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Exergic, economic and environmental impacts of natural gas and diesel in operation of combined cycle power plants

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ABSTRACT

Combined cycle power plants (CCPPs) play an important role in electricity production throughout the world. Their energy efficiency is relatively high and their production rates of greenhouse gases are considerably low. In a country like Iran with huge oil and gas resources, most CCPP's use natural gas as primary fuel and diesel as secondary fuel. In this study, effect of using diesel instead of natural gas for a selected power plant will be investigated in terms of exergy, economic and environmental impacts. The environmental evaluation is performed using life cycle assessment (LCA). In the second step, the operation of the plant will be optimized using exergy and economic objective functions.

The results show that the exergy efficiency of the plant with natural gas as fuel is equal to 43.11%, while this efficiency with diesel will be 42.03%. Furthermore, the annual cost of plant using diesel is twice as that of plant using natural gas. Finally, diesel utilization leads to more contaminants production. Thus, environmental effects of diesel are much higher than that of natural gas. The optimization results demonstrate that in case of natural gas, exergy efficiency and annual cost of the power plant improve 2.34% and 4.99%, respectively. While these improvements for diesel are 2.36% and 1.97%.

1. Introduction

Combustion of fossil fuels in thermal power plants is a well-known method to generate electricity. The United States Energy Information Administration reports that fossil fuels were responsible for 66.8% of total global generated electricity in 2009 [1]. Because of underdevelopment of renewable energies in Iran, fossil fuels play a key role in electricity generation and provide 86.2% of total generated electricity. Most of Iran's electricity energy is produced in combined cycle power plants, which use natural gas and diesel as fuels. Optimizing these power plants has a huge effect on their performance. Exergy analysis is an important tool to improve the plants efficiency and decrease the irreversibility.

Verkhivker et al. [2] studied the performance of conventional and nuclear power plants using exergy concept. Ashouri et al. [3] performed an exergy analysis on a Kalina cycle driven by Trough collector. Aljundi [4] performed an energy and exergy analyses on a steam power plant and determined energy and exergy losses for each component separately. The results showed that condenser and boiler has the most energy loss and exergy destruction, respectively. Ameri et al. [5] carried out energy, exergy and exergoeconomic analyses for a steam power plant. They investigated the influence of the ambient temperature and load variations on energy and exergy efficiencies. It was found that with increasing the ambient temperature, irreversibility rate of the plant increased. In addition, as the load rose, exergy efficiency of the components was improved. Also the results of exergoeconomic analysis showed that the boiler had the highest rate of exergy destruction. Bolatturk et al. [6] carried out exergoeconomic analysis on a steam power plant in Turkey. Ray et al. [7] performed an exergy analysis on a steam power plant, considering both design and off-design conditions. The results showed that the second law of thermodynamics is a better criterion to reflect the degradation of the system. Due to chemical reaction occurrence, most exergy destruction of power plants happens in combustion chamber. Taniguchi et al. [8] studied the combustion processes and performed an exergy analysis on them. Almasi [9] simulated gas turbine power plant in Mahshahr and optimized the plant in terms of exergy and economic. GanjeKaviri et al. [10] modeled a dual pressure combined cycle power plant equipped with a duct burner and optimized the plant based on exergy and economic objective functions. The results showed that gas turbine inlet temperature, compressor pressure ratio and pinch point temperatures have significant impact on the performance of the plant.

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Nomenclature

A	area (m^2)
CRF	capital recovery factor
$\dot{E}x$	exergy flow rate (kW)
ex	specific exergy (kJ/kg)
$\overline{ex}_i^{ch}$	standard chemical exergy (kJ/kmol)
$\dot{E}x_D$	exergy destruction rate (kW)
h	specific enthalpy (kJ/kg)
H	hour
HRSG	heat recovery steam generator
i	interest rate
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
n	number of years
P	pressure (bar)
$\dot{Q}$	heat (kW)
R	gas universal constant (kJ/kg K)
r_p	pressure ratio
s	specific entropy (kJ/kg K)
T	temperature (K)
U	total heat transfer coefficient
$\dot{W}$	power (kW)
y	molar fraction
Z	cost ($)

