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Advanced exergy analysis of an electricity-generating facility using natural gas

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ABSTRACT

This paper deals with the performance assessment of an electricity generation facility located in the Eskisehir Industry Estate Zone in Turkey using advanced exergy analysis method. The exergy efficiency of the system is determined to be 40.2% while the total exergy destruction rate of the system is calculated to be 78.242 MW. The exergy destruction rate within the facility's components is divided into four parts, namely endogenous, exogenous, avoidable and unavoidable exergy destruction rates. Through this analysis, the improvement potentials of both the components and the overall system along with the interactions between the components are deducted based on the actual operational data. The analysis indicates that the combustion chamber, the high pressure steam turbine and the condenser have high improvement potentials. The relations between the components are weak because of the ratio of the endogenous exergy rates of 70%. The improvement potential of the system is 38%. It may be concluded that one should focus on the gas turbine and combustion chamber for improving the system, being the most important components of the system.

1. Introduction

Gas turbines consist of a compressor, a combustion chamber and a turbine while they have been widely used in the industry and transportation sectors. For example, they are used in energy production facilities, aircrafts, transport ships, and even cars and motorcycles. Gas turbines have some particular advantages, such as low annual cost, fast activation, flexible operation, and fast and easy maintenance. In addition, the most important advantage of gas turbines is that their efficiency is high (approximately 40%). Unfortunately, gas turbines also have disadvantages. Gas turbine maintenance costs are high, they are sensitive to ambient conditions, and they are sensitive to electricity voltage change. Gas turbines are primarily used in combined heat and power (CHP) generation facilities in industry. CHP facilities produce electricity and heat energy from one type of fuel, generally natural gas. The efficiency of such a facility can reach 70–80% [1]. In addition to the economic and efficiency benefits, their environmental impact is an important factor. Gas turbines have low greenhouse gas emissions compared to many other power generation systems.

All energy conversion systems must be analyzed in terms of energetic, economic, and environmental aspects for a proper management. Exergy-based analyses are very convenient methods for assessing the performance of energy conversion systems. Exergy is the maximum work that can be obtained from a system. Exergy-based analyses help determine the irreversibilities (entropy generation) and how a source can be used effectively. However, exergy-based analyses lack some information, which will be discussed in Section 3.2 in more detail. Basically, the results of an exergy-based analysis cannot be used to consider the potential improvement of the system or its components, and they do not provide any information about how one component affects one another. This lack of information can be addressed through advanced exergy-based methods [2,3].

There are a few studies on advanced exergy-based analyses of power-generating systems in the open literature [3–15]. Tsatsaronis [3] discussed the weaknesses of conventional exergy-based analyses in developing improvement strategies and presented advanced exergy, advanced exergoeconomic and exergoenvironmental analyses as solutions to these weaknesses. Tsatsaronis and Moung-Ho [4] were the first to develop the concepts of avoidable and unavoidable exergy destruction, which were used to determine the potential of improving the thermodynamic performance and cost effectiveness of a system. Cziesla et al. [5] investigated

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Nomenclature

$\dot{E}$	exergy rate (MW)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
T	temperature (K)
y	exergy destruction ratio

Abbreviations

AC	air compressor
CC	combustion chamber
COND	condenser
GT	gas turbine
HPST	high pressure steam turbine
HRSG	heat recovery steam generator
LPST	low pressure steam generator

Subscripts

D	destruction
F	fuel
k	kth component
L	loss
P	product
tot	total

Superscripts

AV	available
EN	endogenous
EX	exogenous
UN	unavoidable

Greek letters

η	isentropic/energetic efficiency (%)
φ	exergetic efficiency (%)

