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Evaluation of a novel coupling system for various load conditions under different operating strategies

Shushuo Kang, Hongqiang Li *, Lifang Liu, Rong Zeng, Guoqiang Zhang *

College of Civil Engineering, National Center for International Research Collaboration in Building Safety and Environment, Hunan University, Changsha, Hunan 410082, China

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ABSTRACT

In previous research, a novel coupling system, which integrates the combined heating and power system and the ground source heat pump system, is proposed and investigated. In this paper, in order to make the novel system more suitable for the buildings load demand, the performance characteristics for various load conditions are evaluated under two different operation strategies: following the thermal load and following the electricity load. For the comparison, the reference system integrated with common approach is also presented. The models for both systems are developed to examine their primary energy consumption. Energy saving ratio is selected as the evaluation criteria. Furthermore, a numerical case is given to illustrate the feasibility and availability of the novel system. The results show that the primary energy consumption of novel system is fewer than the reference system. The outlet temperature from the ground source heat pump system in novel system is the key design parameter; the lower outlet temperature can lead to a fewer primary energy consumption and a bigger energy saving ratio. Additionally, for the application of the novel system, the following the electricity load operation strategy should be preferred.

1. Introduction

As an energy-efficient and environmental-friendly technology, combined heating and power system (CHP) is broadly identified as a highly efficient way to use both fossil and renewable fuels and to make a significant contribution to the sustainable energy development. The main idea of the CHP is to utilize the excess heat discharged from the power generation unit (PGU) to regenerate thermal energy [1–4]. Thus the utilization of the flue gas heat plays a significant role in the efficiency improvement of the CHP. In the CHP, the flue gas heat is always used directly by the heat exchanger (HEX) to produce heat [2,3] or generate hot water [4]. However, the flue gas heat often cannot meet the heat load demand of buildings. The additional heat needs to be generated by other equipments or systems, such as the ground source heat pump system (GSHP). The GSHP technology is paid attention from the researchers and policy makers due to its energy saving and environmental advantages [5,6]. Therefore many CHP–GSHP coupling systems are presented [7–9]. Ommen [7] gave five configurations for the CHP and GSHP system. Liu [8] proposed a coupling system which integrates CCHP and two GSHP systems. Entchev [9] presented the coupling system composed of GSHP and fuel cell CHP system. It is vital to find an effective system integrating method to utilize the flue gas heat and improve the system performances. Thus, based on the principle of the temperature grade counterparts and heat transfer mechanism, the novel CHP–GSHP coupling system was proposed by the authors [10]. The performance advantages and the influence characteristics of the novel system were also investigated based on the set load conditions. Because the load condition always fluctuates dramatically over time, it will be crucial to study the operation strategies and availability of the novel system under various load conditions.

In general, the coupling systems are usually operated via using two basic strategies: following the electricity load (FEL) and following the thermal load (FTL) [11,12]. For the former strategy, the system can be operated according to the electricity load; while the latter one works in accordance with the thermal load. Some researchers such as Jalalzadeh-Azar [13], Mago et al. [14,15] investigated the operation of coupling systems under these operation strategies. For example, Jalalzadeh-Azar [13] analyzed the cost and primary energy consumption (PEC) of coupling system operated under FEL and FTL strategies. The results showed an 11% reduction in total energy consumption when the coupling system is operated under the FTL strategy instead of the FEL strategy. Mago et al. [14] compared FEL and FTL strategies for the coupling

* Corresponding authors. Tel.: +86 731 88821040; fax: +86 731 88821004.
E-mail addresses: lhq@hnu.edu.cn (H. Li), gqzhang@hnu.edu.cn (G. Zhang).

