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Off-design heating/power flexibility for steam injected gas turbine based CCHP considering variable geometry operation

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ABSTRACT

Owing to the fluctuating energy demand from consumer side, combined cooling, heating and power (CCHP) system operates at off-design condition most of the time. Moreover, the heating/power surplus is a common problem for the conventional CCHP system. In order to improve the precision of performance prediction and partly relieve the heating surplus, a steam injected gas turbine (STIG) based CCHP system considering off-design condition is proposed. The system consists of a steam injected gas turbine, double-pressure heat recovery steam generator (HRSG), heat exchanger, absorption chiller and auxiliary boiler. Two different operation strategies including turbine inlet temperature (TIT) strategy and variable guide vanes (VGVs) strategy, are illustrated to access the part-load performance of gas turbine and CCHP system. The performance indicators, like primary energy saving rate (PESR), primary energy rate (PER) are set up to evaluate the thermodynamic performance of the CCHP system. A simple gas turbine (SGT) based CCHP is chosen as the comparative object and two energy demand cases are selected to validate the advancement. The results show that VGVs strategy does not improve the gas turbine efficiency significantly but bring more exhaust heat into HRSG. VGVs strategy advances the heating to power ratio, PESR and PER around the whole part load condition, i.e., PESR is elevated from 0.3254 to 0.3743 by VGVs at the half of gas turbine load without injected steam. Injecting steam is a more effective way to improve gas turbine efficiency rather than using VGVs strategy while implementing same gas turbine load. Steam injection does not always enhance the PESR, but the PER keeps decreasing as injected steam flow increases around the whole load. STIG based CCHP system with VGVs operation strategy gets the best performance among these studied approaches, and the maximum enhancement of PESR reaches 0.3171 in the proposed energy demand cases.

1. Introduction

Availability of sources and global warming are the two main concerns for the sustainability of energy production in the future [1]. Cogeneration system is an alternative way to mitigate negative environmental impacts and improve energy utilization efficiency simultaneously, because these systems lead to higher global efficiencies in comparison with stand-alone generation in large power plants [2,3]. Gas turbine unit is used for on-site power generation, usually in combination with process heat production, such as, hot water and steam, which is known as combined heating and power (CHP) [4]. When the cooling air is further required by the users, CHP is evolved into combined cooling, heating and power (CCHP) system, or referred to as tri-generation system in some literature. Thus, CCHP can be defined as a more extensive concept than CHP [5].

Due to the necessary of suppressing or compensating the power decrease of gas turbines caused by the ambient temperature rise, or further utilizing the waste heat from turbine exhaust, inlet air cooling or/and humidification technologies are regarded as the most technically viable option. One group of humidification technologies deal with the air at the compressor inlet. Inlet fogging [6] or wet media evaporative cooling [7] for gas turbine engines is a considerable way to compensate the power output due to the ease of installation and the relatively low first cost, however, these technologies become less effective as the relative humidity of the inlet air increases. Therefore, chillers [8] were used to cope with high temperature and relative humidity. They investigated an

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Nomenclature

Acronyms

AP	approach point
CCP	combined cooling and power
CCHP	combined cooling heating and power
CHP	combined heating and power
ECO	economizer
EVA	evaporator
FEL	following electric load
FGR	flue gas re-injecting
GT	gas turbine
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
LHV	lower heating value
LP	low pressure
PER	primary energy rate
PESR	primary energy saving rate
PP	pinch point
SGT	simple gas turbine
SH	superheater
SP	separate system
STIG	steam injected gas turbine
TIT	turbine inlet temperature
VGVs	variable guide vanes
VSVs	variable stator vanes

Symbols

α	angle
δ	expansion ratio
ε	pressure loss coefficient
η	efficiency
π	pressure ratio
ϕ	cooling effectiveness
Δ	difference
a	coefficient for compressor or turbine model
C	coefficient for turbine blade cooling
c_p	constant pressure specific heat
F	fuel energy consumption
h	specific enthalpy
k	length of kinetic mechanism
l	length of kinetic mechanism
m	mass flow rate
N	rotational speed
n	count number
PF	pattern factor
Q	heat
r	ratio
T	temperature
W	mechanical power

Subscripts

ac	absorption chiller
aux	auxiliary boiler
ave	average
b	blade
c	compressor
cl	cooling flow
com	combustion
corrected	corrected parameters
e	electricity
exh	exhaust
f	fuel
g	gas
grid	national grid
gt	gas turbine
he	heat exchanger
hrsg	heat recovery steam generator
hp	high pressure
hpr	heating to power ratio
hrsg	heat recovery steam generator
hpsh	high pressure superheater
hw	hot water
i	count for compressor stage
in	inlet
j	count for turbine stage
lp	low pressure
lpsh	low pressure superheater
max	maximum
out	outlet
ref	design condition
sj	steam injection
sp	separation system
t	turbine
w	water/steam

analytical method for applicability evaluation of gas turbine combined cycle inlet air cooling (GTCCIAC) with absorption chiller (inlet chilling) and saturated evaporative cooler (inlet fogging). Their results show that the applicability of GTCCIAC with chilling and fogging depends on the design economic efficiency of GTCC power plant. Inlet fogging is superior in power efficiency at ambient temperature range of 15–20 °C whereas absorption chiller is preferable in the zones with ambient temperature beyond 25 °C and relative humidity beyond 0.4. All in all, this type of humidification technology is more dependent on environment condition, which gets more benefits in the high temperature and low relative humidity.

The other group of humidification technology is increasing the mass flow through the turbine nozzle by re-injecting steam into the combustion chamber, which is known as steam injected method. Meanwhile, high possibility of reducing NOx is an additional advantage for the method. Shukla et al. [9] evaluated steam injected gas turbine (STIG) based power plant with inlet evaporative cooling. They investigated the combined effect of inlet evaporative cooling, steam injection and film cooling on the power augmentation of simple gas turbine (SGT) cycle. Kayadelen et al. [10] presented the performance and environmental impacts for the steam injected gas turbine cycles. Selwynraj et al. [11] analyzed the exergy and annual exergetic performance for a solar hybrid STIG cycles. These studies are mainly focusing on the gas turbine itself, investigating the effects of steam to air ratio, pressure ratio on the performance of gas turbine. However, the waste heat is not always utilized sufficiently in the various steam to air ratios. The surplus heating except the injected steam should be further considered from views of improving energy utilization. Integrating the STIG into a CHP or CCHP is an optimal method to improve the energy utilization rate, since the surplus heating can be adopted to satisfy