Energy Conversion and Management 106 (2015) 1097–1108

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Analysis and optimisation of combined cycles gas turbines working with partial recuperation

Antonio Rovira *, Consuelo Sánchez, Marta Muñoz

E.T.S. Ingenieros Industriales – UNED, C/Juan del Rosal, 12, 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 28 July 2015
Accepted 16 October 2015
Available online 11 November 2015

Keywords:
Combined cycle
Recuperative gas turbine
Thermoeconomic optimisation

ABSTRACT

The objective of this paper is the analysis and the optimisation of several configurations of combined cycle gas turbines using a partially recuperative gas turbine and heat recovery steam generators (HRSG) of two and three pressure levels.

The proposed configuration consists of the thermal recuperation of a fraction of the total exhaust gas mass flow, which preheats the air exiting from the compressor. The exhaust gas mass fraction that is not directed to the recuperator goes to the high temperature heat exchangers (superheaters and reheaters). As the temperature of the gas at the superheater inlet is maintained, the temperature of the produced steam is not decreased and the performance of the steam cycle is also maintained.

In order to analyse and homogeneously compare the proposed configuration to the conventional and completely recuperative ones, three optimisations are carried out: (1) a thermodynamic optimisation, maximising the thermal efficiency; (2) a thermodynamic optimisation with the total heat exchange area constrained; and (3) a thermo-economic optimisation that minimises the generation cost.

Results show the convenience of using recuperative gas turbines for the dual pressure configurations and, especially, the use of partial recuperation for both dual and triple pressure configurations. In almost all cases the optimal recuperative mass fraction is located at roughly 90%. In dual pressure level heat recovery steam generators, the use of a recuperative gas turbine is advisable both from the thermodynamic and economical points of view, but results are improved using high partial recuperation. In triple pressure level configurations, fully-recuperative gas turbines are not advisable but the performance and cost may be enhanced if the gas turbine is partially recuperative.

1. Introduction

As it is well known, commercial combined cycle gas turbines (CCGT) comprise a gas turbine as the high temperature cycle and a steam cycle as the low temperature one. Several configurations of gas turbines and Rankine cycles are commonly used, that allow very high heat-to-electricity conversion efficiency. The most usual configurations are well established since several decades ago [1,2], and they include several pressure levels at the heat recovery steam generator (HRSG) and heat recovery of the gas turbine cooling (using air or steam from the Rankine cycle). Najjar [3] makes a comprehensive analysis on the different technologies that may be installed.

In the technical literature there are many works aimed to increase the thermal efficiency of combined cycles, some of them including analysis of the suitability of the use of a recuperative gas turbine cycle. Among them stand, for example, those carried out by Franco [4–6], which show the convenience of using sequential combustion together with a recuperative gas turbine; Carcasci and Facchini [7], who study heat recovery of the gas turbine cooling and also sequential combustion; the works of Bassily involving recuperative gas turbines [8] and air/steam blade cooling [9,10]. Sequential combustion, intercooling and supplemental firing of the exhaust gas have been also studied in [11], the utilization of heat from the turbine cooling is studied in [12,13], the use of recuperative gas turbines also in [14] and the effect of the steam quality at the exit of the steam turbine on the results of the optimisations is studied in [15]. Finally, in [16,17] authors suggest heat recuperation to pre-heat not only the air at the compressor outlet but also the fuel entering to the combustion chamber.

Although some of these works may advice the use of recuperative gas turbines, this solution has not been commercially considered. As it is well known, recuperative gas turbines include an additional heat exchanger (recuperator) that preheats the air

* Corresponding author. Tel.: +34 913988224.
E-mail addresses: rovira@ind.uned.es (A. Rovira), csanchez@ind.uned.es (C. Sánchez), mmunoz@ind.uned.es (M. Muñoz).

