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Off-design performances of gas turbine-based CCHP combined with solar and compressed air energy storage with organic Rankine cycle

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A B S T R A C T

The conventional CCHP systems often operate at part load and cause power surplus under the operation mode of power following thermal load. In order to improve the energy efficiency of CCHP systems, a novel combined cooling, heating and power (CCHP) system combined with compressed air energy storage (CAES) was proposed. However, the output power of CAES was probably not high due to the low temperature of high-pressure air at air turbine inlet. In this paper, solar energy was introduced to heat the high-pressure air from air storage cavern. For the further energy utilization of the air turbine exhaust with relatively high temperature, an organic Rankine cycle (ORC) was proposed to recover the heat carried by air turbine exhaust. To obtain the off-design characteristics of the proposed system, the typical off-design models of gas turbine, compressor and air turbine were built through the performance equations of each component. The sensitivity analysis on S-CAES with ORC system was investigated to evaluate the effects of several key parameters on its performances. The results show that the energy efficiency and exergy efficiency of S-CAES with ORC system reach 98.30% and 68.94% respectively, in a whole round trip cycle. A case study of the proposed system in a typical hotel building with 180,000 m^2 located in South China concludes that, compared with the conventional CCHP, the energy consumption can be reduced by 124.78 GJ, 33.82 GJ and 62.1 GJ and the average energy efficiency increased by 7.72%, 1.47% and 3.61% in summer, transition season and winter typical days, respectively.

1. Introduction

The energy consumption has risen greatly with the development of industry and the increment of population in the last 30 years [1]. Almost 33% of the global total final energy is consumed in buildings in 2013 for cooling, heating, cooking and other purposes [2]. Consumption of this amount of energy brings out environment and economic problems inevitably. Because the combined cooling, heating and power system (CCHP) can convert 75–80% of the fuel source into useful energy [3], CCHP is considered as one of the most promising solutions to reduce energy consumption in buildings [4].

CCHP system has obvious advantages in energy utilization, which can dramatically reduce the primary energy consumption and improve the energy efficiency [5], and produce low greenhouse gas emissions as well [6]. In China, approximately 80% of the total installed capacity of distributed energy system (DES) was driven by small or micro gas turbines by the end of 2015, according to the report from China Gas Association [7].

CCHP systems usually operate under two modes, i.e., FTL (power following thermal load) and FPL (thermal following power load). Generally, FTL mode is more helpful to increase the thermal utilization efficiency. However, the power surplus is inevitable in the case of small heat-to-electric ratio on the demand side, even in an optimal CCHP configuration in FTL mode. Therefore, many energy storage systems were introduced in CCHP system. Liu and Chen [8] proposed a CCHP system combined with ground-source heat-pumps and thermal energy storage (TES), with an advantage in reduction by 15.8% of the total installed cooling capacity and 37.5% of the total installed heating capacity of the CCHP system. Jiang and Zeng [9] established a theoretical system to evaluate the performance of CCHP systems with energy storage units. Li and Wang [10] presented an energy storage system which stored excessive energy in the form of compressed air and thermal heat in a CCHP system. The average comprehensive efficiency was found to be much higher than the conventional CCHP system, arriving at 50% and 35% in winter and summer, respectively. Many of these systems refer to store thermal energy, while few store surplus electric power directly, although the latter has obvious advantages in FTL operation strategy. Also, compressed air energy storage system (CAES) is superior to other electric storage system in longer lifetime, lower cost and higher efficiency.

