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Modelling and exergoeconomic-environmental analysis of combined cycle power generation system using flameless burner for steam generation

Seyed Ehsan Hosseini [a,*], Hasan Barzegaravval [a], Abdolsaeid Ganjehkaviri [b], Mazlan Abdul Wahid [a], M.N. Mohd Jaafar [b]

[a] High-Speed Reacting Flow Laboratory, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, UTM, 81310 Skudai, Johor, Malaysia
[b] Institute for Vehicle Systems and Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

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ABSTRACT

To have an optimum condition for the performance of a combined cycle power generation, using supplementary firing system after gas turbine was investigated by various researchers. Since the temperature of turbine exhaust is higher than auto-ignition temperature of the fuel in optimum condition, using flameless burner is modelled in this paper. Flameless burner is installed between gas turbine cycle and Rankine cycle of a combined cycle power plant which one end is connected to the outlet of gas turbine (as primary combustion oxidizer) and the other end opened to the heat recovery steam generator. Then, the exergoeconomic-environmental analysis of the proposed model is evaluated. Results demonstrate that efficiency of the combined cycle power plant increases about 6% and CO_2 emission reduces up to 5.63% in this proposed model. It is found that the variation in the cost is less than 1% due to the fact that a cost constraint is implemented to be equal or lower than the design point cost. Moreover, exergy of flow gases increases in all points except in heat recovery steam generator. Hence, available exergy for work production in both gas cycle and steam cycle will increase in new model.

1. Introduction

Depletion of fossil fuel resources and the high prices of energy have highlighted the necessity of optimum application of energy and the management of energy consumption. Combined cycle (CC) power generation system is one of the best choices to generate energy due to the application of low carbon content fuels, high efficiency and operational flexibility. CC plant is a couple of the Brayton cycle (top cycle) with the Rankine one (bottoming cycle). This technology plays a promising role in global warming mitigation as they decrease carbon dioxide (CO_2) by using the energy losses from gas turbines (GT) to make steam for bottom cycle [1]. Compared to the Bryton Cycle, the return work ratio in Rankine cycle is much smaller, because in a steam power plant the fluid being displaced by pumps has a small specific volume. Consequently, the steam turbine (ST) output work is much higher than the input work into the pump and the return work ratio is small. However, in the GT power plants, air as the working fluid is compressed in compressor, where its specific volume increases. Hence, a major portion of the GT output work is used by the compressor and the power plant generates lower work per unit volume of the carrier fluid. Utilization of the hot exhaust gases at the end of the expansion stage in the top cycle, to generate hot high-pressure steam in the bottoming cycle is the basic idea of CC plants [2].

Literature on the subject demonstrates that several efforts have been performed on the plant optimization. Optimization of annual return and energy consumption minimization and other approaches have been used. Energy and exergy analysis of a system based on the first and second thermodynamic laws is an important tool to evaluate the performance of the systems. The second law of thermodynamics deals with the quality of energy and specifies the

Abbreviations: a, air; act, actual; ch, chemical; AC, air compressor; BFP, boiler feed pump; CW, cooling water; CC, combined cycle; CCPP, combined cycle power plant; CRF, capital recovery factor; Cond, condenser; D, destruction; DB, duct burner; DEA, deaerator; Ec-Pr, economizer preheater; Evap, evaporator; Eco, economizer; *f*, fuel; FB, flameless burner; GHGs, greenhouse gases; GT, gas turbine; HP, high pressure; HRSG, heat recovery steam generator; *h*, specific heat (kJ/kg); is, isentropic; *j*, *j*th stream; k, *k*th component; LHV, lower heating value [kJ/kg]; LP, low pressure; Pc, probability; Ph, physical; PP, pinch point; Q, heat; R, gas constant; SFS, supplementary fire system; ST, steam turbine; Sup, superheat; TIT, turbine inlet temperature.

* Corresponding author.
E-mail address: seyed.ehsan.hosseini@gmail.com (S.E. Hosseini).

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Nomenclature

c	cost per exergy unit [$/MJ]	T_{pz}	temperature of the primary zone at combustion
c_f	cost of fuel per energy unit [$/MJ]	τ	the residence time in the combustion zone
$\dot{C}$	cost flow rate ($/s)	$\dot{W}_{net}$	net power output [MW]
c_p	specific heat at constant pressure [kJ/kg·K]	Z	capital cost of a component [$]
$\dot{E}x$	exergy flow rate [MW]	$\dot{Z}$	capital cost rate [$/s]
$\dot{E}x_D$	exergy destruction rate [MW]	η_{Comp}	compressor isentropic efficiency
Ex_{ph}	physical exergy [MW]	η_{cc}	combustion chamber first law efficiency
ex^{ch}_{mix}	mixture chemical exergy [MW]	η_{st}	steam turbine isentropic efficiency
G^E	the excess free Gibbs energy	η_{GT}	gas turbine isentropic efficiency
$\dot{m}$	mass flow rate [kg/s]	γ	specific heat ratio
$\dot{n}_{da}$	the mole of diluted air	φ	maintenance factor
$\dot{n}_f$	the mole of fuel	ξ	coefficient of Fuel Chemical exergy
$\dot{n}_p$	the mole of products	$\bar{\lambda}$	fuel-air ratio on a molar basis
r_c	compressor pressure ratio	θ	dimensionless temperature
		π	dimensionless pressure

