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Assessment of design strategies in a ground source heat pump system

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ABSTRACT

Among many new and renewable energy technologies, a ground source heat pump system has been declared as an energy efficient and an environmentally friendly system in meeting the thermal energy demands for residential and commercial applications. One major drawback for ground source heat pump system is the high initial cost and a relatively longer payback period of the system. In this study, a numerical analysis and an experimental investigation were carried out on the effects of the heat pump performance and the building load for a ground loop heat exchanger design. A decrease of heat pump unit fluid flow rate and an increment of COP for the heat pump unit resulted in the reduction of the ground loop heat exchanger size in the cooling mode. It was observed that reducing the peak load of building has the potential for reduction in the ground loop heat exchanger length. Matching the heat pump capacity with the building peak load variation, a decrease of 40% in the cooling and heating peak load resulted in a decrease of 44.5% and 69.2% in the total ground loop heat exchangers required in the cooling and heating mode, respectively.

1. Introduction

Conventional heating and cooling systems such as fossil fuel heating (boiler and furnaces) and electric resistance heating systems have been used to meet the increase in the heating and cooling energy demands in most countries [1–4]. However, those systems have been found to contribute to the global warming potential of the atmosphere. In the aspect of energy savings and environmentally friendliness, many researches have focused on developing an energy efficient technologies to meet the increasing demands for heating, refrigeration, air conditioning, hot water generation, drying etc. using new and renewable energy sources. Among many energy efficient technologies, ground source heat pump (GSHP) appears to be a promising technology for providing the heating, cooling, drying as well as hot water generation energy needs in an environmentally friendly and energy conservative manner. This is as a result of the higher performance, lower energy consumption and higher potential for CO_2 emission reduction [5–8]. The earth provides an approximately constant ground temperatures year-round. GSHP systems make use of this free and available heat stored in the ground as a heat source in the heating mode and as a heat sink in the cooling mode. This is achieved by circulating heat transfer fluid in a closed loop through heat exchanging pipes. Commonly used heat exchanging pipes are high density polyethylene pipes (HDPE). Vertical-type GSHP systems have been mostly preferred among the various GSHP systems for commercial or residential buildings that require geothermal hot water generation, cooling and heating within a restricted and small installation area [8–10]. Mostly, vertical-type GSHP has one or more U-tube HDPE pipes embedded in a vertical borehole and a grout is used to fill the space between the pipe and the ground. Generally GSHP systems have higher costs than air-to-air systems or other conventional heating systems due to the high installation cost of the ground loop heat exchangers [8,11].

There have been many researches on the design and optimization of GSHP systems. Cho and Choi [11], performed a quantitative evaluation of the effects of design parameters on a GSHP. It was proposed that, the reduction of the size of ground loop heat exchanger length is a determining factor in the aspect of saving total installation cost of a GSHP system. Choi et al. [8], performed a numerical simulation of vertical-type ground heat exchangers under intermittent operation in an unsaturated soil conditions. It was concluded that it was very important to consider unsaturated soil conditions in the design and evaluation of ground loop heat exchangers. Zeng et al. and Cui et al. [12,13], performed numerical heat transfer analysis of ground loop heat exchangers(GLHXs) with inclined and

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Nomenclature

GSHP	Ground source heat pump
GLHX	Ground loop heat exchanger
EWT	Entering water temperature
GLD	Ground loop design
HDPE	High density polyethylene pipe
HTR	Heater
TRT	Thermal response test
COP	Coefficient of performance
RT	Refrigeration ton

vertical boreholes. A review of existing heat transfer models for vertical-type GLHXs was presented by Javed et al. [6]. A comparison of the existing design models for vertical-type GLHXs for residential applications was presented by Shonder et al. [14]. Many research works have been done on the optimisation of GSHP system designs [15–20]. Most of researches have focused on the GLHX design and performance according to the ground properties and conditions. There have been rare studies on the design of GLHXs considering the building load and heat pump unit performance. However, it is important to minimize the total cost of installation, while ensuring higher system performance of the GSHP. One possible way is to size the GLHX according to the available building load and the size of the heat pump unit. This study presents a numerical simulation on the optimum design of a closed loop vertical-type ground heat exchanger considering the building load and heat pump performance. An experimental work is also performed to validate the simulation analysis.

