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Exergoeconomic analysis and optimization of a triple-pressure combined cycle plant using evolutionary algorithm

Sina Kazemi Bakhshmand [a], Rahim Khoshbakhti Saray [a, *], Keyvan Bahlouli [a], Hajar Eftekhari [a], Afshin Ebrahimi [b]

[a] Faculty of Mechanical Engineering, Sahand University of Technology, Sahand New Town, Tabriz, Iran
[b] Faculty of Electrical Engineering, Sahand University of Technology, Sahand New Town, Tabriz, Iran

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ABSTRACT

Among power generation systems, CCPPs (combined cycle power plants) are attractive due to their higher efficiency and lower environmental impacts. Optimization process is a promising manner in order to find the best performance criteria of complex energy conversion systems. In present paper, exergoeconomic analysis and optimization of a triple-pressure combined cycle plant with one reheat stage is under investigation. The objective function which is utilized in the optimization study is the total cost rate of the plant. The results show that optimization process leads to an increase of about 3% in both energetic and exergetic efficiencies and also, a reduction of about 9% in the cost criteria. In addition, the specific cost of product of the plant is reduced from 21.48 (€/h) for the base case to 20.90 (€/h) for the optimum case; thus, the optimization process causes about 3% decrement in the specific cost of product and consequently cost of produced electricity.

1. Introduction

Energy plays a vital role in both industrial and residential applications, and its costs have risen in the past decades. With this large increase in energy costs, inefficient energy conversion systems would not be acceptable. Fossil fuels are the most important resources of global energy production and have a significant impact on climate change and environmental pollutions. Efficient use of energy and designing cost effective energy conversion systems would be a promising option to reduce fuel consumption and greenhouse emissions. Among power generation systems, CCPPs (combined cycle power plants) have recently been attractive because of their high efficiency and low environmental impacts. In such power plants, Brayton and Rankine cycles merge together and make a unit cycle where the gas turbine cycle (topping cycle) and steam turbine cycle (bottoming cycle) are connected through a HRSG (heat recovery steam generator). The hot outlet gas from gas turbine is used to generate steam in HRSG and the generated steam is utilized in steam turbine to generate power [1–7]. CCPPs have higher efficiencies in contrast to simple Brayton and Rankine cycles, hence these cycles are widely used all around the world [5].

Optimization of these power generation systems is an important effort in order to reach more efficient, cost effective and environmental systems. Exergy, exergoeconomic and exergoenvironmental analyses could be useful tools to realize the type, location and the amount of inefficiencies and related costs from various points of view and can play an important issue to improve and to optimize energy systems and particularly power plants [8]. During past decades, most of the research works have been focused on analyzing and optimizing several power plants.

Koch et al. [9] used an evolutionary algorithm to minimize the product cost and to maximize the efficiency of a combined cycle. In this study configuration of the cycle and thermodynamic variables related to the occurred processes in the cycle, were optimized. Finally, a special case study as a combined cycle with a power output of 240 MW has been considered and exergy analysis and optimization of the cycle have been done. Sahoo [10] by considering a combined cogeneration system with power production of 50 MW and 15 kg/s saturated steam, optimized the unit through the exergoeconomic concepts using genetic algorithm. The results showed that the cost of power and heat generation in the optimum case is 9.9% lower than the base case, meanwhile the exergetic

* Corresponding author. Tel./fax: +98 411 3459476.
E-mail address: khoshbakhti@sut.ac.ir (R.K. Saray).

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Nomenclature

$\dot{C}$	cost rate (€/h)
e	specific exergy (kJ/kg)
$\dot{E}$	exergy flow rate (kW)
f_k	exergoeconomic factor
h	specific enthalpy (kJ/kg)
$\bar{h}$	specific enthalpy (kJ/kmol)
LHV	lower heating value (kJ/kg)
M	molar mass (kg/kmol)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
$\dot{Q}$	heat transfer rate
R_p	pressure ratio
s	specific entropy (kJ/kg K)
T	temperature (K)
$\dot{W}$	power (kW)
x	mole fraction
$\dot{Z}$	investment cost rate (€/h)

Greek symbols

η	energetic efficiency (%)
ε	exergetic efficiency (%)

Subscripts

0	environment state
air	air
CH	chemical
D	destruction
e	exit
F	fuel
G	Gas
in	inlet
is	isentropic
k	component
L	loss
P	product
mix	mixture
PP	pinch point
q	heat
s	Steam
total	total
w	work

Abbreviations

AC	air compressor
CC	combustion chamber
CCPP	combined cycle power plant
CLC	chemical looping combustion
Condpump	condenser pump
GA	genetic algorithm
GT	gas turbine
GTIT	gas turbine inlet temperature
HP	high pressure
HPECON	high pressure economizer
HPEVAP	high pressure evaporator
HPP	high pressure pump
HPSH	high pressure superheater
HPST	high pressure steam turbine
HRSG	heat recovery steam generator
IP	intermediate pressure
IPECON	intermediate pressure economizer
IPEVAP	intermediate pressure evaporator
IPP	intermediate pressure pump
IPST	intermediate pressure steam turbine
LP	low pressure
LPECON	low pressure economizer
LPEVAP	low pressure evaporator
LPP	low pressure pump
LPST	low pressure steam turbine
RH	reheater

efficiency is increased from 46.5% to 53.9%. Sayyadi [11] performed exergy, exergoeconomic and exergoenvironmental analyses of a CGAM problem and optimized the cycle. In this work, three objective functions which are consist of the exergetic efficiency, product cost rate and environmental cost rate have been considered. Results showed that optimization process leads to about 1.51% increase in the exergetic efficiency and reduction of about 7.14% and 4.28% in the product cost rate and the environmental cost rate, respectively. Baraco and Siri [12] optimized the performance of heat recovery steam generator in a combined cycle. They improved the efficiency of the cycle by defining objective functions based on the exergy rates of the fluid passing through the heat recovery steam generators and exergy destruction values. Thus, by maximizing the objective function based on exergy rates and minimizing the other objective function based on exergy destructions, an optimum range of the system performance was determined. Ahmadi and Dincer [13], by considering appropriate decision variables and objective function, optimized a combined cycle with supplementary firing using genetic algorithm. The objective functions were considered to be the cost rate of fuel, investment cost rate and exergy destruction cost rates. They found that in the case with fixed output power, by raising the unit cost of fuel, parameters such as isentropic efficiency of compressor, gas turbine isentropic efficiency and mass flow rate of fuel in supplementary firing section would be reduced. Petrakopoulou et al. [14] carried out exergoeconomic and exergoenvironmental analysis of a combined power plant based on CLC (chemical looping combustion) and compared the results with a reference case as a conventional combustion chamber. The work demonstrated that the highest exergy destruction occurred in the gas turbine system due to existence of chemical reaction and also, the exergy destruction through the combustion process can be reduced by 12% using CLC reactors comparing to the conventional combustion chamber. Therefore, CO_2 capture process caused an increase in the cost of electricity in about 24%.

In recent years many researchers have carried out advanced exergy, exergoeconomic and exergoenvironmental analyses of energy conversion systems. This concept splits the exergy destruction into endogenous/exogenous and avoidable/unavoidable parts, which may cause further understanding of the system inefficiencies and it can be used as a powerful tool to improve the system performance [15–20].

Conventional and advanced exergy, exergoeconomic and exergoenvironmental analyses can give much more information about thermal performance of the system but they won't be able to predict optimal design parameters in the system, lonely. Therefore, optimization of the system by using thermodynamic laws would be an essential effort. By reviewing the previous studies [14,19], it is