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Nomenclature

Abbreviations		*Subscripts*	
CHP	combined heating and power system	*chp*	combined heating and power system
HEX	heat exchanger	*gshp*	ground source heat pump system
GSHP	ground source heat pump system	*b*	boiler
FTL	following the thermal load	*pec*	primary energy consumption
FEL	following the electricity load	*rpec*	PEC for the reference system
COP	coefficient of performance	*npec*	PEC for the novel system
PEC	primary energy consumption, kW	*grid*	grid
ESR	energy saving ratio, %	*max*	maximum
E	electricity load demand, kW	*req*	required energy
F	fuel energy, kW	*rec*	heat recovery
f	part load ratio	*load*	buildings load demand
Q	heat load demand, kW	*f*	feed water pump
T	temperature, °C	*c*	circulation pump
R	ratio	*w*	warm water
		el	electricity
Greek symbol			
η	efficiency		

system that used an internal combustion engine as the PGU for a small office building in four different climate regions. Comparisons made are based on the PEC, cost, and carbon dioxide emissions. They concluded that, the FTL strategy generally performed better than the FEL strategy.

Additionally, the energy systems are always assessed based on primary energy saving [16–18], energy consumption [13,14,18], operation cost [14,17–19] and system efficiency (electrical, thermal, and total) [20]. Mago et al. [14,15], introduced different perspectives for evaluating system performance. In their work, they demonstrated that coupling system can be evaluated based on the reduction of PEC, operational cost and carbon dioxide emission for different climate conditions. Jing et al. [18] developed a multi-objective optimization design method based on life cycle assessment, in which several objectives (energetic and environmental goals) are combined into a single objective by weighted method. Some researcher also evaluated and analyzed the benefits of systems in terms of reduction of pollutants for different applications. Some of them are: Möllersten et al. [21], Mancarella et al. [22] and Lund et al. [23], et al.

In this paper, in order to make the novel system more suitable for the buildings load demand, the performance characteristics for various load conditions are evaluated under two different operation strategies. The main contributions of this paper can be outlined as follows:

(1) The models for both systems (the novel system and reference system) under FEL and FTL strategies are built and calculated. The ESR is employed in order to evaluate the system performance.
(2) The performance characteristics of both systems for various load conditions under two operation strategies are performed and compared.
(3) The key design parameter for the novel system is revealed; and the preferred operation strategy is also suggested.

The paper is structured as follows. Beside of introduction and review, the system configurations of the novel system and reference system are introduced in Section 2. In Section 3, the mathematical modeling and the evaluation criteria for both systems are presented. In Section 4, a numerical case is analyzed to illustrate the feasibility and availability of the novel system. In the last section, the main conclusions are summarized.

2. System description

In this section, the novel coupling system, which integrates the CHP-subsystem and the GSHP-subsystem, is introduced. For the comparison, the reference system integrated with common approach is also presented. The distinctions between the two systems are also given.

2.1. Novel system

It can be observed from Fig. 1 that: the compressed natural gas and air will be sent into combustor; after combustion the flue gas with high temperature (1040 °C) and high pressure (13 atm) flows into gas turbine to generate power; then the exit flue gas with temperature (508 °C) and pressure (1.2 atm) flows into the HEX to reheat the warm water (e.g. 35 °C) generated by the GSHP-subsystem to meet the requirement temperature (e.g. 55 °C). It should be pointed out that the temperature of warm water (e.g. 35 °C) is dropped actively from the required temperature (e.g. 55 °C), which will lead to increase the coefficient of performance (COP) of GSHP-subsystem.

2.2. Reference system

A reference system is used to compare with the novel system. In the reference system, CHP-subsystem and GSHP-subsystem are operated in a parallel mode (namely in complementary pattern), in other words, both systems are operated independently. The schematic of the reference system is shown in Fig. 2.

As shown in Fig. 2, the compressed natural gas and air will be sent into combustor; after combustion the flue gas with the high temperature (1040 °C) and high pressure (13 atm) flows into the gas turbine to generate power; then the exit flue gas with temperature (508 °C) and pressure (1.2 atm) flows into the HEX to generate domestic hot water at the required temperature (e.g. 55 °C). Then, the left demand of the domestic hot water at the required temperature (e.g. 55 °C) will be generated by the GSHP-subsystem.

It can be found that the major differences between the systems above are as follows: First is the utilization approach of the flue gas from CHP-subsystem. Second, the GSHP-subsystem no longer generates hot water at the required temperature (e.g. 55 °C) as the reference system directly, but generates the warm water (e.g. 35 °C) instead. Third, the inlet temperature of the cool water in the HEX