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The energy-saving effects of ground-coupled heat pump system integrated with borehole free cooling: A study in China

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HIGHLIGHTS

- Investigate the suitable application scope of free cooling system.
- Simulate and predict its COP and carbon reduction.
- Compare the temperature changes of underground soil between free cooling mode and conventional cooling mode.
- Suggest the use of free cooling.

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ABSTRACT

Ground coupled heat pump (GCHP) systems have been widely implemented due to its potential benefits of energy savings. However, very few studies attempted to examine the operational performance of GCHP system integrated with borehole free cooling (i.e. using the circulating water in ground heat exchanger for the cooling purpose). A typical office building in Tianjin was chosen for a detailed case study. Both experiments and numerical simulation are employed to examine the efficiency of proposed GCHP system by means of comparing the normal running mode (NRM) and the energy-saving running mode (ESRM) in terms of the energy consumption and soil temperature variation. The results showed that the energy efficiency ratio (EER_{system}) of the system increased every year in winter but decreased gradually in summer during 10 years of operation. In winter, the EER_{system} of NRM was 3.4% higher than that of ESRM. In summer, the EER_{system} of NRM was 0.5% lower than that of ESRM under the same normal cooling mode (NM_c). The EER_{system} of free cooling mode (FM_c) could reach as high as 23.35, which was 5.2 times higher than that of NM_c. In summer, the EER_{system} of ESRM was 13.58 on average, which was 2.6 times higher than that of NRM. The soil temperature gained minor rise under both modes during 10 years' operation. This study revealed that there are significant energy savings benefits if the GCHP system is integrated with FM_c. Meanwhile, the requirements related to temperature and humidity can be satisfied when the indoor thermal and moisture load are not too high. Therefore, the integration of FM_c with GCHP system could be considered for the operation of office buildings in the future.

1. Introduction

Building energy consumption accounted for around 27% of the total energy consumption in China. It is estimated that this proportion will increase to 35% by 2020 [1,2]. The energy used for cooling and heating accounted for as much as 60% of the total building energy consumption [3]. Therefore, it presents a significant challenge to reduce the energy consumption on cooling and heating not on the cost of thermal comfort [4,5]. Ground coupled heat pump (GCHP) is less affected by the outdoor temperature compared to traditional air conditioning system [6]. The GCHP systems have advantages of relative high operational efficiency [7–9], and comparatively lower electric energy consumption [10,11] as well as less carbon dioxide emission [12–14]. As a result, GCHP systems have gained wide implementation in buildings [15–18]. By the end

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Nomenclature

c	specific heat (J/kg/°C)
CHW	chilled water
COP	coefficient of performance of pump units in winter
DHW	daily hot water
EER	energy efficiency ratio of pump units in summer
EER_{system}	energy efficiency ratio of GCHP system
$ESRM$	energy-saving running mode
F_c	cooling operation share (ratio of pump units running time and cooling season time)
FCU	fan coil unit
F_{h}	heating operation share(ratio of pump units running time and heating season time)
FM_c	free cooling mode
G_1	circulating pump flow of ground source side (m^3/h)
G_2	circulating pump flow of air conditioning side (m^3/h)
$HVAC$	heating, ventilation and air conditioning
HW	hot water
L_c	overall length of buried pipes under summer condition (m)
L_{h}	overall length of buried pipes under winter condition (m)
NM_c	normal cooling mode
NM_h	normal heating mode
NRM	normal running mode
PE	polyethylene
Q	cooling/heating load (kW)
Q_{ab}	maximum heat amount exchanged of buried pipes in winter (kW h)
Q_c	rated cooling load of heat pump units (kW)
$Q_{cooling}$	cooling capacity (kW h)
Q_{ex}	maximum heat amount exchanged of buried pipes in summer (kW h)
Q_h	rated heating load of heat pump units (kW)
$Q_{heating}$	heating capacity (kW h)
R	function of independent variables
R_b	thermal resistance of backfill material $((\mathrm{m}\cdot\mathrm{K})/\mathrm{W})$
R_f	convective heat resistance between fluid and pipe wall $((\mathrm{m}\cdot\mathrm{K})/\mathrm{W})$
R_p	thermal resistance of buried pipes wall $((\mathrm{m}\cdot\mathrm{K})/\mathrm{W})$
R_s	thermal resistance of soil $((\mathrm{m}\cdot\mathrm{K})/\mathrm{W})$
R_{sp}	additional resistance caused by short-term continuous pulse load, $((\mathrm{m}\cdot\mathrm{K})/\mathrm{W})$
T_c	design temperature of heat transfer medium in heat exchanger under cooling condition (°C)
$t_{cooling}$	cooling time (h)
T_h	design temperature of heat transfer medium in heat exchanger under heating condition (°C)
$t_{heating}$	heating time (h)
T_i	inlet water temperature (°C)
T_o	outlet water temperature (°C)
$TRNSYS$	Transient System Simulation Program
U_R	uncertainty of independent variables
V	volumetric flow rate (m^3/h)
W_c	refrigeration power of compressor (kW)
W_h	heating power of compressor (kW)
W_t	compressor shaft power (kW)
x_n	independent variable
ρ	density kg/(m^3)
$\sum W$	total power of system (kW)
Δt_1	temperature difference between supply water and return water of user side (°C)
$\triangle t_2$	temperature difference between supply water and return water of ground source side (°C)

