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Studying the effects of combining internal and external heat recovery on techno-economic performances of gas–steam power plants ☆

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ABSTRACT

Thermodynamic regeneration is regarded as a conventional technique to enhance the efficiency of gas turbines, by means of an internal recovery of waste heat from exhaust gases. In combined cycle power plants (CCGTs), only external heat recovery is usually applied, in order to achieve the highest steam cycle power. Combining internal and external recovery, while decreasing the power plant rated capacity, has the potential to boost the efficiency of CCGTs.

This paper aims to examine the effects of thermodynamic regeneration on steam–gas power plants from the energy and economic point of view. First, a dual pressure combined cycle based on a regenerative gas turbine is designed using GateCycle software and effects on energy and economic performances are evaluated varying gas turbine operating parameters. Then, an off-design simulation of different CCGT configurations is carried out, in order to evaluate the power increase achieved by-passing the regenerator and its effects on efficiency and cost of electricity.

The study has shown that the improvement of energy and economic performances of regenerative CCGTs is more and more pronounced with the increase of turbine inlet temperature (TIT). Additionally, regeneration enhances the power plant operational flexibility, allowing to obtain a 30% power increase with respect to the design value, if the regenerator is fully by-passed and the bottoming steam cycle is designed to manage the increased flue gas temperature.

1. Introduction

Efficiency enhancement of gas turbines can be achieved through conventional and advanced techniques for waste heat recuperation [1]. Thermodynamic regeneration is a conventional technique of internal recovery, that allows the air preheating at combustion chamber inlet through the recirculation of waste heat from exhaust gases [2]. Over the last decades the technological development in the gas turbine sector has been marked by a progressive increase of pressure ratio [3] that has reduced the margins for thermodynamic regeneration, due to reduction of temperature difference between exhaust gases and compressed air. Thus, thermodynamic constraints of internal recovery have increased the interest toward the external heat recovery operated by a heat recovery steam generator (HRSG), where exhausts at gas turbine outlet are used to generate steam for industrial processes or electricity. In the last case, steam is used as a working fluid that evolves in a bottoming Rankine cycle. Current commercially available combined cycle plants achieve efficiency in the range of 50–60%, depending on gas turbine technology and HRSG layout [4,5].

Nowadays, internal and external heat recovery techniques of waste heat are regarded as two alternative options for performance improvement, with the only exception of micro-gas turbine for cogeneration applications, where this combination is permitted by low values of compressor pressure ratio, along with steam requirements at low-medium temperatures [6,7].

Conversely, CCGTs are usually designed to promote the external recovery, in order to ensure the maximum power production of bottoming steam cycle, usually corresponding to about one third of the overall capacity. According to data provided by manufacturer reference lists [8–10], the operating parameters of steam section are strictly related to the CCGT rated capacity. Focusing on the admission conditions to the high-pressure steam turbine, the operating pressure steadily increases from 6 to 130 bar for a CCGT power output lower than 200 MW; accordingly, the steam flow production and temperature of superheated steam vary from 5 to 100 kg/s and from 160 to 570 °C respectively. On the other hand, for a CCGT power output higher than 200 MW, high steam

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Nomenclature

Symbols
$CO_{2,em}$ specific carbon dioxide emissions, kg/MW h
m mass flow rate, kg/s
p pressure, bar
P power, MW
R_{gas} universal gas constant
Q heat, MW
T temperature, °C

Greek symbols
β compressor pressure ratio
γ specific heat ratio
ε fraction of waste heat recovery
φ regenerator effectiveness
η efficiency
λ deviation fraction from regenerator
π relative variation of power
χ relative variation of primary thermal energy

Subscripts and superscripts
C compressor
COMB combustor
CC combined cycle
CC-RG regenerative combined cycle
COND condenser
d design
E expander
EXH exhaust
EXT external
GT gas turbine
HPST high pressure steam turbine
INT internal
LPST low pressure steam turbine
RG regenerator
RH reheat
SH superheated
ST steam section
WH waste heat

Acronyms
AUX auxiliary system
CAP capital charge
CCGT combined cycle gas turbine
COE cost of electricity
COND condensing system
GT gas turbine
HP high pressure
HRSG heat recovery steam generator
IP intermediate pressure
LP low pressure
O&M operating and maintenance
ST steam turbine
TEC total equipment cost
TET turbine exit temperature
TIT turbine inlet temperature

vaporizing pressure and temperature are slightly affected by plant size, varying in the range of 90–170 bar and 520–570 °C respectively; conversely, the high pressure steam flow rate shows a more pronounced variation, increasing from 40 to 125 kg/s. In this regard, Table 1 summarizes the main technical features of some CCGTs installations [8].

Thermodynamic regeneration in CCGT power plants produces two contrasting effects; on the one side, it reduces the margin for external recovery, due to the reduction of exhaust gas temperature at HRSG inlet; on the other side, it enhances the efficiency of topping cycle, due to preheating of compressed air at combustor inlet. Thus, CCGTs based on regenerative gas turbines have lower rated capacity, but higher efficiency, with respect to traditional CCGTs having the same turbine inlet temperature and compressor pressure ratio.

The regenerative gas turbines have been widely investigated in literature. In [11,12] energy and economic performances of simple and regenerative gas turbines have been compared, at varying of different operating parameters, including compressor pressure ratio, ambient temperature, regenerator effectiveness and turbine inlet temperature. The behavior of a regenerative gas turbine at part load operation has been investigated in [13], considering different engine configurations and power control strategies. An alternative configuration of regenerative gas turbine with a recuperator located between HP and LP turbines has been analyzed in [14,15] and its performances have been compared with simple and conventional recuperative gas cycles. The integration of an air pre-heater into an existing simple gas turbine power plant has also been investigated in [16], with the aim to evaluate the potential for efficiency enhancement. The study in [17] used the exergy analysis to compare several options to retrofit an existing regenerative gas turbine, including inlet air cooling and steam injection.

Another research branch combined first and second laws of thermodynamic to investigate the influence of operating parameters on the performances of a regenerative gas turbine cogeneration plant [18,19].

For the best of our knowledge, only few studies have dealt with steam–gas power plants based on regenerative gas turbines. In [20] the effect of thermodynamic regeneration on CCGTs has been examined, at varying of pressure ratio and ambient temperature. A new layout of combined cycle with air pre-heating has been proposed in [21]; unlike conventional configurations, the increase of air temperature was obtained using the high pressure steam generated in the HRSG, with the aim to enhance the heat exchange process and reduce the regenerator surface. In [22] energy performances of a CCGT combining air and fuel preheating have been compared to the case of simple CCGT, varying the gas turbine pressure ratio.

However these studies have focused the attention on the evaluation of efficiency improvement of regenerative CCGTs, neglecting to investigate the interplay between internal and external thermal power recovery, as well as the impact of gas cycle regeneration on economic performances. Moreover none of these studies have carried out an off-design analysis, with the aim to evaluate the enhancement of CCGT operational flexibility resulting from the partial by-pass of regenerative heat-exchanger.

The aim of this paper is to investigate the effects of combining internal heat recovery (through a regenerator) and external heat recovery (through a steam bottoming cycle) in gas turbine power plants. Considering a CCGT based on a dual pressure HRSG, two analyses are carried out. The first one evaluates energy and economic performances of CCGT, varying the regenerator effectiveness and the maximum turbine inlet temperature. The energy parameters investigated include the efficiency and power plant rated capacity, as well as the extent of thermal power recovered from

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