http://dx.doi.org/10.1016/j.enconman.2015.10.046
0196-8904/

Nomenclature

Symbols

C	cost (€, $)
C_{kWh}	generation cost (€ kW^{-1} h^{-1})
CCGT	combined cycle gas turbine
$CCGT^{r}$	combined cycle with recuperative gas turbine
$CCGT^{pr}$	combined cycle with partially recuperative gas turbine
E, E^{Q}	exergy flow, exergy content of the thermal power (W)
g, G	free Gibbs energy (J kg^{-1}, W)
h, $\dot{H}$	enthalpy (J kg^{-1}, W), hours (h)
H_c	heating value (J kg^{-1})
HRSG	heat recovery steam generator
HT	high temperature
I	irreversibility (W)
LT	low temperature
$\dot{m}$	mass flow (kg s^{-1})
p	pressure (Pa)
pp	pinch point (K)
Q	thermal energy (J kg^{-1})
r, r_c	pressure ratio, compression ratio (–)
r_e	expansion ratio (–)
s, $\dot{S}$	entropy (J kg^{-1} K^{-1}, W K^{-1})
T	temperature (K)
TIT	turbine inlet temperature (K)
U	overall heat-transfer coefficient and the heat exchange area (W K^{-1} m^{-2})
UA	UA factor, product of the overall heat-transfer coefficient and the heat exchange area (W K^{-1})
W	power (W)
$\widetilde{W}$	equivalent mean power (W)

Greek letters

α	recuperative mass fraction (–)
Δ	increment
ε	effectiveness of the regenerator (–)
η	efficiency (–)
η_p	polytropic efficiency of the turbomachinery (–)
η_s	isentropic efficiency (–)
ξ	percentage of pressure loss (–)

Subscripts

a	air, amortisation
amb	ambient
CC	combined cycle
comb	combustion chamber
comp	compressor
cond	condensation
ex	extraction
exh	exhaust
f	fuel
g	gas
GT	gas turbine
HP	high pressure level
IP	intermediate pressure level
LP	low pressure level
max	maximum
O&M	operation and maintenance
R	recuperator
ref	reference
rh	reheater
sh	superheater
ST	steam turbine
turb	turbine

coming from the compressor using the exhaust gas coming from the turbine, which allows fuel saving due to the air preheat.

One of the reasons why this configuration has not been considered is that the turbine exhaust temperature decreases during the recuperation process, which leads to an exergy decrease of the hot stream that is directed to the HRSG. Therefore, quality of the produced steam decreases and, consequently, also the efficiency of the steam cycle, which reduces, at some extent, the overall efficiency improvement of the combined cycle.

In summary, although with the use of recuperative gas turbines the efficiency of the combined cycle may increase in comparison to a non-recuperative one, the effect of having a lower temperature at the inlet of the HRSG penalizes this improvement that may not be significant, and this, together with the complexity of including a recuperator, makes not advisable its installation.

In the present paper a different layout with partial recuperation is proposed, which allows the use of a recuperative gas turbine and the associated fuel saving, but avoiding the temperature decrease of the exhaust gas directed to the HRSG. The proposed configuration, using two and three pressure levels HRSGs, is analysed from a thermodynamic and thermo-economic perspective in order to show and quantify the possible advantages. Specifically, the main parameters of the cycle are varied and three optimisations are performed. Firstly, a thermodynamic optimisation that maximises the thermal efficiency, in order to highlight the efficiency increase; then, a thermodynamic optimisation but considering the total heat exchange area, to homogeneously compare the different configurations to the conventional ones; and finally, a thermo-economic optimisation that minimises the generation cost and provides information about the feasibility of the configurations.

2. Combined cycle gas turbine with partial recuperation

As mentioned, the objective of the proposed configuration (partially recuperative CCGT, $CCGT^{pr}$) is to allow fuel saving by means of a recuperative heat exchanger but without decreasing the temperature of the exhaust gas (T_{exh}) of the gas turbine that goes to the HRSG. Fig. 1 shows the scheme of the configuration. As observed, the gas flow at the outlet of the turbine is divided into two streams. A fraction of the gas goes to the recuperator while the other is directed to the HRSG. The stream circulating by the recuperator pre-heats the air coming from the compressor before it is introduced in the combustion chamber. The other part of the exhaust gas goes to the HRSG, whose layout differs from that of the conventional ones, particularly in the high temperature zone.

Specifically, the HRSG is divided into two zones, one of high temperature (HT) including only superheaters (and also the reheater if the HRSG includes one) that is fed by the exhaust gas stream that is not directed to the recuperator; and the other of low temperature (LT) following a conventional layout and that holds the economisers, evaporators and superheaters of the intermediate and low pressure levels. At the inlet of this zone, both exhaust gas streams (coming from the HT and from the recuperator, respectively) are mixed.

With such a layout, the gas turbine may work following a recuperative cycle while the HT part of the HRSG is still in contact with the gas exiting from the turbine. Absolute inflow exergy at the HT part of the HRSG is lower than conventionally, due to the lower mass flow, but specific exergy does not vary and allows high quality steam production. This effect is depicted in Fig. 2, where it is shown that the same amount of steam at the same thermodynamic