of 2010, there were more than 7000 GCHP projects in China [19], with construction area of more than 200 million m^2 [20,21].

A number of factors affect the operational performance of GCHP systems. These include: soil thermal conductivity [22–25], amounts of wells [26], backfill materials [27–30], forms of buried pipe [31–33], depth of buried pipes [34–36], spacing of buried pipes [37–39], types of ground heat exchanger [40–42], velocity of circulation fluid in buried pipe [43–45], soil heat accumulation [46–49]. Energy savings derived from GCHP systems is determined by Coefficient of Performance (COP) value of the heat pump unit. Furthermore, the temperature of outlet fluid and inlet fluid are two most influential factors to the COP [50,51], whereas the soil temperature determines the outlet fluid temperature [52,53]. Soil temperature is related to not only the region and climate, but also the heat exchange amount between ground heat exchanger and soil. When the annual heat absorption by heat pump units at the ground source side was similar to the heat extraction from the ground, the variation of annual soil temperature around the heat exchanger was small [54,52,55]. In such circumstance, the heat pump units can maintain a stable operation.

The heat pump units accounted for about 50–60% of the total energy consumption of air conditioning systems [56]. Therefore, it is imperative to improve the efficiency of heat pump so that the energy consumption of air conditioning systems could be reduced. The operational efficiency of GCHP units is affected by a large number of factors. Vast majority of previous studies placed focuses on aspects such as optimizing the supply and return water temperature, determining the running frequency of GCHP units according to the demand as well as manufacturing GCHP units. By using the natural cooling source, the energy consumption could be reduced significantly [57–60]. Previous study [61] has shown that the GCHP system can keep the soil temperature within a certain range in as long as the underground temperature is normal. When the outlet fluid temperature of heat exchanger is lower than the air temperature, the underground water (free cooling source) can be used for cooling directly without operating the heat pump units [62,63]. Wang et al.'s study is among very few studies that attempted to examine the operational performance of free cooling [64]. They examined the operational performance of GCHP system in Harbin and found that the energy efficiency ratio of GCHP system ($\mathrm{EER}_{\mathrm{system}}$) reached 21.35 when the circulating water was used for cooling directly. However, their study focused on residential buildings in a severe cold region where the heat absorption by heat pump units is greater than the heat extraction. Moreover, the fact that cooling requirement in Harbin is significantly less than other regions contributes to lower soil temperature. As a result, the operational performance of free cooling is exceptional. It remains unknown whether free cooling can be used in office buildings of other regions such as cold regions in China as well as the running efficiency. How can the operational strategy be designed to maintain a high efficiency of the GCHP system? This presents significant challenges to utilize free cooling to fulfill users' requirements.

This paper focused on climate conditions and the characteristics of energy utilization in cold regions. The energy demand of office building is examined through the energy simulation software where an optimal GCHP system is proposed. Consequently, Transient System Simulation Program (TRNSYS) software was employed to predict the operation performance of GCHP system under different running modes. Key issues examined in this study include: $\mathrm{EER}_{\mathrm{system}}$, energy consumption, and variation of soil