2. GSHP design and analysis according to building load

2.1. System design and modelling

Ground Loop Design program, GLD program [21], was used to perform the design of the GSHP system. GLD is a flexible commercial software for designing vertical, horizontal and surface water geothermal heat pump systems. The software program is composed of a building load, borehole design, and heat pump modules that enable the designer to perform a complete design of the ground loop heat exchanger. The building load block module has two different modules namely average block and zone load modules. The average block module is suitably used when the designer has total building block loads and quickly wants to size heating and cooling geothermal system. The zone block module is well suited when there is a zone differentiated heating and cooling profile. The heat gains or heat losses may be entered either by design day loads or monthly building loads obtained from building load calculation methods. The heat pump module enables for a standard heat pump unit specifications to be selected or customized. The borehole design module can select ground heat exchanger type and structure. Table 1 shows the basic design input data used in the simulation [21]. It is assumed that the GSHP takes a period of 15years to 20years after first installation based on previous data [11], hence the numerical analysis is simulated for a period of 20 years. In cooling mode and heating mode, a standard EWT of 12 °C and 40 °C respectively was used. The underground circulation fluid type used was a mixture of water and 13.6% concentration of ethanol. A U-tube pipe type SDR11 was selected. The ground temperature used for the simulation was 15 °C.

In order to design ground loop heat exchangers by GLD program, the monthly and daily building load data should be given.

Table 1
Design input data of GHSP.

Design input data	Specification
EWT(Entering water temp.) in load side	Cooling: 12 °C, Heating: 40 °C
EWT(Entering water temp.) in source side	Cooling: 20–35 °C, Heating: 0–15 °C
Fluid type	Water + Ethanol 13.6%
Fluid specific heat	4.182 kJ/kg K
Thermal diffusivity	0.07 m^2/day
Thermal resistance	0.131 m*K/W
Pipe type	SDR11
Borehole diameter	150 mm
Grout thermal conductivity	2.1 W/(m*K)
Circulation pump power	2.1 kW
Ground temperature	15 °C
Thermal conductivity of borehole	2.0, 2.8 W/m*K
Prediction time	20 Years

Table 2
Building loads.

	Cooling load		Heating load	
Month	[kWh]	Peak [kW]	[kWh]	Peak [kW]
1	0.0	0.0	1585904.3	4637.7
2	0.0	0.0	1056965.5	3704.8
3	0.0	0.0	577983.5	2232.6
4	0.0	0.0	268744.1	1148.3
5	0.0	0.0	0.0	0.0
6	1244526.9	3951.6	0.0	0.0
7	1627791.0	4682.7	0.0	0.0
8	1572632.0	4181.9	0.0	0.0
9	734957.1	3801.3	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	701533.9	2835.3
12	0.0	0.0	1314144.5	3852.7
Annual	5179907.0	–	5505275.8	–

This building load data used for the residential apartment was given from the previous literature [22], as shown in Table 2. Total building area was by 87,264 m^2. For the buildings, the cooling peak load is slightly higher than the heating peak load, while the total annual cooling load is lower than the total annual heating load. These building load data was entered into the GLD building load module for the simulation of the GHSP closed-loop vertical heat exchanger. The peak cooling and heating loads were to be 4682.7 and 4637.7 kW, respectively.

Table 3 shows heat pump unit models used as an input data for designing the ground loop heat exchangers (GLHXs). The heat pumps which have different COP or flow rate were selected from the previous literature [23] to investigate the effect of heat pump performance on the length of GLHXs. One set of heat pump units (Model A, B, and C) had the same COP, while the flow rates were different. The other set of heat pump units (Model A, D, and E) indicated the same flow rate and different COPs. Model A was used as a standard heat pump unit. The capacity of each heat pump was normalized to match the building peak load. The unit of flow rate (LPM/3.5 kW), used in GLD software, represents the required circulating flow rate (LPM) per unit capacity (1RT = 3.5 kW) of the heat pump unit. The GLHX design simulation was also executed according to the building peak load. The peak load was changed from 60% to 100%.

2.2. Results and discussion of the GLHX design

Fig. 1 and Fig. 2 show the variation of GLHX length according to the flow rate of heat pump units (Model A, B, and C in Table 3). As the flow rate of heat pump unit increased, the length of the designed GLHX was increased. It was observed that an 11.14% increase in the underground flow rate resulted in an increase of 1.92% in the GLHX length in the cooling mode. In the heating mode, an increase