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Optimization and the effect of steam turbine outlet quality on the output power of a combined cycle power plant

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ABSTRACT

A narrow path exists to a sustainable solution which passes through careful steps of efficiency improvement (resource management) and provides environmental friendly energies. Thermal power plants are more common in many power production sites around the world. Therefore, in this current research study a comprehensive thermodynamic modeling of a combined cycle power plant with dual pressure heat recovery steam generator is presented. Since the steam turbine outlet quality is a restrictive parameter, optimization of three cases with different steam quality are conducted and discussed. In other hand, energy and exergy analysis of each components for these three different cases estimated and compared. Obtained results show that it is really important to keep the quality of the vapor at turbine outlet constant in 88% for the results to be more realistic and also optimization and data are more technically feasible and applicable.

1. Introduction

Energy is one of the main driving forces, which helps to sustain human life. Energy is available in several forms, e.g., heat, light, electricity. Energy, economic and environmental impact considerations have gained a lot of attentions during the last three decades. Energy resources in the market are getting less and at higher prices as the industrial revolution progress. This is due to several reasons such as the growth in global economy, depletion of energy resources, and the environmental impacts of energy production. Therefore, these energy issues are now threatening many aspects of human lives on the planet. Concerns exist regarding energy conversion from thermal sources to electrical sources. In this regard, power plants play main role in electricity production. Among different kinds of power plants, combined cycle power plants (CCPPs) gained a lot of attentions due to the fact that they are attractive in power generation field because of higher thermal efficiency rather than individual gas turbine or steam power plants. In addition, they are also important due to their relatively high energy efficiencies, low pollutant and greenhouse gas emissions, and operational flexibility. Literature on the subject shows that several efforts have been carried out on the plant optimizations. Energy consumption minimization, optimization of annual return and other approaches were used. Unlike energy, exergy is a measure of the quality of energy that can be considered to evaluate, analyze and optimize the system. Exergy analysis is utilized to define the maximum performance of a system and to specify its irreversibilities. Therefore, exergy is a powerful tool for evaluating the performance of the cycle and also one objective approached usually with the lack of economic, technical and environmental feasibilities. Recently, combination of tools like exergy, economic and environmental assessments have received increasing attention around the word. Therefore the method which considered all the objectives and provides a feasible solution is currently needed by CCPPs plant designers. In this respect, different studies [1–8] have been carried out to investigate the combined cycle power plants, however a few multi-objective optimization of such plant which accounts for all the three main issues simultaneously have done to the best of our knowledge [2].

Exergy analysis is a useful tool to find the locations, types and magnitudes of true inefficiencies (irreversibilities) and recommend ways to improve the overall efficiency of the system [2,9–12]. In the literature, there have been various studies associated with exergy analyses of plants. Lior [13] proposed a concept about future power generation systems and the role of exergy analysis in their development. He illustrated some thoughts to meet the power demands under the constraints of increased population and land use when holding the environmental impact to a tolerable one. Next he focused on exergy analysis which would be essential in the conception and development of such processes. Finally he discussed about

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Nomenclature

List of abbreviations	
a	air
act	actual
c	cost per exergy unit [$/MJ]
c_f	cost of fuel per energy unit [$/MJ]
$\dot{C}$	cost flow rate ($/s)
ch	chemical
c_p	specific heat at constant pressure [kJ/kg K]
CW	cooling water
D	destruction
Env	environmental
$\dot{E}x$	exergy flow rate [MW]
$\dot{E}x_D$	exergy destruction rate [MW]
f	fuel
F	fuel for a component
g	gas
h	specific heat (kJ/kg)
is	isentropic
j	jth stream
k	kth component
LHV	lower heating value [kJ/kg]
$\dot{m}$	mass flow rate [kg/s]
Pc	probability
Ph	physical
PP	pinch point
Q	heat
R	gas constant
ref	reference
r_{Comp}	compressor pressure ratio
$\dot{W}_{net}$	net power output [MW]
Z	capital cost of a component [$]
$\dot{Z}$	capital cost rate [$/s]
η_{Comp}	compressor isentropic efficiency
η_{cc}	combustion chamber first law efficiency
η_{GT}	gas turbine isentropic efficiency
γ	specific heat ratio
φ	maintenance factor
ξ	coefficient of Fuel Chemical exergy

