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The exergy and energy level analysis of a combined cooling, heating and power system driven by a small scale gas turbine at off design condition

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HIGHLIGHTS

- The design and off-design performance of a small-scale gas turbine is studied.
- The design and off-design performance of an absorption chiller is studied.
- An analysis module based on the concept of energy level is developed in this paper.
- Energy level and exergy analysis was conducted on the CCHP system.
- The CCHP performance serving a building cluster was evaluated by the dynamic data.

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ABSTRACT

This paper presents the off design performance analysis of a combined cooling, heating, and power (CCHP) system consisting of a small-scale gas turbine, an exhaust-fired double-effect absorption chiller, and a heat exchanger. The energy and exergy analyses of the CCHP system are investigated under the rated and part-load conditions. Energy level analysis is implemented on the energy conversion processes to reveal the mechanisms of the deterioration of the CCHP performance under part-load conditions. The results show that the CCHP system is energy saving when the power output of the gas turbine exceeds 30% of the full load. It is also found that the CO_2 emission of the CCHP system reduced by 66.7%–70.5%, compared with conventional separation system, when the power output of gas turbine increased from about 30% to 100%. Energy level results reveal that the combustor of the small-scale gas turbine mainly contributed to the deteriorated performance of the CCHP system. In addition, a case study is carried out to illustrate the advantage of using dynamic data in the performance assessment. The case results indicate that using off-design data leads to a more realistic evaluation of the CCHP system.

1. Introduction

Combined cooling, heating, and power (CCHP) systems are integrated energy systems that produce electricity, cooling, and heating simultaneously, which are also referred to as trigeneration [1,2]. In a CCHP plant, the exhaust heat of a power generation unit was recovered for further utility, such as cooling and heating, among others, instead of ejecting to the environment as that in a conventional power plant. In China, CCHP has a great potential in issues concerning the sustainable energy system transition [3]. With the availability of gas turbine spanning an increasingly wide range of capacities, the utilization of CCHP has becoming increasingly attractive via a combination of gas turbines and absorption chillers [2,4–6].

Much research on gas turbine CCHP systems has been conducted in recent years. Bassols et al. [7] have presented different examples of the application of CCHP systems driven by gas turbine in the food industry, of which the waste heat was recovered by ammonia absorption chiller. Ghaebi et al. [8] have analyzed gas turbine powered CCHP system from exergetic and thermoeconomic points of view. The analysis were carried out based on the combination of energy, exergy and thermoeconomic analyses. Khaliq [9,10] performed a second law performance analysis on the gas turbine trigeneration system, which consists of a gas turbine, a heat

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recovery steam generator, and a single effect absorption chiller. The effect of the parameters, such as the pressure ratio and the process steam pressure on the thermodynamic performance of the system, were studied. The exergy destruction on each component of the system was calculated under a different pressure ratio of the gas turbine. Kong et al. [11] analyzed the problem of optimal energy management in the CCHP system by using a simple linear programming model, and concluded that the operation of the turbine may not be optimized when the electric-to-gas cost ratio is very low. The energy system consists of a gas turbine, an absorption chiller, and a heat recovery boiler. Ghaebi et al. [12] have investigated the exergoeconomic optimization of a CCHP system consisting of a gas turbine, a heat recovery steam generator and a single effect absorption chiller. Ahmadi et al. [13] have presented exergy-based optimization for the best design parameters chosen for a polygeneration system. In another research, Ahmadi et al. [14] proposed a new multigeneration system consisting of a gas turbine, a dual pressure heat recovery steam generator, an absorption chiller, an ejector refrigeration cycle, and a proton exchange membrane electrolyzer. Energy, exergy analyses and an environmental impact assessment are carried out.

The integration of a micro gas turbine that is coupled directly with the Lithium Bromide–water (LiBr–H_2O) absorption chiller is another emerging technology for the spread of distributed energy. Bruno et al. [15] compared the different configuration, and the Coefficient of Performance (COP) of the chillers is found to be higher than that in a single effect configuration. A wider range of chilled water production is also available because of the decoupled chillers. Huicochea et al. [16] evaluated the theoretical performance of a CCHP system consisting of a micro gas turbine and a double-effect absorption chiller. Experimental data was used from the manufacturer to determine the performance of the micro gas turbine. Different operating conditions such as the ambient temperature, generation temperatures, and micro gas turbine fuel mass flow were taken into consideration. The default configuration has a low exhaust gas temperature from the prime mover, which is difficult to drive a double-effect absorption chiller. Ahmadi et al. [17] investigated the exergo-environmental impact of the CCHP system, and revealed that the compressor pressure ratio, the gas turbine inlet temperature and the gas turbine isentropic efficiency significantly affect the exergy efficiency and environmental impact of the trigeneration system.

