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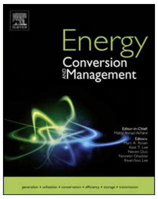

Exergy-energy-environ evaluation of combined cooling heating and power system based on a double stage compression regenerative gas turbine in large scales

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ABSTRACT

In the present paper a combined cooling heating and power cycle is proposed to recover exhaust and compression heat of a 35.5 MW industrial gas turbine rated in summer operation. The cogeneration cycle comprises of double stage compressor, a regenerative gas turbine, absorption chiller, pumps and heat recovery units. The thermodynamical and environmental mathematical model of the cycle is developed using the Engineering Equation Solver software. The epsilon-number of transfer unit method is used to analyze the heat recovery system. A fitness function is proposed to aggregate five thermodynamical and environmental criteria and genetic algorithm is used for optimization. The results of the gas turbine and absorption chiller models are validated with the available data in the references and good agreement is achieved. Four design parameters of combustion temperature, compression ratio, pinch point temperature difference, and evaporator temperature are used for optimization. In the optimum state, the overall energy and exergy efficiencies are about 56% and 69%. Electricity production is 42.8 MW and 6.6% and 9.4% of the fuel energy can be recovered from the compression heat and exhaust gases. This heat recovery corresponds to producing 24.5 tons/h of superheated steam at 134.8 °C and 167.4 kPa. The chiller produces 7.8 MW of cooling and its coefficient of performance is 0.68. The carbon monoxide, carbon dioxide and nitrogen oxides reduction are more than 87%, 17%, and 13% respectively.

1. Introduction

Statistics and predictions reported by Energy Information Administration (EIA) [1] has shown that in 2016 only 14.77% of the total electricity generation was provided by all renewable energy resources (solar, hydroelectric and other types), and the rest of 84.88% was provided by different fossil fuels (and the remaining 0.33% was provided by other resources). EIA has also predicted that the share of renewable energy resources for the total energy demand of world would become 16% until 2040. It means that at the year of 2040, 84% of the world energy demand would be provided by the fossil fuel resources still. Consequently, according to these results the fossil fuels would be the primary energy source for the world up to the mid-century. Consequently, optimizing the existing energy processes and related technologies is essential to reduce emission production and increase the overall efficiency of energy systems.

Industrial gas turbines (GT) play a very important role for power generation in both central and distributed power plants around the world. In central power systems, electricity is produced in the giant power plants, transferred and distributed through the public electricity grids. It is evident that the electricity loss due to the public grid would be eliminated in the distributed power systems. GTs have been used widely for power generation standing alone or as upper gas cycle for the steam bottoming cycles such as Rankine cycles, Kalina cycles, trilateral flash cycles, and organic Rankine cycles (ORC). They have also been used as the upper cycle of gas bottoming cycles such as Stirling engine, Brayton cycle, and hydrogen fuelled internal combustion engine [2].

Using GT exhaust gas as the main energy source for running steam or gas bottoming cycles is not the only method to increase the cycle efficiency. The efficiency can be boosted even more by using multi-stage compression/expansion and using intercooler/reheater between compression/ expansion stages. In addition, if it is supposed to use multi-stage compression/expansion, intercooler/reheater it is recommended to use regenerator for preheating of compressed air before the combustion chamber by using the energy content of the exhaust gases. It is well proved that using multi-stage compression/expansion; intercooler/reheater with regenerator increases the GT cycle efficiency in comparison with the simple cycle GT [3]. Despite the energy

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Nomenclature

Abbreviations

CCHP	combined cooling heating and power
COP	coefficient of performance
CR	circulation ratio
FUF	fuel utilisation factor
GT	gas turbine
HRSG	heat recovery steam generator
ICE	internal combustion engine
MGT	micro gas turbine
ORC	organic Rankine cycle
RFR	recovered fuel ratio

Parameters

h	enthalpy (kJ kg^{-1})
A	heat surface area (m^2)
U	overall heat transfer coefficient (kW K^{-1})
I	exergy destruction rate (kW)
k	heat capacity ratio
LHV	lower heating value (kJ kg^{-1})
P	pressure (kPa)
Q	heat rate (kW)
r	compression ratio
R	reduction of pollutants
s	entropy (kJ kg^{-1} K^{-1})
T	temperature (°C)
W	power (kW)
w	weight
X	solution concentration

