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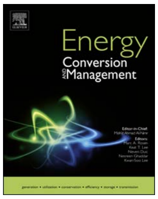

Performance analysis of partially recuperative gas turbine combined cycle under off-design conditions

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ABSTRACT

A partially recuperative gas turbine combined cycle (GTCC^{pr}) is proposed in this paper to improve the off-design performance of power plants. The performance coupling with a new operation strategy is also analyzed. In the proposed GTCC^{pr}, the gas flow at the outlet of the turbine is divided into two streams, and only a part of exhaust gas from the turbine is used to preheat the outlet air of the compressor. Exhaust gas streams from the recuperator are mixed with flue from the second reheater at the inlet of the first reheater to achieve similar temperature level. Specifically, the fraction of exhaust gas that preheats air can be changed to adjust the load of the combined cycle. The PG9351FA gas turbine unit is selected as the reference unit for comparison. Then, the design/off-design characteristics of the two cycles are compared and analyzed with the same turbine initial temperature. Results indicate that the partially recuperative GTCC^{pr} running with the new operation has better off-design performances than the reference unit with approximately 1.7% maximum difference of efficiency. At the design point, the exhaust gas used for partial recuperation only accounts for 10% of the total mass, and the effect of recuperation is not evident. Therefore, the two cycles possess nearly similar output and efficiency. The efficiency of partially recuperative GTCC^{pr} is nearly unchanged with the increasing recuperative mass fraction, which changes its specific power to adjust the load. At low loads, with decreasing turbine exhaust gas temperature, the efficiency improvement also decreases due to the partial recuperation. A comprehensive comparison with the reference unit revealed that GTCC^{pr} with the proposed "recuperation adjustment" method can maintain a higher off-design efficiency and slightly lower design power output compared with the conventional cycle. Specific power adjustment of recuperation is one of the efficient methods for load adjustment, and GTCC^{pr} is one of the best options.

1. Introduction

Gas turbines have been the focus of increasing attention due to their high thermodynamic efficiency, low pollution, high reliability, and a few other advantages. With the rapid development of gas turbines in recent decades, the compressor pressure ratio is increased from 12.3 to 23, and the turbine initial temperature are increased from the beginning of 1204 °C to more than 1436 °C, gradually [1]. Consequently, the exhaust gas temperature of the turbine continuously increases. A steam cycle (usually called bottoming cycle), which comprises heat recovery steam generator (HRSG) and several steam turbines, are installed to efficiently utilize this part of the waste heat [2]. The gas turbine and steam cycle are coupled with each other in a cyclic mode, that is, the gas turbine combined cycle.

Detailed thermodynamic analysis and optimizations for combined cycles have been extensively carried out, including studying the factors that may affect the performance and adopting reasonable operation regulation. A parametric study of the new generation of prospective gas turbine units showed that cooling air flow ratio, turbine initial temperature and compression ratio were significant for further enhancing the performance [3]. The effects of ambient temperature and compression ratio on the performances of the combined cycles with different configurations are analyzed, including the regenerative gas turbine combined cycle [4]. The gas turbine power output is found to be lowered as the ambient temperature rises, because the air density falls and the inlet mass flow through the gas turbine is reduced [5,6]. The gas turbine combined cycle also often runs at partial load condition to satisfy the power grid demand. Therefore, various methods have been applied to maximize the gas turbine performance under off-design conditions, including the regulation of compressor inlet guide vane (IGV or VIGV or VGV), variable speed, and variable turbine geometry adjustment. Aguilar et al. [7] investigated the effects of several

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Nomenclature

Symbols

A	area [m^2]
K	constant
h	enthalpy [kJ/kg]
n	rotational speed [r/min]
m	mass flow rate [kg/s]
p	pressure [MPa]
q	thermodynamic parameter, defined as the ratio of C to UA
T	temperature [K]
c_P	specific heat at constant pressure [J/(kg K)]
C	heat capacity [J/K]
U	overall heat transfer coefficient [W/(m^2 K)]
ΔT	log-mean temperature difference
Δp	pressure loss [kPa]

Greek Letters

α	recuperative gas mass fraction
β	vane outlet absolute flow angle
ϕ	flow coefficient
ε	recuperator effectiveness
ψ	pressure coefficent

