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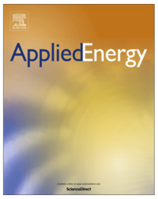

Optimum design of horizontal ground-coupled heat pump systems using spiral-coil-loop heat exchangers

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HIGHLIGHTS

- Optimum design of horizontal ground heat pump systems is presented.
- Accuracy of numerical model is verified through indoor thermal response tests.
- A total of 160 parametric studies are conducted using numerical simulation models.
- Heat efficiencies are compared for 160 major combinations of design factors.
- Optimum design conditions are suggested using several economic analysis tools.

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ABSTRACT

This paper deals with an optimum design of horizontal ground heat pump systems for spiral-coil-loop heat exchangers. A three dimensional numerical analysis model simulating the thermal behavior of a horizontal spiral-coil-loop heat exchanger was developed, and the accuracy of the model was verified through indoor thermal response tests. After that, a total of 160 parametric studies were conducted using numerical simulation models in order to grasp the degree of effects that key input parameters used in the model would have on the output. Then, an optimum design condition for horizontal ground coupled heat pump system was suggested using several economic analysis tools. Economic analysis factors, such as internal rate of return, savings to investment ratio, and simple payback period, show that certain design conditions (coil pitch: 0.08 m, setting depth: 2.5 m, circulating fluid velocity: 0.7 m s^{-1}) provide the most economic feasibility. However, this condition also varies with the unit cost of operation and initial investment.

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1. Introduction

Due to the recent rise in fuel costs and global warming problems, interest in alternative energy sources that are renewable and pollute less, has gradually increased. Particularly, ground-coupled heat pump systems (GCHPs) have been recognized to be highly cost effective and environmentally friendly for space heating and cooling of buildings [1–5]. This system uses relatively constant ground temperatures as a heat reservoir: heat source for heating in winter, and heat sink for cooling in summer. The GCHPs are classified into open and closed loop systems; the most common system is a vertical closed system with deep borehole ground heat exchangers (GHEs). However, high initial installation costs related to the drilling operation have been considered a fatal drawback of vertical borehole GHEs. Thus, horizontal ground-coupled heat pump systems (HGCHPs) are often preferred over vertical systems if the site has adequate space. Owing to the lower initial installation costs, the use of horizontal ground heat exchangers (HGHEs) can provide a viable alternative solution that reaches a good compromise between efficiency and costs [6].

The major heat transfer mechanisms of HGCHPs involve multiple processes: heat convection between the circulating fluid and the pipe, and heat conduction inside the ground. Since the HGHEs are generally buried at shallow depths (1–3 m), the heat conduction is also influenced by the land surface temperature. Thus, there have been extensive studies on the heat transfer mechanisms of HGHEs considering various ground conditions, both in the area of numerical modeling and in field experiments. For example, Tarnawski et al. [7] conducted numerical simulations of a HGCHPs operating in heating and cooling modes for a typical residential house, located in Sapporo (Japan). The selected GCHPs showed an

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Nomenclature

Symbol

a	half difference between the maximum and minimum annual temperatures (K)
A_p	pipe cross section area (m^2)
C_p	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
D_T	thermal diffusivity of soil ($m^2\,s^{-1}$)
f_D	coefficient of friction
hZ	equivalent convective heat transfer coefficient
h_{int}	film heat transfer coefficients inside the tube ($W\,m^{-2}\,K^{-1}$)
h_{ext}	film heat transfer coefficients outside the tube ($W\,m^{-2}\,K^{-1}$)
Q	general heat sources ($W\,m^{-3}$)
r_n	outer radius of wall n (m)
T	temperature (K)
T_{ext}	external temperature outside the pipe (K)
T_f	fluid temperature (K)
T_{in}	inlet fluid temperature (K)
T_{out}	outlet fluid temperature (K)
T_M	mean temperature in the year of the climatic zone (K)
t	time (s)
t_M	time when the maximum temperature on the ground surface occurs (day)
u	fluid velocity ($m\,s^{-1}$)

