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Thermodynamic analysis of combined cycle under design/off-design conditions for its efficient design and operation

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ABSTRACT

To achieve a highly efficient design and operation of combined cycles, this study analyzed in detail the off-design characteristics of the main components of three combined cycles with different compressor pressure ratios (PRs) based on real units. The off-design model of combined cycle was built consisting of a compressor, a combustor, a gas turbine, and a heat recovery steam generator (HRSG). The PG9351FA unit is selected as the benchmark unit, on the basis of which the compressor is redesigned with two different PRs. Then, the design/off-design characteristics of the three units with different design PRs and the interactive relations between topping and bottoming cycles are analyzed with the same turbine inlet temperature (TIT). The results show that the off-design characteristics of the topping cycle affect dramatically the combined cycle performance. The variation range of the exergy efficiency of the topping cycle for the three units is between 11.9% and 12.4% under the design/off-design conditions. This range is larger than that of the bottoming cycle (between 9.2% and 9.5%). The HRSG can effectively recycle the heat/heat exergy of the gas turbine exhaust. Comparison among the three units shows that for a traditional gas-steam combined cycle, a high design efficiency results in a high off-design efficiency in the usual PR range. The combined cycle design efficiency of higher pressure ratio is almost equal to that of the PG9351FA, but its off-design efficiency is higher (maximum 0.42%) and the specific power decreases. As for the combined cycle with a design PR of 12.73, the decrement of the efficiency under the design/off-design conditions is in the range of 0.20–0.39%, however, its specific power increases. Thus, for the efficient design of a combined cycle, its optimal efficiency and maximum specific power, instead of that of the topping cycle, should be considered. For the operation strategy, the performance of the topping cycle should be kept at a high level first (the turbine inlet temperature should be as high as possible), followed by the high setting of the turbine exhaust temperature.

1. Introduction

Gas turbines own many advantages, including rapid startup, high thermodynamic efficiency, and excellent load regulating capacity. Heavy-duty gas turbines, in particular, are developing rapidly, as evidenced by the continuous increase in their design pressure ratio (PR) and turbine inlet temperature (TIT) and the improvement in their efficiency and power output [1]. With the increase in the gas turbine exhaust parameters, the pattern of heat recovery steam generators (HRSGs) has developed from a single-pressure reheat to a dual-/triple-pressure reheat, so that the gas turbine exhaust heat can be recycled effectively [2].

Thermodynamic analysis and optimization for Brayton cycles [3–5] and combine cycles [6] have been widely investigated in previous literatures under design condition. However, the combined cycle gas turbine (CCGT) often runs at partial load conditions because it is frequently constrained to peak regulation in a power grid. Thus, investigating CCGT off-design thermodynamic performance is necessary. The off-design performance prediction of gas-steam combined cycle depends on the off-design modelling of each component of overall thermodynamic system. Therefore, the off-design simulation methodologies of main components of gas-steam combined cycle should be discussed and analyzed.

The compressor is the “heart” of a gas turbine, and its off-design performance prediction is vital. The traditional stage stacking method is often applied to predict the performance of multi-stage axial flow compressors with geometry angle variations [7–10]. Kim et al. [11] proposed an improved method that

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Nomenclature

A	area [m^2]
h	enthalpy [kJ/kg]
L	theoretical air quantity [kg/kg]
n	rotational speed [r/min]
m	mass flow [kg/s]
Ma	Mach number [–]
PR	pressure ratio [–]
p	pressure [MPa]
$Q_{\mathrm{ar,net,p}}$	lower heating value of the fuel [kJ/kg]
R	gas constant
T	temperature [K]
Y	constant
Δp	pressure loss [kPa]

Greek letters

α	absolute flow angle
β	excess air coefficient
δ	expansion ratio
ϕ	flow coefficient

$\varphi = (\gamma - 1)/\gamma$

γ	specific heat ratio
η	efficiency
κ	comprehensive parameter
σ	constant
ς	mixing loss coefficient
ψ	pressure coefficient

Subscripts and superscripts

0	environment condition
2	compressor outlet
3	combustion chamber outlet
a	air
c	compressor,
cc	combustion chamber
ca	cooling air,
d	design condition
f	fuel
g	gas
in	inlet
opt	maximum efficiency points
t	gas turbine
$*$	stagnation parameter

Acronyms

C	compressor
CC	combustion chamber
CCGT	combine cycle gas turbine
CP	condensate pump
EV	evaporator
FP	feed water pump
GT	gas turbine
HP	high pressure
HRSG	heat recover steam generator
IGV	inlet guide vane
IP	intermediate pressure
LP	low pressure
ORC	Organic Rankine Cycle
PR	pressure ratio
RH	reheater
RP	recycle pump
SH	surperheater
TIT	turbine initial temperature
TET	turbine exhaust temperature
TEF	turbine exhaust flow

incorporates governing equations and stage characteristics, can calculate all inter-stage variables simultaneously, and evaluates the off-design performance of various multi-stage compressors. In recent years, to improvement the off-design performance prediction accuracy of gas turbines, various mathematical methods adopted to generate the compressor map have attracted remarkable attention [12,13]. Tsoutsanis et al. [14] proposed a novel compressor map tuning method to improve the accuracy and fidelity of gas turbine models for performance prediction and diagnostics in steady-state and transient conditions. The off-design model of turbines is often based on the Stodola equation or Flugel formula [15], which can be found in many studies on the off-design performance prediction of gas turbines or combined cycles.

HRSG off-design modelling mainly focuses on the overall heat transfer coefficient calculation methods. The relatively simplified methodology, which only relates to gas turbine exhaust mass flow and temperature, is applied in Refs. [16,17]. For another similar overall heat transfer coefficient formula, it is affected by gas turbine exhaust temperature, mass flow rate, and pressure [18]. The relationship between the overall heat transfer coefficient and the thermodynamic parameters of gas/(water, steam) sides was also described for each heating surface [19,20]. Ganapathy [21] proposed an HRSG off-design performance prediction method, in which relatively detailed thermodynamic design parameters of HRSG and off-design gas turbine exhaust parameters (e.g., temperature, flow, gas composition, and several physical properties) are considered in estimating the overall heat transfer coefficients of different heating surfaces. In addition, Zhang et al. [22] proposed concise semi-theoretical, semi-empirical formulas to predict the off-design performance of the bottoming cycle of the gas-steam turbine combined cycle. The off-design characteristics of steam turbines, including off-design performance prediction [23,24] and cylinder efficiency calculation [25], were also studied.

To achieve relatively high design/off-design efficiencies of power plants, the thermodynamic performance of gas turbine/combined cycle with different equipment/system configurations and various operation strategies are analyzed comprehensively and corresponding thermodynamic systems were optimally integrated. Goodarzi [26] investigated a new regenerative Brayton cycle and the results shown that the new regenerative Brayton cycle has higher thermal efficiency than the original one at the same pressure ratio, and also lower heat absorption and exhausted heat per unite output power. The influence of shaft configurations on the design/off-design point performances of simple, regenerative, and intercooled-regenerative gas turbines was also studied [27]. For a recuperated gas turbine cycle, a single-shaft configuration with variable speed operation is the best combination, followed by the double-shaft configuration with a variable area nozzle (VAN) [28]. For alternative recuperated gas turbine cycles with divided turbine expansion, a single-shaft configuration is less sensitive to compressor PR in comparison with a double-shaft configuration, and variable speed control is recommended [29]. The variable inlet guide vane modulation positively affects the single-shaft combined cycle performance, especially at high load ranges,