Subscripts

abc	absorption chiller
abs	absorber
amb	ambient
atm	atmosphere
cc	combustion chamber
comp	compressor
cond	condenser
ele	electrical
eva	evaporator
fcu	fan coil unit
gen	generator
HE	heat exchanger
HP	high pressure
hs	heat source
In, out	input, output
LP	low pressure
NG	natural gas
PP	pinch point
is	isentropic
SH	super heat
tu	turbine
0	dead state
β	exergy efficiency
η	energy efficiency
$\dot{m}$	mass flow rate (kg s^{-1})
ε	effectiveness
Φ	exergy rate (kW)
ψ	specific exergy (kJ kg^{-1})

efficiency advantages of using multi-compression/expansion, intercooler/reheater, using this type of GTs cause some operational and maintenance problems. For example the surge control will become more complicated because the cooling liquid temperature and its flow rate can affect the gas temperature. In addition any maintenance job in the recirculation pumps, filtration, filling packs, water nozzles, and control valves of cooling tower can cause shut down to the GT. Furthermore due to having complicated casing for the GT the maintenance becomes more costly and time consuming. In addition to the investment costs related to the cooling system, reheating system, etc the cost of cooling water loss, electricity consumption of pumps, and maintenance costs would be considered as negative cash flows of the project.

In addition to the methods described to improve power generation efficiency, regular energy audit such as those presented in [4], component auditing of power plants, punctual maintenance and correct operation of energy converter equipments, and energy management can assist to keep the thermal efficiency of energy systems as high as possible [5]. However the fuel energy utilization can be improved further especially in power generation systems such as gas turbines [6]. Combined cooling heating and power or CCHP, which is also called trigeneration is among the most popular methods that is still under investigation to increase fuel energy utilization in power generation units [7]. CCHP units are capable of producing simultaneous cooling, heating and power/electricity by using a single energy source.

In the following the recent GT-CCHP cycles which are designed, optimized, or manufactured in the last decade are reviewed to discuss what is done. Kong et al. [8] presented an energy model for a GT-CCHP cycle and optimized the cycle from energy point of view. The cycle consisted of a gas turbine, an absorption chiller, and a heat recovery boiler. They presented a linear model for the cycle to find an optimal energy management strategy. For this purpose they also minimized the cycle energy cost function. They concluded that according to the energy cost analysis it may not be optimum to run the gas turbine some times. The model presented in this research [8] cannot predict the thermodynamic states in different points of the cycle; as a result presenting an exergy evaluation is not possible by using this model. In addition the heat recovery boiler is not discussed in details, for example the pinch point temperature difference of the heat recovery is neither calculated nor proposed. Furthermore, no simulation was presented for evaluation of the energy or exergy share in different components of the absorption chiller.

Yang et al. [9] presented an analytical model for a GT-CCHP cycle. The GT-CCHP cycle presented in [9] consisted of a GT, a double-effect absorption chiller, and a HRSG unit. The analyses include calculating the economic exergy efficiency and thermal efficiency. They also investigated the impact of ambient temperature on the cycle behavior. In the simulation they have also considered constraints for the GT operation in part load to avoid surging in the compressor and furthermore, they used other constraints to avoid operation of absorption chiller bellow or over the minimum and maximum recommended operating conditions. Some details of the HRSG unit such as approach temperature, pinch temperature, operating pressure and temperature are also given. They concluded that the economic exergy efficiency and thermal efficiency of the CCHP rise with the increase of power output, and trend towards a slight decline at the near-full cooling load of chiller. In addition, increasing the cooling load caused the economic exergy efficiency and thermal efficiency to increase for a wide range of CCHP operation. Furthermore higher ambient temperature has decreased the capacity to produce power, cool, and heat.

Liu et al. [10] presented an hourly analysis for a CCHP cycle with alternatives for power generation unit. They used GT and ICE. The other components of the CCHP cycle were an absorption chiller, two