Energy and Buildings 80 (2014) 268–275

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Advanced exergy analysis of a trigeneration system with a diesel–gas engine operating in a refrigerator plant building

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ARTICLE INFO

Article history:
Received 9 March 2014
Received in revised form 22 May 2014
Accepted 23 May 2014
Available online 3 June 2014

Keywords:
Exergy analysis
Advanced exergetic analysis
Exergy destruction
Trigeneration system

ABSTRACT

In this paper, a trigeneration system is analyzed using an advanced exergy analysis. The trigeneration system is located in the Eskisehir Industry Estate Zone in Turkey. The exergy efficiency of the system was found to be 0.354, while the total exergy destruction rate of the system was 16.695 MW. The purpose of this study is to determine the improvement potential of the system. The exergy destruction within the components of the facility is divided into four parts: endogenous, exogenous, avoidable and unavoidable exergy destruction. The components of the trigeneration system have strong relationships with each other since the endogenous exergy destruction of the components is smaller than the exogenous exergy destruction. The avoidable exergy destruction rates are generally greater than the unavoidable ones. Thus, the trigeneration system possesses a high potential for improvement. This analysis indicates that from a thermodynamic perspective, the turbo air compressor is the most important component in the system. Through the advanced exergy analysis, information about the relationships among the system components as well as the potential for further improvements may be provided in more detail.

1. Introduction

The world's energy demands have been increasing dramatically over the past decade. Despite the increasing energy demand, environmental issues have gained importance, due to the harmful effects of global warming and the burning of fossil fuels. Therefore, improving the efficiency of power plants and investigating more efficient energy conversion systems has become a priority. The efficiency of conventional power plants based on single prime movers is usually less than 39% [1]. Thus, most of the energy is lost as waste heat. Integrating cooling and heating subsystems into a conventional plant could increase the plant's overall efficiency to 80% [1–3]. Trigeneration is a system used to produce power, heating and cooling using a primary energy source. Trigeneration can be described as a special type of the combined heat and power (CHP) systems that provide heat and power using a primary energy source. In a trigeneration plant, the waste energy from a generation unit, such as a gas turbine, is used to drive both the heating and cooling systems. Therefore, the use of a trigeneration plant results in an improvement of the total efficiency and a reduction of the contamination to the environment.

As it is known, buildings have great ratio in the total energy consumption. Therefore, integrating trigeneration systems to buildings are interoperated as reasonable solutions. Furthermore, exergy based analyses should be performed to use resources efficiently and to protect environment in the buildings. For this reason, researches have started conducting various exergetic, exergoeconomic and exergoenvironmental studies about trigeneration systems in the buildings. Some research examples can be arranged as follows: Santo investigated energy and exergy efficiencies of atrigeneration system using at a building under two different operation strategies [4]. Basrawi et al. [5] made a theoretical evaluation of a micro co/trigeneration system in a tropic region. Lozano et al. [6] analyzed a trigeneration system installed in a building economically. A trigeneration system was evaluated by integrated cascade refrigerators for supermarkets [7]. Coskun et al. [8,9] proposed new thermodynamic parameters for evaluating the performance of geothermal district heating systems.

Each energy conversion system must be analyzed to determine the inefficiencies in the system. Conventional exergy-based analyses are powerful tools that are used to determine such inefficiencies. Exergy is the maximum work that is obtained from the system. However, conventional exergy-based analyses only

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http://dx.doi.org/10.1016/j.enbuild.2014.05.029
0378-7788/

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
ACH	absorption chiller
CAC	compressed air cooler
E	engine
G	generator
HESG	heat recovery steam generator
JWC	jacket water cooler
JWH	jacket water heater
LOC	lubrication oil cooler
LOH	low pressure steam generator
LTC	low temperature cooler
PEC	purchased equipment cost ($)
T	turbine
TAC	Turbo Air Compressor