Greek letters

ρ	density ($kg\,m^{-3}$)
ρ_f	fluid density ($kg\,m^{-3}$)
ρC	equivalent volumetric heat capacity ($J\,K^{-1}\,m^{-3}$)
λ_{eff}	effective thermal conductivity of medium ($W\,m^{-1}\,K^{-1}$)
λ_f	fluid thermal conductivity ($W\,m^{-1}\,K^{-1}$)
λ_n	thermal conductivity of wall n (W/m K)
λ_{solid}	thermal conductivity of solid particle (W/m K)
λ_{pore}	thermal conductivity of pore (W/m K)
χ_{solid}	volumetric fraction
τ	period (year)

Subscripts

NPV	net present value
IRR	internal rate of return
SIR	savings to investment ratio
SPP	simple payback period (year)

overall annual COP of 3.26 and required 19.7 GJ/year of total electrical consumption, which means that 100 Yen is equivalent to about 19 kW h of heat output. For the same cost, the corresponding heat output produced by an oil furnace was around 12.5 kW h. Based on these results, the conclusion was that GCHPs is more beneficial alternatives for space heating than are oil furnaces for given geological and weather conditions. Wu et al. [8] conducted 3D numerical analyses for a slinky HGHE, and its performance was compared with that of a straight GHE. After running the systems for 140 h, the specific heat extraction of the straight pipe was 3.5 W/m higher than that of the slinky pipe. However, the heat extraction per unit length of soil for the slinky heat exchanger was significantly higher than that of the straight system. Furthermore, Sanaye and Niroomand [9] presented a thermal-economic optimal design method to obtain the various optimum design parameters of straight HGHEs. The optimum design parameters of the system were estimated by minimizing a defined objective function (total annual cost, TAC). The results show that the TAC values approximately change linearly with capacity, and that soils with greater heat transfer coefficient have lower optimized TAC. Li et al. [10] examined the groundwater effect on the performance of coil-type HGHEs, which enabled the establishment of a moving ring source model, and they analytically solved the temperature response of coil-type HGHEs using groundwater flows. According to their analysis, for the same heat extraction rate, the layout of the heat exchanger arranged perpendicular to the trench and the water flow direction exhibited the highest average tube surface temperature. Furthermore, under the same heat flux, the tube surface could recover to reach its initial level more quickly in the presence of water flow. Congedo et al. [6] conducted simulations on several different types of HGHEs using the CFD (computational fluid dynamics) code Fluent. The system performance was evaluated by considering different soil thermal conductivities, GHE configurations, heat-transfer-fluid velocities, and the depth of installation. According to their analysis, the most important parameter for the system performance was the ground thermal conductivity, and comparing the geometry arrangements led to a choice of the helical heat exchanger as the best performing one. Gonzalez et al. [11] focused on the interactions between the trench, HGHEs, and the aboveground environment; then analyzed the key factors that influence the efficiency of a HGCHPs. Their results showed that the soil temperatures and soil moisture content could change the heat transport in the soil and hence they could affect the GCHP performance. The slinky HGHE influenced soil temperatures up to 0.9 m from the installation depth in winter, and the consistent differences in soil moisture content measurements between the reference and GCHP profile could be explained by temperature-gradient-induced moisture gradients and a decrease in hydraulic conductivity due to decreased temperatures (causing increased viscosity). Fujii et al. [12] conducted long-term cooling and heating tests to compare the heat exchange capacities of double-layer slinky-coil HGHEs with single-layer HGHEs, and then they developed a numerical simulation model considering the surface boundary conditions. Through the sensitivity analyses, they suggested an optimum design depth for the double-layer HGHEs (1.5 m upper layer when the lower layer was fixed at 2.0 m). Ghong et al. [13] also evaluated the thermal performance of HGHEs using numerical analyses, and examined the effect of loop pitch, loop diameter, soil properties, and intermittent operation on system performance. According to their analysis, reducing the loop pitch/spacing of the slinky exchanger improved the overall thermal performance of the system. Moreover, the influence of loop diameter was smaller than the effect of loop pitch, and the increase of thermal diffusivity increased the overall system performance. Furthermore, running the system in intermittent operation had a higher heat transfer rate than under continuous operation. Bazkiaei et al. [14] developed a numerical model for HGCHPs with a non-homogeneous soil layer and confirmed that a non-homogeneous soil profile exhibited a great potential for enhancing a HGCHPs performance by increasing the energy extraction from the ground. Moreover, using the numerical model coupled with a generic algorithm, they suggested the operational parameters that maximize heat efficiency. The optimized seasonal energy extraction rates from the ground exhibited significant difference (an

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