maximum amount of achievable work from an energy resource. Exergy analyses have been employed in power plants to determine the type and the true magnitude of exergy loss (or destruction) in the power generation cycle and its location to provide guidelines for more effective use of energy in the plants. Exergy is usually employed as one objective approached with the lack of economic, technical and environmental feasibilities [1,3]. In the literature, there have been various investigations associated with exergy analyses of power plants.

Cihan et al. [4] performed energy and exergy analyses for a combined cycle power plant (CCPP) in Turkey and suggested some modifications to mitigate the exergy destruction in CC. The authors pointed out that the main sources of irreversibilities are combustion chamber, gas turbines and heat recovery steam generator (HRSG) where over 85% of the overall exergy losses were observed in these components. Although increasing turbine inlet temperature (TIT) enhances the efficiency of CCPP, the considerable technological efforts is required to cool down the blades of the GT [5].

Casarosa et al. [6] pointed out that GT exhaust gases temperature should be higher than 850 K in the inlet of HRSG to have an optimum condition for CC performance. It was found that an increase in TIT and compressor pressure ratio (r_c) has positive influence on most of the component's potential improvements and accordingly, higher efficiency and lower exergy destruction in CC power plant is unavoidable [7].

Using supplementary firing system (SFS) after GT has been developed by various researchers as a way to increase net power output in CCPP, especially in warm days. By using SFS, the inlet gas temperature of HRSG and consequently the power generation of steam turbine enhance. Furthermore, by utilizing of some kinds of low calorific value fuels that cannot be employed in GT cycle, SFS can increase the efficiency of HRSG and keeping constant the net power output when environmental conditions change [8].

Gnanapragasam et al. [9] analysed the impacts of applying SFS on the performance of CC as well as CO_2 emission of an integrated gasification CCPP. The authors concluded that the supplementary firing cannot improve the CC efficiency. Moreover, mitigation of CCPP efficiency and the increase of total exergy destruction as well as economic costs are the most important drawbacks of using SFS. To increase the inlet temperature of HRSG of Neka CCPP, Ameri et al. [10] proposed using a duct burner (DB) between top and bottom cycles. Based on practical data, TIT was considered 1244.15 K and the outlet temperature of the GT was 773.15 K. The mass flow rate of injected fuel to the DB was 0.8 kg/s and the hot exhaust gases of GT (773.15 K, 500 kg/s) includes 16.55% O_2 were employed as the oxidizer of DB. The authors claimed that the output power of CCPP increases by 7.38% at the present of DB. Nevertheless, it was found that the DB has a negative influence on the total CCPP exergy and thermal cycle efficiencies.

Ganjehkaviri et al. [11] evaluated the effect of steam turbine outlet quality on the output power of a CCPP. Since TIT was one of the decision variables, the optimum TIT was found 1336.78 K to simultaneously minimize initial investment and environmental burden and maximize exergy efficiency of the CCPP. Moreover, based on a multi-objective study done by Kaviri et al. [12] about the same CCPP using a genetic algorithm, it was pointed out that by using 1 kg/s fuel in DB, the temperature of exhaust gases at the inlet of HRSG increases around 70 K.

Boyaghchi and Molaie [13] investigated the influence of DB fuel mass flow rate on exergy destruction of each component of CCPP. It was revealed that by the increase of DB fuel flow rate, the avoidable exergy destruction of CCPP reduces within 23.9% while its unavoidable part increases by around 50%. Indeed, by increasing DB fuel flow rate the endogenous avoidable exergy destruction of CCPP gets 3 times where its exogenous part of avoidable decreases within 86%.

Although, several attempts have been made to analyse CCPP with additional SFS in the literature, the characteristics of DB and the effects of its combustion method on the performance of CCPP has not been developed properly yet to the best of authors' knowledge. In this paper, a new design of DB named flameless burner (FB) is proposed and the thermodynamic analyses of the CCPP is carried out.

The specific contributions of this article are as follows:

- Idea of FB implication in power generation is introduced and investigated.
- Modelling method of CC system with FB, its exergy and economic analyses are carried out.
- Optimization of CC with proposed FB is carried out.
- Environmental footprints reduction of proposed optimum cycle is evaluated and compared with the base case.

2. Flameless combustion

Preheating of the oxidizer and making the temperature inside the chamber over the auto-ignition temperature of the fuel is the basic principal of flameless combustion formation [14]. Dally et al. [15] stipulated that the structure of flame starts to alter when the level of oxygen reduces and it happens at high Reynolds number for air jet and low oxygen concentration. It was reported that in flameless combustion system, fuel consumption and the size of