Energy Conversion and Management 173 (2018) 271–282

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Ability of adjusting heating/power for combined cooling heating and power system using alternative gas turbine operation strategies in combined cycle units

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ARTICLE INFO

Keywords:
Combined cooling heating and power (CCHP)
Exergy and energy
Gas turbine combined cycle (GTCC)
Operation strategy
Peak power shaving

ABSTRACT

Gas turbine combined cycle (GTCC) based combined cooling, heating and power (CCHP) or combined heating and power (CHP) system driven by natural gas is encouraged to set up for district heating/cooling demand in China due to the clean and efficient energy conversion. This paper presents a GTCC based CCHP system, which consists of a heavy-duty gas turbine, triple-pressure heat recovery steam generator (HRSG), steam turbines, heat exchanger and absorption chiller. Turbine inlet temperature (TIT) strategy and inlet guide vanes (IGV) strategy for the gas turbine are adopted to access the part load performance. The energy distribution and exergy destruction of the CCHP system are investigated under different gas turbine loads. The primary energy saving rate (PESR) and carbon dioxide emission rate (CDER) are set up to evaluate the system at various gas turbine loads and steam extraction ratios. The ability of shaving peak power for the system is investigated. The results show that IGV plays a role in increasing the steam turbine power output and reducing the exhaust heat in HRSG but causes more exergy destruction in the steam turbine expansion process. The PESR and CDER have been enhanced as the steam extraction ratio increases for the same gas turbine load. The IGV strategy reinforces the part-load performance of the CCHP system. For instances, the PESR has been enhanced from 0.2409 to 0.3108, and CDER has been strengthened from 0.8274 to 0.8465 by the IGV strategy at half of gas turbine load and without steam extraction. For the same heating load, both PESR and CDER are enhanced by the IGV strategy. The ability of supplying heating is deteriorating as the decrease in TIT. The ability of shaving peaking power is going to be deteriorated as heating load increases. For the small heating load, like 50 MW, the advantage of the IGV strategy is prominent, the PESR and CDER is advanced 5.81% and 1.48% respectively by the IGV strategy.

1. Introduction

The population growth and technological advancement exhibited in the last two decades along with the desire for higher life standards and comfort levels have led to an unprecedented increase in the energy consumption worldwide [1]. Inefficiencies and environmental issues associated with conventional power plants provide the thrust for developments in “on-site” and “near-site” power generation [2]. Combined heating and power (CHP) systems and combined cooling, heating and power (CCHP) systems have become the core solutions to improve the energy efficiency and to reduce greenhouse gas (GHG) emissions [3–5]. Primary energy saving rate (PESR) representing the energy saving against the conventional separation production (SP) system is selected as the indices to evaluate CCHP systems widely [6–9]. In addition, carbon dioxide emission reduce (CDER) is another hot issue nowadays, which is likely to be required to comply with the obligations of the Kyoto protocol on GHG emissions [10].

Two of the most common operation strategies for CCHP system are following electricity load (FEL) and following thermal load (FTL) [11,12]. The least surplus electricity would be produced in the FEL strategy; on the contrary, the least surplus heating would be generated in the FTL strategy. However, the two strategies are so simple that surplus energy is produced considerably. Therefore, some novel strategies were proposed to relieve the uneconomical status. Smith et al. [13] introduced a load-following operational method. The distribution of electricity and heat was divided into seven cases, and the operational strategy was described as five conditions in electricity-heat diagram to minimize the amount of excess electrical or thermal energy produced by the CHP system. Zheng et al. [14] presented an operation strategy named as minimum distance to optimize strategy of CCHP system. The

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https://doi.org/10.1016/j.enconman.2018.07.062
Received 6 April 2018; Received in revised form 26 June 2018; Accepted 21 July 2018

Nomenclature

Acronyms

CCP	combined cooling and power
CCHP	combined cooling heating and power
CDER	carbon dioxide emission reduction
CHP	combined heating and power
COP	coefficient of performance
ECO	economizer
EVA	evaporator
FEL	following electricity load
FTL	following thermal load
FRG	re-injecting strategy
GHG	greenhouse gas
GTCC	gas turbine combined cycle
GTCCICA	inlet air cooling for gas steam combined cycle power plant
HP	high pressure
HRSG	heat recovery steam generator
IAT	inlet air throttling
IGV	inlet guide vane
IP	intermediate pressure
LHV	lower heating value
LP	low pressure
PESR	primary energy saving rate
RH	reheater
SH	superheater
SP	separation system
TCA	turbine cooling system
TET	turbine exhaust temperature
TIT	turbine inlet temperature
VAN	variable area nozzle

Symbols

$\dot{C}$	cooling load flow, kW
$\dot{E}x$	exergy destruction, kW
$\dot{F}$	fuel energy flow, kW
N	rotational speed, rpm
T	temperature, °C
$\dot{Q}$	heat flow rate, kW
$\dot{W}$	work transfer rate, kW
h	enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
n	count number
n_c	number of compressor stages
n_t	number of turbine stages
r	ratio
s	entropy, kJ/(kg·K)
ε	exergy, kJ/kg
μ_{CO2}	carbon dioxide factor
η	efficiency

Subscripts

D	destruction
Q	thermal energy
a	air
ac	absorption chiller
aux	auxiliary
c	compressor
ca	cool air
cchp	combined cooling heating and power
cd	carbon dioxide
chem	chemical
con	condenser
com	combustion
d	demand
e	electricity
ext	extraction
exh	exhaust
f	fuel
g	gas
gear	gear box
gen	power generation unit
gt	gas turbine
he	heat exchanger
hp	high pressure
hpr	heat to power ratio
hrsg	heat recovery steam generator
hw	hot water
i	counter
ip	intermediate pressure
in	inlet
lp	low pressure
mech	mechanical
ng	natural gas
out	outlet
pe	primary energy
sp	separation system
st	steam turbine
t	turbine
w	water/steam
0	design condition

operation points were chosen between the FEL and FTL strategy, in which the least excess energy is produced and supplemented. So the CCHP system can operate at a relatively high performance level at the expense of some surplus energy. Compared with conventional FEL and FTL strategies, these novel operation strategies are flexible and adaptable, which leads to a better matching performance of a CCHP system. But, most of the literatures coupled the prime mover with absorption chiller or heat exchanger directly, in which the range of heat to power ratio the system can offer is very limited. Once the heating/power is mismatched between provider and consumers, surplus energy is inevitable to be waste, since surplus electricity is not allowed to be sold back to the national grid or the surplus heating cannot be stored without the additional investment in thermal storage components for these conventional small-scale CCHP systems. So, it is hard to fit the heat to power ratio precisely under the fluctuating load demands.

Moreover, the above studies were mainly focusing on the small-scale gas turbines as the prime mover, few studies concentrated on a heavy-duty gas turbine. Sayegh et al. [15] pointed out that gas turbine combined cycle (GTCC) power plants are suitable for covering large proportion of distributed heating system demands. Wu et al. [16] considered the low-energy-grade heat sources in GTCC as a way to drive heating/cooling components, such as low-pressure steam extracted from a steam turbine. Generally, GTCC based CHP or CCHP system belongs to large-scale cogeneration system and the surplus electricity is allowed to be sold back to the national grid in terms of the relative policy in China. Following thermal load and considering peak power shaving are the two main purposes to set up this type of cogeneration plants. Hence, a GTCC based CCHP system in which steam is extracted from exhaust of IP cylinder to drive heating/cooling components is proposed in this study. In the system, surplus energy can be avoided