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Simulation and multi-objective optimization of a combined heat and power (CHP) system integrated with low-energy buildings

Jamasb Pirkandi [a], Mohammad Ali Jokar [b], Mohammad Sameti [b,*], Alibakhsh Kasaeian [b], Fazel Kasaeian [c]

[a] Department of Aerospace Engineering, Malek Ashtar University of Technology, Tehran, Iran
[b] Department of Renewable Energies, University of Tehran, Tehran, Iran
[c] Department of Materials Science and Engineering, Sharif University of Technology, Tehran, Iran

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ABSTRACT

One of the novel applications of gas turbine technology is the integration of combined heat and power (CHP) system with micro-gas turbine which is spreading widely in the field of distributed generation and low-energy buildings. It has a promising great potential to meet the electrical and heating demands of residential buildings. In this study, a MATLAB code was developed to simulate and optimize the thermoeconomic performance of a gas turbine based CHP cycle. Three design parameters of this cycle considered in this research are compressor pressure ratio, turbine inlet temperature, and air mass flow rate. Firstly, two objective functions including exergetic efficiency and net power output were chosen to achieve their maximum level. Variation of exergy destruction rate and exergetic efficiency with three turbine inlet temperatures (1000, 1100, and 1200 K) and three air mass flow rates (0.25, 0.3, and 0.35 kg/s) were also studied for each component. Exergetic efficiency increased relatively to maximum 3% within this temperature limit. Based on the exergetic analysis, suggestions were given for reducing the overall irreversibility of the thermodynamic cycle. To have a good insight into this study, a sensitivity analysis for important parameters was also carried out. Finally, based on the exergy analysis and utilization of economic and environmental functions, a multi-objective approach was taken to optimize the system performance.

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1. Introduction

A low-energy building is any type of building that from design, technologies, and building products uses less energy, from any source, than a traditional or average contemporary house [1]. They are the practice of sustainable design, sustainable architecture, low energy building, energy-efficient landscaping [2], and energy system optimization [3]. Meanwhile, distribute generation (DG) is predicted to play an increasing role into the electric power system for buildings in the near future [4]. Distributed energy resources are small modular power generation systems that can be located at or near the site where energy is used. In conventional energy systems, electrical power is conveyed from large-scale plants located far away from the consuming region, while energy for heating is supplied separately as fuel. In this way, more than 50% of the energy content of the fuel is lost at the power plant alone because of energy conversion inefficiencies and is discharged in the form of waste. Further losses occur in the electric power transmission and distribution network in the form of electric current losses and power transformation losses [5,6]. DG with a cogeneration system is one of the options because it can efficiently utilize exhaust heat. Following are the benefits of such a power generation [7]:

- This system can be easily and effectively installed and operated both in high-demand or rural areas.
- Power can be distributed and transmitted with low losses.
- Exhaust heat can be used efficiently by this system.
- This system can either be used independently or as a supportive system.

Many studies have been conducted many aspects of cogeneration systems. Today the main potential for CHP dissemination seems to be in the residential sector. Until the present, several technical, environmental, economic and legislative problems have curbed the spread of CHP technology in this sector, especially for electric power sizes of a few kW [8–10]. Additionally, authors

* Corresponding author. Fax: +98 21 88617087.
E-mail address: muh.sameti@ut.ac.ir (M. Sameti).

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Nomenclature

C_f	Cost of fuel per energy unit ($/kJ)
C	Cost flow rate ($/s)
C_P	Specific heat at constant pressure (kJ/kg K)
CRF	Capital recovery factor
$\dot{E}x$	Exergy flow rate (kW)
$\dot{E}x_D$	Exergy destruction rate (kW)
e	Specific exergy (kJ/kmol)
h	Enthalpy (kJ/kg)
k	Specific heat ratio (C_p/C_v)
LHV	Lower heating value (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
N	Annual number of the operation hours of the unit
P	Pressure (KPa)
R	Gas constant (kJ/kg K)
r_p	Compressor pressure ratio
S	Entropy (kJ/kg K)
T	Temperature (K)
U	Overall heat transfer coefficient (W/m^2 K)
$\dot{W}_{net}$	Net power output (kW)
Z	Capital cost of the component ($)
$\dot{Z}$	Capital cost rate of the component ($/s)
ΔP	Pressure drop (K Pa)
ΔTLM	Log mean temperature difference (K)
η	Efficiency
ξ	Ratio of chemical exergy to lower heating value
γ	Specific heat ratio
φ	Maintenance factor of the equipment
X_i	Molar fraction