which kind of development is essential for the power generation units in the coming century. The results indicated that exergy analysis will help the designers to come up with a good decision on how to improve the system performance. Rosen and Dincer [14] conducted a comprehensive study of industrial steam heating process through exergy analysis. The results showed that using exergy analysis and the technical factors that influence the feasibility of steam supplied for other energy sources in industrial heating. They presented an example for the Bruce Energy Center in Ontario, Canada to demonstrate the importance of using exergy analysis to assess the feasibility of industrial steam process heating. The results suggested exergy analysis should be used as an important tool in process optimization while the use of large quantities of the steam in energy centers is considered. In recent decades, thermoeconomics and exergoeconomics have been increasingly utilized by researchers, combining thermodynamics with economics. Many such studies have been reported, especially for power generation [15–21]. Abusoglu and Kanoglu [22] surveyed a review of exergoeconomic analysis and optimization of combined heat and power production. This paper was a review on the exergoeconomic analysis and optimization of combined heat and power production systems. They gather brief historical information on the exergoeconomics analysis and optimization. They also discussed the concept of exergy cost and cost accounting methods. Ahmadi and Dincer [1] performed a comprehensive thermodynamic modeling of a dual pressure (HRSG). To find the best design parameters for HRSG, they applied a multi objective optimization. In this regard for this optimization two objective functions are considered. Results showed that increasing the drum pressures results to increase in HRSG exergy efficiency and a decrease in the HRSG exergy destruction rate. Nevertheless, increasing the pinch temperatures resulted in decrease in HRSG exergy efficiency and also increases in HRSG exergy destruction. One of the most important concerns for human is to reduce environmental impact of energy system and make use of sustainable energy technologies to mitigate global warming. Some exergy methods are tried to reduce exergy losses and increase exergy efficiency, But there are some ways that exergy assist to understand and reduce environmental impact. In this regards, many reports in the literature consider environmental aspects of thermal systems [23–25]. Lazzaretto and Toffolo [26] optimized an energy system from energy, economy and environmental aspects. They defined an environmental impact objective function in terms of cost by weighting CO and NO emissions considering their unit damage costs. In optimization approach, three objective functions are selected to find the optimal solutions by using evolutionary algorithm. They applied an additional objective which was the cost related to NO_x and CO emissions in cost terms. In this sense, they proposed the non-abbreviated term thermoenviroeconomic for this objective. Barzegar Avval et al. [25] studied the thermoeconomic environmental multi objective optimization of a gas turbine power plant using evolutionary algorithm. They used multi-objective optimization in order to optimize the system for the better performance assessment. Optimization results showed the overall exergoeconomic factor of the system increases from 32.79% to 62.24% compared with the actual power plant. In another research a comprehensive thermodynamic modeling and exergoenvironmental analysis of a trigeneration system based on a micro an organic Rankine cycle and gas turbine for heating, cooling and electricity purposes are studied by Ahmadi et al. [27].

In this paper, a mathematical model is developed for a combined cycle power plant. Energy, exergy, exergoeconomic and exergoenvironmental analyses of this power plant are conducted. For optimization process, three different objectives function namely exergy efficiency to be maximized, total cost rate of the system product and the CO_2 emission to be minimized are defined and optimized. The optimization is applied for three cases with different qualities at steam turbine outlet. Since the emission and efficiency have an inverse correlation and can be expressed as a function of each other, the Pareto frontier of these three cases is presented as a 3D line instead of a surface. Thereafter, energy efficiency, exergy efficiency, main work flows, purchase cost of each components and emission of these three different cases are conducted and compared.

Therefore, the main objective of this research paper is to carry out the thermodynamic modeling and effects of steam turbine outlet quality on the output power of a combined cycle power plant. The sub objectives of this research study follow:

- A development model for a CCPP based on thermodynamic principles and energy balances.
- Considering three different objective functions to handle the optimization process for three different cases with different steam quality at steam turbine outlet.
- To have a good verification results, energy efficiency, exergy efficiency of the mentioned cases are evaluated and compared.