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Assessment of off-design performance of a combined cooling, heating and power system using exergoeconomic analysis

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ABSTRACT

This paper presents the exergy and exergoeconomic analyses of a typical combined cooling, heating and power (CCHP) system under off-design conditions. The exergoeconomic-related parameters and unit exergoeconomic cost of the flows are discussed using the exergy cost allocation method based on energy level (ECAEL). The absorption chiller is found to have an improved potential because of the highest relative cost difference and its continual increase with the decrease of the output power. According to the exergoeconomic factor analysis, the exergoeconomic performance of the turbine and combustor among all the components can be enhanced by decreasing the investment and destruction, respectively. Next, the unit energy costs of different products in the output power range (100–20%) including electricity, cooling and heating energy for users, are calculated. The results show that the electricity increases faster than that of other products from 0.537 to 1.077 Yuan/kWh. Finally, the sensitivity analyses for the unit energy cost of the products are presented with different influencing parameters, such as the natural gas price, service life and discount rate. This exergoeconomic analysis may provide guidance for evaluating the products in distributed energy systems for energy networks.

1. Introduction

A combined cooling, heating and power (CCHP) system, which consists of the power technologies and surplus heat recovering equipment and is close to end users, can be considered as a powerful supplement to traditional centralized grids. The main advantages of using a CCHP system lays in its high energy efficiency and low pollutant emission owing to the recent cascade in the utilization of fuel energy; therefore, the CCHP system has attracted increasing attention from researchers and had widespread applications [1–3].

Proposing new structures is an applicable method to improve the thermodynamic performance of CCHP systems. Wang et al. [4] proposed a new CCHP system from the basis of the conception of energy cascade utilization. There was more low-temperature exhaust heat (13–14%) deeply-recovered to preheat the feed water, and as a consequence, higher energy efficiency was presented for this system. Due to the mismatch between the energy supply and demand, the system is frequently operated under partial-load conditions, which decreases the performance of the distributed energy system. The energy storage subsystem is always added to balance this difference [5,6]. Moreover, the solar energy has been used in various forms for CCHP systems in recent years. The electric power can be directly generated from the photovoltaic cell to provide the electricity for users [7], and solar thermal energy is used in the CCHP systems [8,9].

The exergy analysis is used to quantify the irreversible destruction of components and presents the energy efficiency of CCHP systems. Mohammadi et al. [10] coupled a Kalina cycle with a reverse osmosis subsystem to produce cooling, heating and power. Optimizing the pressure of the flash evaporator and separator, the exergy efficiency of this system could be increased by 0.6% and 4.64%, respectively. A new CCHP system coupled with an ammonia-water Rankine cycle was proposed by Wang et al. [11] where the exergy destruction of the absorption chiller was decreased compared with that of a typical CCHP system. Chang et al. [12] developed a CCHP system consisting of a high-temperature fuel cell subsystem, an organic cycle and a vapor compression cycle. Based on the exergy efficiency, the output power and absorption chiller coefficient of performance, the best organic solution was selected from six different working fluids. Xu et al. [13] showed the energy and exergy analysis for the CCHP system using supercritical carbon dioxide. The results indicated that the exergy efficiency of this system was boosted from 10.4% to 22.5% when the extraction turbine was added in the traditional carbon dioxide ejector system. Moreover,

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Nomenclature

CCHP	combined cooling, heating and power
COP	coefficient of performance
CRF	capital recovery factor
E	electricity, kW
ECAEL	cost allocation method based on energy level
f	exergoeconomic factor
H	enthalpy, kW
k^*	unit exergoeconomic cost, Yuan/kWh
L^*	unit energy cost, Yuan/kWh
LHV	lower heating value
m	mass flow rate, kg/s
N	annual service hours, h
Q	heat, kW
r	relative cost difference
S	entropy, kW
T	temperature, °C
Z	investment of component, Yuan

Greek letters

η	efficiency
ε	exergy for the gas turbine working flow
π	compressor ratio
λ	factor of the operating and maintenance costs