Subscripts

a	Air
AC	Air compressor
CC	Combustion chamber
e	Exergetic
f	Fuel
FC	Fuel compressor
g	Combustion gases
gen	Generator
GT	Gas turbine
HE	Heat exchanger
Q	Heat rate (kW)
rec	Recuperator
W	Work (kW)

Superscripts

ch	Chemical
ph	Physical

proposed numerous researches in the operation of CHP systems in large power plants e.g. [11,12]. Karaali et al. [12] introduced a novel thermoeconomic optimization method for real complex cycles. The objective of this paper is to apply this method to four cogeneration cycles that are simple cycle, inlet air cooling cycle, air preheated and air–fuel preheated cycles for analyzing and optimizing. The four cycles are thermoeconomically optimized for constant power and steam mass (30 MW and 14 kg/s saturated steamflow rate at 2000 kPa), for constant power (30 MW) and for variable steam mass, and for variable power and steam mass by using the cost equation method and the effect of size on equipment method.

Cogeneration systems utilizing internal combustion engines and gas turbines in open cycle are the most utilized technologies in this field worldwide. The interest of MGTs as distributed energy systems lies in their low environmental impact in terms of pollutants. MGTs present some unique characteristics compared with the larger gas turbine engines. The largest gas turbines operate at 3,000 or 3,600 rpm (revolutions per minute) to match the AC power grid and micro turbines operate around 100,000 rpm. They have the ability to burn most commercial fuels, such as natural gas, propane, diesel and kerosene. They also accept biogas from landfills and sewage treatment plants [13,14].

MGTs are usually designed for natural gas, but there is the ability to utilize other fuels such as those based on biomass. Mozafari et al. [15] performed the optimization of MGT by exergetic–economic–environmental analysis considering various fuels for the system. The results showed that and the trends of variations of second law efficiency and cost rate of owning and operating the whole system are independent of the fuels. In this article the fuel which is used in the combustion chamber is methane (CH_4).

Thermodynamic analysis can be a perfect tool for identifying the ways for improving the efficiency of fuel use, and determining the best configuration and equipment size for a cogeneration plant [16]. As mentioned above, extending this system to combined heat and power generation is a way of increasing productivity with recovery of the heat discarded from the inefficient energy conversion of producing electrical power. These systems are expected to find applications in the cogeneration market for various heating and power requirements [17].

A thermodynamic analysis is proposed in this paper to study MGT to minimize fuel consumption and maximize net exergetic efficiency. Energetic, economic and environmental performance of the system are investigated. The energy and entropy balance equations of the entire system will be additionally obtained. To find the optimum design parameters of the system genetic algorithm is used and a simulation program is developed in MATLAB software. This simulation investigates the effects of various performance parameters, such as the compression ratio (r_p), mass flow rate of air and turbine inlet temperature (TIT), on the exergetic efficiency and irreversibility of the plant. Sensitivity studies for two important parameters including net power generation and exergetic efficiency is done to show the abilities and authenticity of simulated system. Next, a common economic analysis for the system is carried out. The quantity of NO_x and CO emissions is considered for environmental purposes. In the present study, the cost of pollution damage is considered to be added directly to total cost rate of the system production. Therefore, the third objective function is sum of the thermodynamic and environomic objectives.

In the heat production sector, there is several choices to select the kind of heat production including hot water, steam water, hot air and even producing cold water after an absorption chiller cycle. In this article, we really did not discuss this issue and to demystify the exergetic efficiency of the system and calculate the total cost rate, we assume that a water pump is driven using electricity produced by micro-gas turbine to pump the water in ambient temperature into the heat exchanger and hot water temperature of 80 °C will be delivered to the residential consumer.

In the open literature, various configurations of integrating micro-gas turbine and regenerator have been analyzed [18,19,20,21,22]. Caresana et al. focused on the effect of ambient

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