In recent years, a wide consensus has been reached on environment protection and energy security. The CCHP system has benefits in terms of green house gas (GHG) emission reduction with respect to the separate production (SP) as a result of their enhanced energy performance. The potential of CCHP systems for reducing the emission of hazardous GHG have been investigated [18,19]. Mago et al. [20,21] analyzed the optimum operation of CCHP system from the perspective of the environmental impact, energy savings, and operation cost. Mancarella and Chicco [22] set up the global and local emission impact model for the distributed cogeneration system, and analyzed an application based on the emission characteristics of a real micro gas turbine. Ahmadi et al. [23] carried out the green house gas emission and environmental analyses for the gas turbine powered CCHP system. The environmental impacts of the CCHP system were compared with those for a power generation unit and a CHP system. The results show that trigeneration exhibits higher exergy efficiencies and lower environmental impacts, suggesting that can help mitigate green house gas emissions.

It is obvious that the simulation of off-design performance of CCHP system is based on the efficiency constant models in most of the previous studies. The parameters of gas turbine and absorption refrigerator were assumed indeclinable in the part-load operation conditions. Actually the performance of gas turbine or refrigerator will vary dramatically [16] in off-design conditions. Hence, the constant models may decrease the accuracy of the simulation results and the advantage of CCHP may be overestimated. However, little literature investigated the effects of off-design characteristics of equipment on the CCHP performance.

The primary objective of this paper is to investigate design and off-design performance of a combined cooling, heating and power (CCHP) system based on off-design model of gas turbine and absorption refrigerator. The specific objectives are listed as follows:

- To develop the off-design models of a small-scale gas turbine and a double-effect absorption chiller.
- To simulate the off-design performance of the CCHP at different load level.
- To perform exergy and energy level analysis of the CCHP system to investigate the interaction between the gas turbine and absorption chiller.
- To simulate the actual operation of the CCHP to fulfill the energy demand of a business building and compared the results based on the off-design models and efficiency constant models.

2. Description of system

The CCHP system investigated in the present study consists of a small-scale gas turbine, a double-effect absorption LiBr–H_2O chiller, and a heat exchanger. The exhaust gas from the small-scale gas turbine at high temperature is introduced to the generator of the absorption system. The exhaust gas from a double-effect chiller at lower temperature then passes through a heat exchanger to produce hot water. The schematic diagram of the CCHP system is shown in Fig. 1.

A small-scale gas turbine, having a centrifugal compressor and a radial inflow turbine with a power output of 1747 kW, is investigated. As shown in Fig. 1, air is induced into the centrifugal compressor through an inlet duct. The compressed air then flows toward the combustion chamber with a constant combustion efficiency of 0.97. After combustion, the hot gases enter the radial inflow turbine nozzles to drive the external load and the centrifugal compressor. The stack gas with high temperature is ejected to a double-effect absorption chiller to recover waste heat.

The schematic diagram of a double-effect LiBr–H_2O absorption chiller that is activated by an exhaust gas is shown in Fig. 1. The main components of the absorption system includes a condenser (CON), an evaporator (EVA), an absorber (ABS), a solution pump, a high temperature heat exchanger (HTHE), a low temperature heat exchanger (LTHE), a high pressure generator (HPG), a low pressure generator (LPG), two solution reducing valves and two refrigerant expansion valves.

The exhaust gas at high temperature flows into the HPG to generate the primary steam and a concentrated working solution. In the solution circulation, the weak solution (in which the absorbent concentration is low) produced in the absorber is pumped through the LTHE and HTHE to recover the surplus heat of the medium concentration solution from LPG and the strong concentration solution from HPG. The weak solution then is then introduced into the HPG, where it is heated and concentrated into medium concentration solution by exhaust gas, and generates high-pressure refrigerant steam. The medium concentration solution then passes through the HTHE and enters the LPG after decreasing the pressure, where the medium concentration solution is further concentrated into a strong solution. The strong solution enters the absorber after being cooled in the LTHE. In the refrigerant circulation, the refrigerant steam from the HPG condenses in the LPG and low-pressure refrigerant steam is generated.