Subscripts

0	ambition condition
ABC	absorption chiller
C	cooling
COMB	combustor
COMP	compressor
EX	hot water exchanger
F	fuel
GE	generator
H	heating
P	product
TUR	turbine

the largest exergy destruction of different components was found in [14,15], which provided the specific direction and potential to manage the performance of CCHP systems. In actual operations, a much higher operation time is occupied under partial-load conditions to satisfy the variations of the users' energy demand. Chen et al. [16] showed the partial-load performance of the CCHP from the exergy and energy level perspective. Less fuel was consumed in the CCHP system than that of the separate system when the partial-load level was higher than 30%. In addition, the combustor risked for the largest exergy destruction, which accounted for 45% of the input exergy, was followed by the absorption chiller. In the literature [14], the thermodynamic efficiencies of a CCHP system coupled with biomass air gasification in different seasons were investigated. Compared with the other seasons, the exergy efficiency was highest for the summer. Esen et al. presented the energy and exergy analysis of a ground-coupled pump system with two ground heat exchangers. The energetic and exergetic efficiencies was increased with the increasing the heat source temperature in heating season [17].

To investigate the technical feasibility of the proposed energy system, a techno-economic analysis must be presented. The techno-economic analysis is mainly based on the aspect of system payback period, annual cost and net present value [18–20]. Moreover, combined with the economic analysis, the thermodynamic analysis was extended from the exergy to the exergoeconomic analysis proposed by Tribus et al. [21]. In recent years, different exergoeconomic methods, such as the extraction (EX) and equality method [22], the specific exergy costing (SPECO) method [23], and the energy level (ECAEL) method [24] have been proposed. Based on the SPECO method, the possible construction site and components have been suggested for a district heating system [25]. Gungor et al. [26] presented an advanced exergoeconomic analysis on a gas engine heat pump. The exergy destruction presented in an avoidable part could be decreased by improving the structure of the component. Sahoo et al. [27] developed the exergoeconomic optimization for a cogeneration system. As a consequence, the cost of products including steam and electric power, were decreased by 9.9% compared with that of the base case. The double-effect absorption chiller with different structures was discussed from the viewpoint of the exergoeconomic analysis and provided the guidance for the selection [28]. Moreover, Cavalcanti et al. [29] carried out a detailed analysis on a Rankine cycle assisted by solar radiation. The unit cost of electric power and other products was calculated, and the exergoeconomic indexes including the relative cost difference and the exergoeconomic factor for the components, were evaluated. The exergoeconomic analysis was applied to determine the cost of material flows under dynamic conditions in a plant, thus providing the pricing standard in different seasons [30]. The energy-saving potential for a compressed air energy storage system coupled with thermal storage was presented in the literature [31]. According to the exergoeconomic analysis, the cost of electricity was decreased by 13.37% over that of the traditional system without thermal storage. However, there are limited works involving an exergoeconomic analysis with a multi-

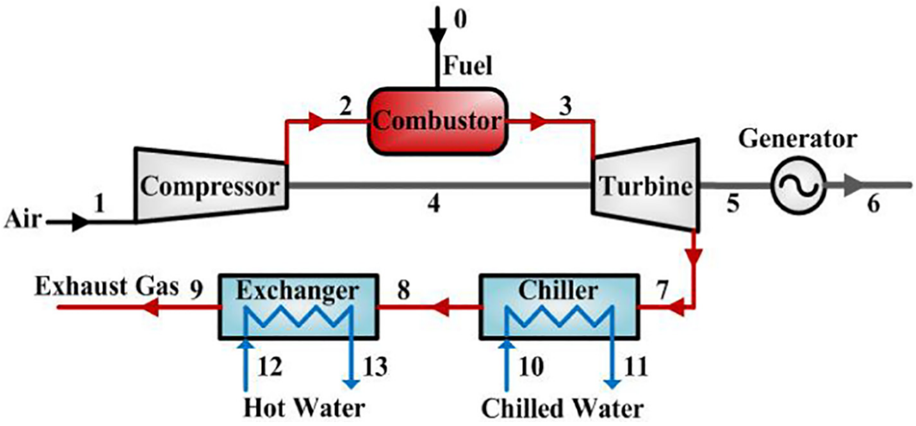

Fig. 1. Schematic diagram of a typical CCHP system.