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Adjustable performance analysis of combined cooling heating and power system integrated with ground source heat pump

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ABSTRACT

The difference in the electricity to cooling/heating ratio between a building and combined cooling, heating, and power (CCHP) system has a significant influence on the system configuration and performance. This paper designs a CCHP system coupled with a ground source heat pump (GSHP) to coordinate the match between system supplies and building demands. The energy flows in the cooling and heating work conditions are analyzed, and the thermodynamic models of components constructed. By means of a case study, the performances of the coupling CCHP system, under design and off-design working conditions, are evaluated and analyzed using energetic indicators, including the primary energy ratio and exergy efficiency, respectively. The adjustable areas expressed by electricity and cooling/heating, as well as the adjustable performance distributions, are obtained and discussed in order to guide operation regulation of the CCHP system integrated with the GSHP. Comparisons between the CCHP system with and without GSHP indicate that the coupling CCHP system in the specific case study can save averagely 40.6% and 39.5% of the primary energy in cooling and heating work conditions, respectively.
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1. Introduction

Distributed energy systems have been considered to supplement the traditional central system, owing to their high overall efficiency and environmentally friendly performance [1], of which combined cooling, heating, and power system (CCHP) or combined heating and power system (CHP) is one of key forms [2]. The outstanding feature of the CCHP/CHP system is the cascading utilization of energy. Researches on distributed systems focusing on system configurations [3], performance evaluation [4], operational strategies [5], and optimization methods [6] aimed to establish optimal distributed systems in order to reduce energy consumption and greenhouse gas emissions.

Gradually, renewable energy, including solar, wind, and geothermal energy, as well as bioenergy, has been introduced into distributed energy systems to amplify the benefits gained from energy, environment, and even economy [7]. According to the different technologies and characteristics, various integrated systems have been proposed and analyzed, such as CCHP systems based on biomass gasification with air [8] or steam [9], and CCHP systems coupled with solar collectors [10] or solar fuels [11]. However, one limitation in solar or wind integrated systems is their intermittent nature. Furthermore, hybrid biomass systems may be affected by low heat density and challenges in collection and transportation. Among the available renewable energy sources, geothermal energy has attracted significant attention due to its friendly performance and relative stability, particularly for shallow underground geothermal resources from groundwater or soil coupled with a heat pump system [12], namely a ground source heat pump (GSHP) system.

Typical applications of GSHP systems consist of providing heating and/or cooling for users. Lucia et al. [12] reviewed GSHP systems that include both various GSHP technologies and thermodynamic models. The summaries demonstrated that systems with a GSHP can reduce the environmental impact of buildings. Zhai et al. [13] designed a mini-type GSHP system for a meeting room and discussed output capacities in the typical mode, which demonstrates the GSHP system applicability for building demands. Yuan et al. [14] proposed a control mode for the GSHP with a borehole-free cooling coupled system, and investigated the underground heat balance problem. This research concluded that the mode can improve energy efficiency and decrease energy consumption. In particular, the annual operational cost of the GSHP system is obviously reduced. To improve the performances of GSHP

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Nomenclature

AHP	absorption heat pump
CCHP	combined cooling heating and power
CDE	carbon dioxide emission
CDERR	carbon dioxide emission reduction ratio
CHP	combined heating and power
COP	coefficient of performance
FEL	following electricity load
FTL	following thermal load
GSHP	ground source heat pump
HG	high pressure generator
HX	heat exchanger
ICE	internal combustion engine
LG	low pressure generator
LX	low temperature heat exchanger

Symbols

C	average specific capacity (kJ kg^{-1} K^{-1})
E	electricity (kW)
Ex	exergy (kW)
F	area (m^2)
f	mass flow (kg s^{-1})
h	enthalpy (kJ kg^{-1} K^{-1})
m	mass (kg)
n	variable coefficient
Ne	generation capacity (kW)
P	pressure (kPa)
Q	energy (kW)
R	constant for ideal gas
W	practical power consumption (kW)
η	efficiency
PER	primary energy ratio
T	temperature (K)