Subscripts and superscripts

a	air
d	design condition
g	gas
x, y, z, k	exponent
in	inlet
out	outlet

Acronyms

CO	compressor
CC	combustion chamber
GTCC^{pr}	partially recuperative gas turbine combined cycle
CP	condensate pump
EC	economizer
EV	evaporator
EGT	exhaust gas temperature
FP	feed water pump
GT	gas turbine
HP	high pressure
HPT	high-pressure steam turbine
HRSG	heat recover steam generator
IGV	inlet guide vane
IP	intermediate pressure
IPT	intermediate-pressure steam turbine
LP	low pressure
LPT	low-pressure steam turbine
RH	reheater
RE	recuperator
RP	recycle pump
SH	surperheater
TIT	turbine initial temperature

operation strategies on unit efficiency and energy-saving potential for heat and power cogeneration, and the turbine variable area nozzle (VAN) method showed the best results in terms of efficiency without a wide regulation capacity, while VGV adjustment shows best results in the regulation capacity with second best efficiency. In [8,9], authors proposed simulations of gas turbine using IGV/VIGV regulation for performance analysis or for the accuracy and fidelity of gas turbine models.

Various gas turbine units with new cycles or scheme, such as recuperative cycle, reheat cycle, and intermediate cooling cycle, are also being developed. Reheat, intermediate cooling, and single, and double shaft simple cycles are studied [6], in which the thermal efficiency of the reheating unit is the highest. Pelster et al. [10] investigated the effects of steam injection, intermediate cooling, and supplemental firing on the 50 MW combined cycle unit, these methods can allow engines to run at a high pressure ratio and combustion temperature with a low turbine exhaust temperature.

Increasing attention has been provided to recuperative gas turbines due to their excellent performance. With an additional heat exchanger commonly known as the recuperator, the air from the compressor is preheated by high-temperature turbine exhaust gas, which increases its temperature into the combustion chamber and allows fuel saving. Lee et al. [11] analyzed the influence of water and steam injection on the performance of a recuperated cycle microturbine and presented that the injection of steam at the recuperator inlet was most promising in terms of power generation efficiency. A meso-scale gas turbine with 8 kW design power output with a radial configuration recuperator is constructed and the thermal generation efficiency is expect to be improved by 25–30% [12]. Franco and Casarosa [13] studied the peak thermal efficiency of the units with different coupled methods including recuperation, reheat and intermediate cooling for heavy duty gas turbine cycle. The thermo-economic analysis for three different size intercooled reheat gas turbines with and without recuperation was performed in heat and power cogeneration applications [14]. The recuperated gas turbine with organic Rankine cycle bottoming cycle is proved to have better performance than the gas turbine with steam Rankine combined cycle [15]. Bassily [16] analyzed the performance of the recuperated gas-reheat combined cycle with HRSG optimization, and the new cycle efficiency is increased by 1.18–3.16 percentage points compared with the commercially-available combined cycle at the same value of turbine initial temperature. The performance of recuperative combined cycles are studied, in which both air and fuel are considered to be preheated by the turbine exhaust combining the impact of steam injection [17,18]. Kim and Hwang [19] analyzed the performance characteristics of recuperative gas turbine cycles of single- shaft and two-shaft at part-load conditions with various operation strategies. Carapellucci and Giordano [20] established the recuperative gas turbine model using GateCycle software and evaluated the influence of operation parameters on the performance, finding that recuperation reduce the power output but can improve the thermal efficiency. Rovira et al. [21] analyzed and optimized several configurations of combined cycle gas turbines using a partially recuperative gas turbine, and the results showed that the optimal recuperative mass fraction is located at roughly 90% in nearly all cases.

For recuperative combined cycles, the impact of recuperation on the off-design performance needs further study, especially for partially recuperative gas turbine. This study aims to improve the off-design thermal efficiency of a combined cycle through partial recuperation. A recuperated combined cycle is designed with the flow diagram and its main parameters considering the limited size and pressure drop of the heat exchangers. A dual-pressure HRSG, rather than a triple-pressure type, is adopted by considering the impact of the recuperator. A new operation strategy is proposed which is recommended to other recuperated combined cycle performance at variable working conditions. The thermodynamic analysis is carried out through modeling and simulation to prove the efficiency improvement of this partially