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Simulation-based analysis of a ground source heat pump system using super-long flexible heat pipes coupled borehole heat exchanger during heating season

Xiaoyuan Wang[a], Yinfeng Wang[a], Zhi Wang[a], Yuxuan Liu[b], Yuezhao Zhu[a,*], Haijun Chen[a]

[a] Jiangsu Key Laboratory of Process Enhancement and New Energy Equipment Technology, School of Mechanical and Power Engineering, Nanjing Tech University, No. 30 Pu Zhu South Road, Nanjing 211816, China
[b] Hefei General Machinery Research Institute, No. 888 Changjiang West Road, Hefei 230000, China

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ABSTRACT

A hybrid ground source heat pump system employing the super-long flexible heat pipes to extract heat from ground is proposed in this work. To evaluate its energy performance and the temperature recovery characteristics near boreholes during space heating season, a comprehensive simulation model was developed considering the dynamic performance of heat pump and the heat transfer of heat pipes and surrounded soil. The results show that the depth of boreholes should be not less 70 m to guarantee a higher long-term energy efficiency. The seasonal coefficient of performance increases with increasing groundwater advection velocity and decreasing building load, with a maximum value up to 4.2 under examined conditions. The short-term variations of ground temperature near boreholes are sensitive to the borehole depth and building load. The overall ground temperature continuously decreases under the condition with no groundwater advection throughout the heating season, but with the presence of groundwater advection, the variation tendency would almost level out after several days of decrease. In addition, it is also revealed that this system has a potential to reduce the ratio of the electrical consumption of circulation pumps to the total consumption, with a reduction of about 7%, showing an advantage of saving energy over the traditional ground-source heat pumps.

1. Introduction

Global warming, or referred to as climate change, has received more and more attention recently due to its worldwide negative effects like rising sea levels, changing precipitation, expansion of deserts, and higher frequency of meteorological catastrophes [1]. The public is gradually realizing that there is an urgent need to reduce the emission of greenhouse gases, namely decreasing the usage of fossil fuels, to avoid these problems. Utilization of renewable energy is an effective way to relieve them, and during the past several decades renewable energy has developed rapidly, accelerating the penetration into market, particularly the solar energy [2], wind energy [3], geothermal energy [4], and hydropower [5].

The energy used in buildings, statistically, accounts for approximately 40% of the annual world energy consumption [6]. And the energy demand for space heating and hot water in houses and utility buildings is responsible for 80% [7]. Ground Source Heat Pump (GSHP) systems, through which heat or cooling is generated by reverse Carnot cycle employing the ground or groundwater as heat source/sink, have received unprecedented interest due to their high efficiency and reliable operation. In addition, these systems are environmental friendly, contributing to reduction of greenhouse gases and pollutants, in comparison with conventional systems using fossil fuels such as centralized heating system [8].

The widely used GSHP systems commonly adopt closed loop on ground side, with vertical or horizontal type of Borehole Heat Exchangers (BHEs), in which heat-carrier fluid is circulated to exchange heat between the ground and the refrigerant in heat pump [9]. The main inferiority of these systems, compared with Air Source Heat Pump (ASHP) systems, lies in the high cost of initial installation of drilling and more demand of electrical consumption for heat-carrier circulation [8]. And so, GSHP systems are not financially attractive unless the design life is up to 20 years that the relatively higher energy performance (independent of ambient air temperature variation) can compensate its initial cost [10]. Many efforts have been made by researchers to improve the Coefficient of Performance (*COP*) of GSHP systems. The main factors influencing *COP* significantly, according to the precedent investigations, include the flow rate of heat-carrier fluid, ground

* Corresponding author.
E-mail addresses: wangxy_njtu@163.com (X. Wang), zyz@njtech.edu.cn (Y. Zhu).

