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Thermodynamic model development and performance analysis of a novel combined cooling, heating and power system integrated with trigenerative compressed air energy storage

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ABSTRACT

As an energy comprehensive utilization technology, combined cooling, heating and power (CCHP) system has received much attention in many countries. Due to the variability of users demand, the CCHP system is often running at off-design condition. CCHP system integrated with energy storage system is an efficient method to improve the off-design performance of CCHP system. A novel CCHP system with trigenerative compressed air energy storage (T-CAES) is proposed in the paper, which can meet various forms energy demand of users. A comprehensive thermodynamic model of the system has been set up, and the thermodynamic performance analysis has been done. Furthermore, a sensitivity analysis is conducted by the key parameters effected on performance of CCHP system integrated with T-CAES. The comparison of thermodynamic and economic analysis between the novel CCHP system and conventional CCHP system are carried out in application of office building. The primary energy rate of novel CCHP system is 85.57%, the primary energy saving ratio of novel CCHP system is 26.87%, and the total cost saving ratio of novel CCHP system is 30.55%. The result shows that the performance of the CCHP system integrated with T-CAES is superior to conventional CCHP system.

1. Introduction

With the rapid development of global economy, the problems of energy shortage, environmental pollution and ecological deterioration have become increasingly prominent. It is urgent to seek new technologies to solve those problems [1,2]. As an energy comprehensive utilization technology, combined cooling, heating and power (CCHP) systems have received much attention in many countries. Energy saving, fuel independency, electrical grid improvement, environmental protection and increased competitiveness of business are part of many advantages of CCHP systems [3–5].

At present, the CCHP system technology already become one of the most appealing and available energy saving measures. A lot of survey of CCHP system have been carried out, along with design, optimization, decision making, selection approach, energetic and exergetic analysis, economic analysis, operation strategy and so on [5–9]. At the same time, CCHP system has been applied in a great deal of practical engineering in the past decades. To ensure that the system can completely satisfy load of users demand, it is often connected with grid. Once a CCHP system is selected, the capacity of individual components of the system is determined, especially the prime mover. Due to the load variations of users demand, the electric load of users demand sometimes is larger than capacity of gas turbine, sometimes less than capacity of gas turbine. When electric load of users demand is greater than prime mover capacity, the electricity produced by CCHP system cannot satisfy users demand, and insufficient electricity should be purchased from grid to meet users demand. However, electric load of users demand is less than prime mover capacity, the prime mover operation deviates from design condition, the lower of gas turbine output power, and the worse of system performance. Though the CCHP system can easily, efficiently and quickly adapt to electric load variations of users demand, the prime mover of CCHP system is often under off-design operation, which can lead to deterioration on performance of CCHP system [10,11]. In order to ensure a supply of electrical energy to offset the impact of users demand fluctuation on CCHP system performance, electrical energy storage system should be considered to integrate with CCHP system [12,13].

Considering energy range, physical principles and operation time, there are various technologies of electrical energy storage, such as super-capacitors, pumped hydro, different kinds of batteries, flywheels and compressed air energy storage (CAES) and so on [14,15].Comparing with other energy storage technologies, the CAES is regarded as

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Nomenclature

Abbreviation

CAES	compressed air energy storage
CCHP	combined cooling, heating and power
T-CAES	trigenerative compressed air energy storage

Symbols

COP	coefficient of performance
c	specific heat capacity (kJ/kg·K)
Ex	exergy (kJ)
k	air specific heat ratio
LHV	lower calorific value of fuel (kJ/m^3)
$\dot{m}$	mass flow rate (kg/s)
m	mass (kg)
P	power (kW)
PER	primary energy rate
$PESR$	primary energy saving ratio
p	pressure (MPa)
$\dot{Q}$	flux of heat (kW)
Q	heat (kJ)
R	gas constant (kJ/kg·K)
T	temperature (K)
t	time (s)
V	volume (m^3)
W	work (kJ)
η	efficiency
π	pressure ratio
ρ	density (kg/m^3)
τ	temperature ratio

Subscripts

a	air
ab	absorption chiller
ac	air mass flow rate of compressor
at	air mass flow rate of turbine
b	boiler
CAR	compressed air reservoir
c	compressor
cl	cooling
cs	cold source
cp	charging process
ct	charging time
d	users demand
dp	discharging process
dt	discharging time
e	energy
ec	electric compression refrigerator
el	electrical grid
ex	exergy
f	fuel
fg	flue gas
fin	final
g	gas turbine
gab	high pressure generator of absorption chiller
h	heat
hs	heat source
hx5	heat exchanger 5
in	input
ini	initial
n	nominal
out	output
p	pressure
t	turbine
w	work
0	ambient

one of the most important and popular energy storage technology for its high reliability, flexibility, high energy-capacity, relatively low cost, long life, etc. At very beginning, CAES is as one of promising energy storage methods to compensate the intermittent and fluctuation of Renewable Energy Source based plants with electricity supply. With the development, the CAES is integrated with grid. When the electricity is in off-peak, the power from the grid is driven compressor to produce high pressure air. When the electricity is in on-peak, the high pressure air is used to drive turbine to produce power [16,17]. Although there is a great deal of research about large-scale CAES currently, only two commercial CAES plants have been applied in the world. The large-scale CAES requires suitable geographical sites for air storage, such as underground cavern, which limits the wide application. Accordingly, the micro-CAES is proposed for using artificial air reservoir to substitute underground cavern, and it can obtain more flexible application, especially for CCHP systems [18–20]. Therefore, considering the integration micro-CAES with CCHP system is a promising solution to improve performance of the system.

Recently, there are several studies about the CCHP system integrated with micro-CAES. Erren Yao et al. proposed a CCHP system based on CAES, a gas engine and an ejector refrigeration system. During off-peak time, the compressor of CAES was driven by renewable energies to compress air from atmosphere. During on-peak time, the gas engine and turbine of CAES both generate electricity. The thermo-economic optimization of the system had been investigated, and it showed that exergy efficiency about 51% were promising for practical design [21]. Afterwards, Erren Yao et al. brought up another CCHP system integrated with CAES, mainly consisted of a gas engine, a CAES and ammonia water refrigeration system, and the work principle of the system was the same as the previous system. It showed the results of multi-objective optimization and exergoeconomic analysis [22]. Yi Yan et al. presented a novel hybrid CCHP system integrated with CAES, which basically contained internal combustion engine, CAES, electric chiller and absorption chiller. The CAES received redundant power from wind turbine and photovoltaic cells and supplemented the shortfall power of users. The multi-objective optimization model with minimizing the total cost and emissions had been set up. The overall energy utilization and ability for renewable energy consumption had been improved through optimization [23]. Amin Mohammadi et al. had proposed a CCHP system integrated with CAES coupled with wind energy. The CCHP system included a gas turbine, an absorption refrigeration system and an organic Rankine cycle. Energy and exergy analysis and effect of key parameters had been carried out [24].

Above mentioned researches, the power stored in CAES of CCHP system comes from renewable resources, such as wind power and photovoltaic cells. When the power produced by CCHP system exceeds or dissatisfy the users demand, it should be considered how to deal with. Therefore, another form of CCHP system integrated with CAES had been investigated to solve the problem. The excessive power of CCHP system can be stored in CAES via compressed air during off-peak time, and the energy in CAES can be discharged to generate power during on-peak time. Xinjing Zhang et al. proposed a hybrid distributed generation with CAES and thermal energy storage, which was mainly composed of a diesel engine, an absorption chiller, CAES, thermal