Subscripts

ac	absorption heat pump
c	compressor
ch	chilled water
co	condenser
e	electricity
ev	evaporator
ex	exergy
g	ground source heat pump
gr	ground source water
$grid$	electricity grid
hw	hot water
i	ICE
in	inlet
mix	mixed hot water
n	nominal
ng	natural gas
out	outlet
sys	system
t	throttle value
0	standard reference state

system, the exergy analysis was often used to discover the segments with more exergy destruction. Menberg et al. [15] proposed a water-based hybrid GSHP system and gas-fired boiler, and analyzed the exergy loss and destruction of the hybrid system by modeling each subsystem. Esen et al. [16,17] predicted the daily performance of GSHP in a fuzzy weighted pre-processing method with the limited experimental data and investigated the GSHP's energy and exergy performances as a function of depth trenches for heating season. The investigations shown that the energetic and exergetic efficiencies of the system increase when increasing the heat source (ground) temperature for heating season. Besides space heating/cooling provided by GSHP system, Balbay et al. [18,19] studied the using of GSHP systems for snow melting on bridge slabs and pavements, and researched the temperature distribution of slabs and pavements. Moreover, the GSHP have coupled with solar energy in recent researches [20]. Esen et al. [21] have analyzed a solar-assisted GSHP system, and obtained its coefficient of performance (COP) and other performances.

Moreover, a GSHP system for heating and cooling is coupled with a CCHP system for electricity, heating, and cooling in order to supplement each other and relieve the limitation of the fixed heat to electricity ratio of the CCHP system. The CCHP and GSHP coupling system usually consists of a prime mover, waste heat utilization system, and GSHP. The electricity produced by the prime mover is fed to the building and GSHP. The cooling and heating demands can be met by the waste heat utilization system and GSHP. Typically, the alternatives of waste heat utilization system for producing chilled water includes absorption chiller/heat pump or adsorption chiller driven by heat sources with different heating temperature. The absorption chiller or heat pump is driven by the exhausted gas from power generation unit with high temperature. Wang et al. [8] employed the absorption chiller driven by three kinds of heat sources to recover the waste heat from the exhausted gas to produce chilled water and hot water for space cooling and heating respectively and domestic hot water. Yang et al. [22] proposed and researched a new open-cycle absorption heat pump system to recover the waste heat from flue gas, and found that this system can get an excellent output even at high return water temperature. In addition, the adsorption chillers with the low temperature heat source could recover the waste heat with low grade energy level. Chorowski et al. [23] investigated an adsorption chiller which utilizes low-temperature heat from cogeneration and demonstrated that the adsorption chiller can be worked with a hot water of 65 °C, a typical cogeneration heating temperature in distributed energy systems. The performance of adsorption chiller directly influences the operation parameters on cooling capacity [24] and then determines the recovery efficiency of waste heat in CCHP system. Although the recovery efficiency of adsorption chiller is lower than the absorption chiller, it provides one alternative to utilize the waste heat with the lower temperature.

The researches on CCHP and GSHP coupling systems with the typical absorption chiller or heat pump have started to emerge in the last few years, only in performance analysis and configuration strategy. Kang et al. [25] proposed a hybrid system with four subsystems, including a power generation unit, GSHP unit, absorption chiller, and storage tank, and analyzed the energy and environmental performances in three basic modes. Similarly, Kang et al. [26] employed a comprehensive matrix approach to compare the configurations and performances of CCHP-organic Rankine cycle system with a GSHP in three energy management modes. Liu et al. [27] focused on hourly operation strategy of a CCHP system with GSHP and thermal energy storage under variable loads and discussed the economic and environmental benefits of the CCHP system with thermal energy storage. Moreover, aimed to obtain more benefits of CCHP and GSHP coupling system, optimization

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