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Nomenclature

A	area, m^2
c_p	heat capacity, J/(kg·K)
C_2	inertial resistance factor
d	diameter, m
D	diameter/equivalent diameter, m
D_p	mean particle diameter, m
g	gravitational acceleration, m/s^2
G	mass flow rate, kg/s
h	heat transfer coefficient, W/(m^2)
h_{lv}	latent heat, J/kg
l	length, m
L	characteristic length of heat transfer, m
Nu	Nusselt number
P	electrical power, W
Pr	Prandtl number
p	pressure, Pa
Q	heat exchange rate, W
q	heat flux, W/m^2
q_{ext}	heat extraction rate from ground, W/m
R	thermal resistance, K/W
Re	Reynolds number
S_i	source term in momentum equation
T	temperature, K
u	velocity, m/s
V	volumetric flow rate, m^3/s
v_{gw}	advection velocity of groundwater

Greek letters

α	permeability
ε	porosity
ξ	drag coefficient, kg/m^3
η	thermodynamic perfectibility/
η_{pump}	total energy efficiency of pumps
λ	thermal conductivity, W/(m·K)
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3

Subscripts

a	air
avg	average
b	borehole
c	condensation section/condensation
cond	condenser in heat pump
ci	inner wall of condensation section
co	outer surface of condensation section
cw	condensation section wall in SFHP
evap	evaporator in heat pump
e	evaporation section/evaporation
ei	inner wall of evaporation section
ew	evaporation section wall in SFHP
g	gas
i	inner/counting number
j	jacket/counting number
l	liquid phase
o	outer
s/sat	saturation state
v	vapor phase
veri	verification value

Abbreviation

ASHP	Air Source Heat Pump
BHE	Borehole Heat Exchanger
CFD	Computational Fluid Dynamic
COP	Coefficient of Performance
EER	Energy Efficiency Ratio
GSHP	Ground Source Heat Pump
PE	Polyethylene
SCOP	Seasonal Coefficient of Performance
SFHP	Super-long Heat Pipe

properties, groundwater advection, local climate, and the BHE structure, etc. But for the whole service life of a GSHP system, the long-term sustainability may be the most important aspect that should be considered, especially during the design of GSHP. It must make sure that the heat exchanging with ground between the seasons of heating and cooling can balance, or the ground temperature can recover rapidly with the assistance of ground water advection. Otherwise, the ground temperature would reduce or increase gradually, known as the cold or heat accumulation, inducing a decline in system performance and even cause breakdown of heat pump [11]. The risk of this problem can be avoided by enlarging the heat exchanger length or spacing, but further increase of drilling cost or ground area is also undesirable [12]. For this reason, Yu et al. [13] proposed an operation strategy, referred to as Zoning method, to inhibit the thermal accumulation by only running the central part of BHE during the low load season. As Jalaluddin et al. [14] suggested, intermittent operation can also facilitate the temperature recovery in vicinity of BHE and therefore improve operational efficiency. However, the heating or cooling demand of buildings usually can't guarantee there's sufficient time for ground to recover temperature. Another alternative method to avoid this problem is additionally employing an auxiliary heat extraction/rejection system, e.g., solar collector [15] or cooling tower [16], to compensate load imbalance, which are called as hybrid GSHP system. However, the operation and control strategies are more complex for hybrid GSHP systems compared to conventional ones. Furthermore, in order to improve energy performance of GSHPs making it more competitive, investigations have also been carried out focusing on the control methods of heat pump [17] and the main variables in distribution system on building side [18]. However, for the existing GSHP systems, the energy used for driving circulation heat-carrier fluid, typically in U-tube or spiral coils, generally contributes to 10%–20% of the total energy consumption.

Wickless heat pipe, or known as the thermosyphon, is a kind of passive heat transfer components, through which heat is transported by phase change of working fluid inside a vacuumed and sealed shell [19]. With the use of heat pipes in BHEs, shallow geothermal energy can be extracted from ground without consuming any external energy. The initial application of heat pipes in this field was in 1969 in New Jersey, USA, for the purpose of melting snow and ice on pavements [20]. After that, many demonstration projects have also been carried out to prove the feasibility of extracting geothermal energy by heat pipes [21,22]. Recently, Zorn et al. [23] also implemented a project using CO_2 heat pipes to melt snow with geothermal energy at the entrance of a fire station in Bad Waldsee, Germany. These heat pipes (16 × 1 mm or 10 × 1 mm) were installed in boreholes with the deepest depth up to 75 m. And the heated area of 165 m^2 was always kept above 0 °C and free of snow under the air temperature from −15 °C to −2 °C during winter. Heat pipes can also be used in GSHP system. With its combination into BHEs, the circulating distance of heat-carrier fluid is considerably decreased and hence the electrical consumption. This kind of GSHP system was initially proposed and tested in Austria. René [24] investigated a number of GSHP systems adopting BHEs coupled CO_2 heat pipes experimentally and theoretically for space heating. It is