Subscripts

D	destruction
F	fuel
k	kth component
L	loss
P	product

Superscripts

AV	available
EN	endogenous
EX	exogenous
UN	unavoidable

Greek letters

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

provide information on the inefficiencies (irreversibilities) and merely provide an indication of the quality of energy use; these analyses do not provide information about the relationships among the system components, i.e., they cannot define the potential for improvement. To resolve the deficiencies in the conventional exergy analysis, a thermodynamic analysis method called advanced exergy analysis was developed. There is only limited number of papers in the literature related to such advanced exergy-based analyses of power generating systems [10–23]. In Ref. [10], the avoidable/unavoidable exergy destruction concepts were defined firstly. In Ref. [11], exergy destructions of a combined power cycle were divided into avoidable/unavoidable parts. Tsatsaronis explained advanced exergy – based analyses in detail [12]. Endogenous and exogenous exergy methods were presented detailed in [13]. In [14,15], advanced exergy analysis was applied to simple gas turbine cycles. Advanced exergy based analyses were used in liquid natural gas and electricity generation facilities in the studies reported in the references [16] and [17]. A supercritical power plant was evaluated with advanced exergy methods in Ref. [18]. Conventional and advanced exergy analyses were applied to combined power cycle and results were compared [19]. New methods to assess the thermal systems in terms of environmental and economic ways were investigated in detail [20,21]. In Refs. [22,23], a geothermal district heating system was evaluated as advanced exergy and exergoeconomic analyses.

In this paper, a trigeneration system in a refrigeration plant building was investigated according to an advanced exergy analysis. Thus, the real improvement potential of the system and the relationships among the components were determined in detail, and suggestions were made to improve the performance of the system.

2. System description

The trigeneration system is shown in Fig. 1. This system is located in the Eskişehir Industry Estate Zone in Turkey. The trigeneration system is composed of an engine (E), a turbine (T), an air compressor (AC), a compressed air cooler (CAC), a heat recovery steam generator (HRSG), a lubrication oil heater (LOH), a lubrication oil cooler (LOC), a low temperature cooler (LTC), a jacket water heater (JWH), a jacket water cooler (JWC), an absorption chiller (ACH) and a generator (G). The engine, which is the primary mover of the system, is a duel fuel engine that operates on a combination of the Diesel and Otto cycles, but the engine is more closely to be considered as a Diesel cycle engine. The engine uses pilot fuel to initiate combustion and then operates on natural gas. The trigeneration system generates approximately 5900 kW of electricity, 4300 kW of which is in the form of heat energy that is used to meet the demands of the factory, and 600 kW of which is cooling energy. The combustion equations of the diesel fuel and the natural gas can be expressed as Eqs. (1) and (2), respectively [24,25]:

$$\begin{aligned}&0.000216C_{14.09}H_{24.78}+0.495522(0.7748\,N_2+0.2059O_2\\&+0.0003CO_2+0.019H_2O)\rightarrow 0.003172CO_2+0.012073H_2O\\&+0.097676O_2+0.383931\,N_2\end{aligned}\tag{1}$$

$$\begin{aligned}&0.0021816(0.9334CH_4+0.00211\,C_2H_6+0.00029\,C_3H_8\\&+0.00012\,C_4H_{10}+0.06408\,N_2)+0.383931\,N_2+0.097676O_2\\&+0.003172CO_2+0.012073H_2O0.023656CO_2+\rightarrow 0.052975H_2O\\&+0.056741O_2+0.385329\,N_2\end{aligned}\tag{2}$$

The specific heats of the combustion gas and the air can be calculated using Eqs. (3) and (4), respectively [24,25]:

$$c_{P,gas}(T)=0.93750+\frac{0.01215}{10^2}T+\frac{0.01670}{10^5}T^2-\frac{0.07164}{10^9}T^3\tag{3}$$

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

The lower heating values of the natural gas and the diesel fuel were 44661 kJ/kg and 42640 kJ/kg, while the gas constants of the combustion gas and air were 0.29453 kJ/kg K and 0.2987 kJ/kg K, respectively [22,23]. The specific exergy of the natural gas (C_aH_b) was calculated as follows [26]:

$$\frac{e_{ch,F}}{LHV}=\lambda_F=1.033+0.0169\frac{b}{a}-\frac{0.0698}{a}\tag{5}$$

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