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Nomenclature

A	area (m^2)
C	correction coefficient; heat capacity rate (W/K)
c	specific heat at constant pressure [kJ/(kg·K)]
c_1, c_2, c_3, c_4	compressor parameters
E	energy value (kW), exergy value (kW)
G	flow rate (kg/s)
H	loads of HRSG (kW)
h	enthalpy (kJ/kg)
HRSG	heat recovery steam generator
K	energy storage/release ratio
I	solar radiation intensity (W/m^2)
m	flow rate (kg/s); compressor parameters
n	rational speed (rpm)
NTU	numbers of transfer unit
P	power (kW), pressure (MPa)
p	compressor parameters
Q	thermal energy (kW)
T	temperature (K); power (kW)
t	turbine parameters
U	heat transfer coefficient [$W/(m^2 \cdot K)$]
W	work (kW)

Greek letters

α	turbine coefficient
β	partial load factor of chiller
γ	partial load factor of HRSG
δ	transmission loss
ε	effectiveness of heat exchanger
η	efficiency
π	pressure ratio; expansion ratio
χ	ratio of minimum heat capacity rate to the maximum

Subscript

AC	absorption chiller
air	air
am	ambient temperature
AR	absorption chiller under part loads
average	average efficiency
c	compressor
CCHP	combined heating, cooling, power
coll	solar collector
con	conventional
cool	cool
cp	charge process
cside	cool side
dp	discharge process
e	electric
ec	the increment in energy efficiency
elec	electric
ex	exergy efficiency
f	fuel
gfb	gas-fired boiler
grid	power grid
gt	gas turbine
heat	heat
HRSG	heat recovery steam generator
hside	hot side
i	time
in	inlet; input
min	minimum
max	maximum
oil	thermal oil
ORC	Organic Rankine cycle
ORC fluid	working fluid of ORC
ORC pump	pump of organic Rankine cycle
ORCt	turbine of organic Rankine cycle
out	outlet; output
power	power
pro	proposed
s	solar
S-CAES-ORC	solar and compressed air energy storage with ORC
solar	solar energy
t	turbine
th	energy efficiency; thermal
wi	cooling water inlet
ws	without consideration of solar
0	design state

superscript

*	normalized parameter
–	divided by design value
κ	adiabatic coefficient
s	isentropic

So far, two commercial CAES plants have been built. One is Huntorf plant of 290 MW, which has operated since 1978 in Germany; and the other is McIntosh plant with 110 MW in America, which has operated since 1991 [11]. Japan has built a CAES test station with a certain size. In addition, France, Italy, Russia, Korea, Switzerland and other countries are also developing CAES power stations vigorously [12]. Currently, the researches about CAES mainly focus on the methods for improving its efficiency through simulation, improving the energy utilization rate through combining the CAES with other systems and proposing new compressed air energy storage technology.

Many concepts of CAES systems have been proposed and studied nowadays. Seymour [13] proposed an ocean compressed air energy storage system (OCAES) to keep compressed air at a constant high pressure. Lv and He [14] described a CAES system for tri-generation, where, the prime mover of this system was an electromotor and was different from traditional tri-generation. In a liquid air energy storage system (LAES) depicted by Morgan and Nelmes [15], the cycle efficiency was greatly improved by recycling and storing thermal energy between the charging and discharging parts of the cycle. Adriano and Li [16] developed a dynamic simulation of adiabatic compressed air energy storage (A-CAES) with integrated thermal storage system (THS). It achieved system efficiency in the range of 60–70% when the THS operated with a storage efficiency above 90%.

For the further improvement of CAES efficiency, some bottom cycle has been introduced into CAES system. Zhao and Wang [17] added a Kalina cycle to CAES system to recover the waste heat from turbine exhaust. Amin and Mohammad [18] joined an organic Rankine cycle to CAES system to recover the heat carried by turbine exhaust and produced more power. Additionally, some new energies were also introduced to CAES. Arabkoohsar and Machado [19] presented a CAES unit equipped with a solar heating system in a photovoltaic (PV) plant. Zhao and Dai [20] proposed a CAES system coupled with wind energy.

Recently, some new ideas about small-scale CAES coupled with CCHP have been put forward. Amin and Mohammad [18] developed a CCHP system coupled with wind energy and CAES to provide cooling, heating and power simultaneously, with a round trip energy efficiency