all of an externally fired combined power plant's components according to both avoidable and unavoidable exergy destruction; the associated costs were defined, and the results of their study were discussed. Kelly et al. [6] defined the exogenous and endogenous exergy destructions that determine the interactions between components, and they were the first to submit the calculation method they presented. The calculations were expressed using a simple refrigeration cycle and a simple gas turbine cycle. Razmara and Saray [7] investigated the destruction of exogenous and endogenous exergy by the engineering method for a simple gas turbine cycle operating using different fuels. The irreversibilities observed in the components were described and compared for these fuels. Morosuk and Tsatsaronis [8] applied advanced exergy analysis to a simple gas turbine cycle to assess its performance and discussed their calculation methods in detail. Tsatsaronis and Morosuk [9] performed advanced exergy analysis of a natural gas liquefaction plant using a three-stage refrigeration cycle. They defined the improvement potentials and interactions between the components. Morosuk et al. [10] analyzed a natural gas degasification plant that produced electricity using advanced exergy and advanced exergoenvironmental methods. They concluded that the expander II, the heat exchanger II and the pump deserved the most attention in improving the thermodynamic efficiency and reducing the environmental impact of the plant. Wang et al. [11] analyzed a power plant operating under supercritical conditions using advanced exergy analysis and proposed suitable optimization strategies. They recommend that the generator be improved first, followed by the turbines. Petrakopoulou et al. [12] studied a combined power plant using advanced exergy and conventional analyses and demonstrated the superiority of the former. They reported that an advanced exergy analysis provided a wide range of optimization strategies and potential improvements. Petrakopoulou et al. [13] applied advanced exergy and advanced exergoenvironmental analysis methods to a combined power plant. They determined that 68% of the environmental impact of the system was unavoidable. In Refs. [14,15], an advanced exergoeconomic analysis was applied to a combined (CHP) system and oxy-fuel power plant with CO_2 capture, and the methodology employed to conduct advanced exergoeconomic analysis was explained in a detailed manner.

In the present paper, an advanced exergy analysis method is applied to an electricity-generating facility using natural gas. Thus, the actual potential improvements of the system and the relationships between the components are determined, and possible suggestions towards increasing the system efficiency are provided.

2. System description

The electricity-generating facility using natural gas is shown in Fig. 1. This system is located in the Eskişehir Industry Estate Zone, Turkey. The system consists of a compressor (AC), a combustion chamber (CC), a gas turbine (GT), a heat recovery steam generator (HRSG), a high pressure steam turbine (HPST), a low pressure steam turbine (LPST) and a condenser (COND). Approximately 37 MW of electricity is generated by the system, but the process steam cannot be used because of the chemicals included in the steam. A 45.07 air/fuel ratio combustion equation for natural gas is as follows [16–19]:

$$\begin{aligned}&0.9334CH_4 + 0.00211C_2H_6 + 0.00029C_3H_8 + 0.00012C_4H_{10}\\&+ 0.06408N_2 + 26.5187(0.7748N_2 + 0.2059O_2\\&+ 0.0003CO_2 + 0.01H_2O)\\&\rightarrow 0.9469CO_2 + 2.3800H_2O + 3.5831O_2 + 20.8671N_2\end{aligned} \tag{1}$$

The specific heat of the combustion gas and the air can be calculated from Eqs. (2) and (3), respectively [16–19]:

$$c_{P,gas}(T) = 0.935301 + \frac{0.010577}{10^2}T + \frac{0.017218}{10^5}T^2 - \frac{0.072386}{10^9}T^3 \tag{2}$$

$$c_{P,air}(T) = 1.04841 - 0.000383719T + \frac{9.45378}{10^7}T^2 - \frac{5.49031}{10^{10}}T^3 + \frac{7.92981}{10^{14}}T^4 \tag{3}$$

The lower heating value of the natural gas, the gas constant of the combustion gas and the gas constant of air are 44661 kJ/kg, 0.2947 kJ/kg K and 0.2870 kJ/kg K, respectively, and the specific exergy of natural gas (C_aH_b) is calculated as follows [20]:

$$\frac{e_{ch,F}}{LHV} = \lambda_F = 1.033 + 0.0169\frac{b}{a} - \frac{0.0698}{a} \tag{4}$$

where λ_F is 1.0308. The fixed parameters of the system are listed in Table 1.