind energy, solar energy and ocean energy, are quickly developed in recent years. Today, the fast growing renewable energy has been recognized as the promising power resource throughout the world [2]. However, the non-dispatchable nature of intermittent renewable energy resources is a big challenge which needs to be solved along with the development of renewable energy. Besides, how to address the variable electricity demand cycles is another unsolved issue which has existed for years [3,4].

To solve the two problems mentioned above, different energy storage technologies such as pumped hydro, compressed-air, battery, flywheel, capacitor, supercapacitor, superconducting magnetic and TES (thermal energy storage) systems are explored and developed. Comparison of properties of energy storage technologies is presented in Table 1 [5]. Compared to pumped hydro energy storage, CAES (compressed air energy storage) with artificial vessel is less dependent on local topography; compared to battery, flywheel, capacitor, supercapacitor and superconducting magnetic, discharge time of CAES is longer, discharge loss of CAES is smaller and power rating of CAES is bigger; compared to thermal energy storage, available energy efficiency of CAES is higher because available energy of heat is very small [5]. CAES is considered as a most promising storage option due to its high reliability, environmental friendliness, economic feasibility, and safe and simple operation [2,6–8]. Usually, the compressed air is stored in caverns or artificial vessels. During peak load hours, the air is drawn from the caverns or artificial vessels, heated by fuel, expanded through turbines to produce electricity. In this way it can shave the peak demand of electricity or maintain nearly uniform levels of power generation [9]. Large-scale CAES systems are usually built in underground caverns, and they are used as auxiliary power stations in the period of peak electricity demand. The success of two operated CAES plants shows that the CAES is a reliable energy storage technology, one was built in Huntorf, Germany in 1978, and it is used mainly to provide black-start services to nuclear plant as well as provide relatively inexpensive peak power, the other was built in McIntosh, Alabama in 1991 [10].

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Nomenclature

Acronyms

CAES	compressed air energy storage
EL	electricity
PM	pneumatic motor
TES	thermal energy storage
AC	air compressor
HE	heat exchanger
SV	storage vessel
RV	regulating valve
COP	coefficient of performance

Symbols

p	absolute pressure, kPa
T	absolute temperature, K
n	polytropic exponent of compression process
k	polytropic exponent of pneumatic motor
m	mass, kg
R	gas constant for dry air, 0.287 kJ/kg/K
W	work, kJ
E	specific mechanical energy, kJ/kg
Q	heat energy, kJ
V	volume, m^3
H	heat capacity at constant pressure, kJ/K
h	specific heat capacity at constant pressure, kJ/K/kg
C	cooling capacity, kJ
c	specific cooling capacity, kJ/kg

Greek letters

π	pressure ratio
ε	heat exchanger effectiveness
η	energy efficiency
γ	ratio of specific heats

Subscripts

0	ambient condition
1	condition of compressor outlet
2	condition of heat exchanger outlet
3	condition of storage vessel outlet
4	condition of pneumatic motor inlet
5	condition of pneumatic motor outlet
ac	air compression process
ae	air expansion process
lo	loss
a	air
w	water
ic	initial condition of storage vessel
fc	final condition of storage vessel
ra	rated working condition of pneumatic motor
sv	storage vessel
om	only mechanical power
cmq	combined mechanical power and heat
tot	total
cae	air condition after adiabatic expansion process

Table 1
Comparison of properties of energy storage technologies [5].

Energy storage technology	Discharge time	Discharge loss	Power rating
Pumped hydro energy storage	1–24 h+	Very small	100–5000 MW
Compressed air energy storage	1–24 h+	Small	5–300 MW
Battery energy storage	Seconds-hours	0.1–20%	0–40 MW
Flywheel energy storage	Milliseconds–15 min	100%	0–0.25 MW
supercapacitor	Milliseconds–60 min	20–40%	0–0.3 MW
superconducting magnetic	Milliseconds–8 sec	10–15%	0.1–10 MW
Thermal energy storage	1–24 h	0.05–1%	0–60 MW

To optimize the CAES system design, in recent years, a great deal of investigations on the working characteristics of CAES have been conducted. The thermodynamic effects of air storage chamber, thermal energy storage and heat exchanger on advanced adiabatic CAES system were studied by Refs. [9,11,12]. Adiabatic CAES continues to keep the heat produced by compression, and returns it to the air when the air is expanded to generate power. Through the analysis of different configurations of adiabatic CAES, Hartmann et al. [13] indicated that two-stage adiabatic CAES configuration is deemed to have the highest efficiency. Important operating variables of adiabatic CAES and the effect of the variables on the adiabatic CAES performances were discussed by Ref. [14]. After the discussions of the economic properties of the waste heat recovery from CAES plants [15–17], the three references predicted that the thermal energy recovery of compression stage is useful to balance overall energy demand and supply. To optimize the design of storage cavern, an accurate dynamic simulation model for compressed air storage caverns was developed by Ref. [18]. The thermodynamic responses of underground cavern to charge/discharge cycles of the CAES plants were studied, and the sensitivity analysis of storage temperature and pressure was conducted by Ref. [19].

In addition, some new concepts of CAES systems were proposed. Yang et al. [20] proposed a hybrid thermal-CAES system, in which thermal energy storage units not only absorb the heat released from air compression process, but also the heat energy converted from reluctant wind power using electrical heaters. The thermodynamic analysis showed that this system can absorb much more wind power than the advanced adiabatic CAES systems with the same scale of compressors, turbines, and TES units. Wang et al. and Kim et al. [21,22] proposed a hybrid CAES system which is combined with pumped hydro storage. The hybrid system can optimize the pressure range of the cavern and extend the efficiency of the pumped hydro storage, besides it can be operated over an area which is drought and water shortages. Zhao et al. [23] put forward another hybrid energy storage system which combined adiabatic compressed air with flywheel, this system has an excellent performance on smoothing out the fluctuations of wind power in comparison with independent energy storage system. Wolf et al. [24] presented a low-temperature adiabatic CAES plant, and the plant can avoid the technical challenge of high temperature, which is not easy to handle in traditional adiabatic CAES.