Greek symbols

η	energy efficiency
ξ	chemical exergy/energy ratio
φ	maintenance factor
ψ	exergy efficiency

Subscripts

0	ambient
C	capital cost
ch	chemical
cw	cooling water
e	outlet
eco	economizer
env	environment
eva	evaporator
f	fuel
i	inlet
$O\&M$	operating and maintenance
ph	physical
Pz	primary zone
sup	superheater

With increasing environmental concerns and also due to increased pollution control costs, environmental issues of power plants have become more important. Shahsavari et al. [11] studied 32 gas turbines and 20 steam turbines in Iran and computed the emission factors of these power plants. They compared the obtained emission factors with the standard ones given by Energy protection agency, Euro Union and World Bank. The results showed that gas turbines have a better performance than steam power plants. In another work, Nazari et al. [12] calculated the emission factors of CO_2, SO_2 and NO_x for fifty thermal power plants in Iran. Also they calculated the emission factor of SO_2 in steam power plants which used heavy oil as fuel [13]. Ahmadi et al. [14] took into account the environmental objective function along with exergy and economic objective functions and optimized the plant. They also studied the effect of supplementary firing on CO_2 emissions and the operation of the plant.

Ganjekaviri et al. [15] performed an exergoeconomic analysis on a combined cycle power plant. The results indicated that using the optimum values, 6% increase could be reached, while CO_2 production reduces by 5.63%. However, cost changes were less than 1%. Restrepo et al. [16] studied a pulverized coal power plant in Brazil in terms of exergy and environment and determined the exergy destruction and the environmental impacts of the plant. The environmental analysis performed based on life cycle assessment (LCA) using SimaPro 7.2. Seyyedi et al. [17] proposed a new approach for optimization of thermal plants using exergoeconomic analysis, sensitivity analysis, and structural optimization method. Boyaghchi and Molaie [18] using advanced exergy analysis method, studied the effect of duct burner fuel mass flow on the performance of a combined cycle power plant. It is revealed that with increasing the duct burner fuel mass flow, the avoidable exergy destruction of the plant decreases, while its unavoidable part increases. Acikkalp et al. [19] performed the same analysis on a power plant in Turkey. Meyer et al. [20] combined exergy and environmental analyses and introduced the exergoenviromental objective function. The approach of exergoeconomic analysis has been modified to deal with an evaluation of the ecological impact instead of an economic problem. Petrakopulo [21] used advanced exergoenvironmental method and divided the environmental effects of a combined cycle power plant into avoidable and unavoidable and also internal and external. Silveira et al. [22] compared a 1000 MW combined cycle power plant fed with natural gas and a 1000 kW diesel power plant in terms of efficiency, economic and environmental issues.

The aim of this study is to compare the effects of two commonly used fuels, natural gas and diesel, on the performance of a CCPP. The comparison is performed in terms of exergy, economic and environmental impacts. A common way to perform such analyses is to apply exergoeconomic and exergoenvironmental methods. In these methods, economic and environmental analyses are combined with exergy analysis. The main idea of these methods is based on the assumption that exergy is a basis to assign the cost and environmental impact of energy conversion system equipment. But it should be noted that exergy focuses on the equipment units, rather than the flow sheet level [23]. Furthermore economic and exergetic aspects are often in conflict. In this paper, exergy, economic and environmental analyses of a CCPP which can use natural gas and diesel, are carried out independently and then the effect of these fuels on the performance of the plant is also investigated. The environmental analysis is performed using life cycle assessment. Finally, exergetic efficiency and economic of the plant are optimized using single and multi-objective optimization. To have a better flexibility in the plant performance, a duct burner is added to the cycle and the effect of this component on the plants performance is studied.

2. System description and assumptions made

The analysis is applied to Montazer ghaem combined cycle power plant located in Karaj, Iran which uses natural gas and diesel as fuels. The schematic diagram of the plant is represented in Fig. 1. Natural gas is a hydrocarbon gas mixture consisting primarily of methane. Therefore, natural gas is assumed to be pure methane [18,24,25]. With this assumption, the combustion reaction that takes place in the combustion chamber can be described as follows: