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Performance assessment and optimization of a combined heat and power system based on compressed air energy storage system and humid air turbine cycle

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A B S T R A C T

Renewable energy based power sources have grown rapidly in the past few years owing to the dual constraint of climate change and pollution control. Compressed air energy storage (CAES), as a large-scale energy storage system (ESS) technology, has huge potential to manage the intermittent renewable energy based power sources effectively. However, the compression heat generated during charge and waste heat carried in turbine exhaust during discharge are not fully recuperated in current stage. A combined heat and power (CHP) system consisting of a CAES system and a humid air turbine (HAT) system is proposed to utilize the both types of heat energy. The proposed system can boost the power output, enhance performance and improve efficiency through a simultaneous supply of power and heat. The thermodynamic analysis shows that the expansion train power can be improved about 26% compared with the conventional CAES system. The parametric analysis reveals that the exergy efficiency increases with the turbine inlet temperature (TIT) of high pressure turbine (HPT) and inlet pressure of low pressure turbine (LPT), but decreases with the TIT of LPT, *L/G* ratio and dry air inlet temperature of saturator. Meanwhile, the system optimization is carried out via particle swarm optimization (PSO) to determine the maximum power and exergy efficiency conditions.

1. Introduction

The global energy conversion and supply system faces the challenge of low carbon transition under the dual constraint of climate change and pollution control. Integrating the renewable energy based power sources is one of the most promising methods to handle this challenge. However, the highly erratic and uncertainty features of renewable energy based power sources lead to a new problem on balancing the power production and consumption in power system operation, especially at a high penetration level [1].

The energy storage system (ESS) used in conjunction with renewable energy can help mitigate this negative effect effectively, which stores surplus electricity in other forms suitable for storage and releases when electricity is needed. Compressed air energy storage (CAES) system as one of the bulk energy storage technologies with high power/energy rating can be applied in large-scale renewable energy power system to provide peak shaving and load following services [2]. In effect, the CAES system can be regarded as a variation from the gas turbine cycle, in which the compression process and expansion process operate separately.

As an energy storage system, the energy conversion efficiency is an important criterion to evaluate the CAES system performance. According to the work principle of CAES system, two main parts can be further utilized to improve the system performance. The first part is the heat energy contained in the exhausted gas from turbine during the discharge process, the other one is the compression heat from the compressors during the charge process.

The world first CAES plant, i.e. the Huntorf CAES plant in Germany exhausts the high temperature flue gas from a two-stage turbine to environment without any heat recovery, resulting in a numerous wasteful heat [3]. Up to now, some works related to utilizing the waste heat from turbine exhaust to improve the conventional CAES performance have been investigated. The McIntosh CAES plant in USA, which is the second CAES plant throughout the world, configures a recuperator to absorb the heat in exhausted flue gas to preheat the withdrawn air prior to entering combustor [4]. Zhao et al. [5] employed a Kalina cycle system to convert the waste heat from exhausted flue gas in CAES system to electricity. The second law efficiency can be improved nearly 4%. On the other hand, some researches have been carried out to

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Nomenclature

d	humidity (kg/kg)
Ex	exergy (kW)
f	enhancement factor
h	enthalpy (kJ/kg)
H	vaporization heat (kJ/kg)
$\dot{I}$	exergy destruction rate (kW)
m	mass flow rate (kg/s)
p	pressure (kPa)
s	entropy (kJ/kg K)
T	temperature (K)
W	power (kW)
Δt	temperature difference (K)

Greek letters

η	efficiency
φ	relative humidity
κ	isentropic exponent
π	pressure ratio
ψ	molar friction

Subscripts and superscripts

c	compression train
ch	chemical
cold	cold medium
comb	combustor
comp	compressor
da	dry air
e	expansion train
elec	electrical
ex	exergy
gas	burned gas
ha	humid air
heat	heat
hot	hot medium
in	inlet
out	outlet
ph	physical
pump	pump
sat	saturator
tur	turbine
w	water
wb	wet-bulb temperature
vap	vaporization

Abbreviations

AC	aftercooler
CAES	compressed air energy storage
CHP	combined heat and power system
ESS	energy storage system
HAT	humid turbine cycle
HPC	high pressure compressor
HPT	high pressure turbine
IC	intercooler
LPC	low pressure compressor
LPT	low pressure turbine
RTE	round trip efficiency
TIT	turbine inlet temperature

enhance the CAES system performance by exploiting the compression heat during charging. In order to improve the system efficiency, Safaei et al. [4,6,7] designed a distributed CAES system through locating the compressors near the municipal heat load center to use the compression heat for space and water heating applications. Bagdanavicius and Jenkins [8] evaluated a compressed air energy storage combined with a district energy system (CAES-TS) using the exergy and exergoeconomic analysis. The proposed CAES-TS system utilizes the heat generated during the compression stage for district heating.

In addition, Li et al. [9] designed a CAES based trigeneration system for electrical, heating and cooling power supply, which explores both the waste heat in exhaust flue gas and compression heat. Najjar and Jubeh [10] structured a compressed air storage with humidification (CASH) system through adding a saturator to the CAES system to enhance performance. The saturator in the CASH system is applied for increasing the moisture content of withdrawn air before entering combustor. The hot liquid water used in saturator is warmed by the compression heat and waste heat in exhausted flue gas.

In fact, the integration of saturator into CAES can be regarded as a combination of humid turbine cycle (HAT) and CAES system. The HAT is an advanced power cycle proposed by Mori in 1983 [11]. The HAT system modifies the configuration of gas turbine system by adding a saturator to humidify the pressurized air from compressor. The entering hot liquid water fed into saturator comes from the recuperation of the waste heat contained in the gas turbine exhaust gas. As a consequence, the raised burned gas mass flow flowing across the turbine boosts the power generation. The HAT cycle has successfully used in the applications of solar energy [12], solid oxide fuel cell (SOFC) [13], molten carbonate fuel cell (MCFC) [14], biomass gasification plant [15] and natural gas fired plant [16].

Although the introduction of humidification tower in CAES can boost power output and improve efficiency, the outlet liquid water from saturator is still warm enough to supply heat to end-users, making a further performance improvement. The goal of this paper is to integrate a HAT cycle to CAES system to build a combined heat and power (CHP) system. During the charge process, the majority of the liquid hot water produced by recovering compression heat is stored for later utilization and the rest is sent to the heat load. During the discharge process, not only the electrical power can be enhanced by the humid air, but also the heat energy can be supplied by the outlet hot liquid water from saturator. The performance assessment and optimization of the proposed CAES–HAT based CHP system are conducted in this paper.

2. System description

The schematic diagram of the proposed CAES–HAT based CHP system is shown in Fig. 1. The proposed CHP system is designed by integrating the conventional CAES system with a HAT system, which consists of a compression train, an expansion train, an air storage cavern, a saturator, an air preheater, a water preheater and a water circulatory system. The compression train includes a low pressure compressor (LPC), an intercooler (IC), a high pressure compressor (HPC) and an aftercooler (AC) arranged in series. Similarly, the expansion train contains a high pressure turbine (HPT) and a low pressure turbine (LPT) in tandem with a configuration of combustors 1 and 2 prior to the HPT and the LPT, respectively. The water circulatory system is made up by two water