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Development of a graph method for preliminary design of borehole ground-coupled heat exchanger in North Louisiana

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ABSTRACT

Heating and cooling of a building is a major energy demand and a source of CO_2 emission in the atmosphere. Using geothermal energy in the form of borehole ground coupled heat exchanger (GHX) can be an effective and economical alternative. To make the GHX design quick and easy to do in its preliminary stage, a simple and easily implemented method is needed. This paper synthesizes relations between the GHX spacing, diameter, soil thermal conductivity and peak heating/cooling energy output for a typical building foundation in Louisiana by proposing a graph method. One set of design graphs were developed for northern Louisiana, where subsurface soils are mainly stiff clays and dense sands. The GHX boreholes were designed without any tedious calculation by using these graphs. The GHX solutions from the developed graph-method were reliable and accurate, and agreed fairly well with the results from the industry-popular software packages GLD 2012 and GLHEPRO for a house cooling example that was selected in Ruston, Louisiana.

1. Introduction

This paper presents a simplified method to design a vertical ground coupled heat exchanger (GHX) to use geothermal energy. It is a promising sustainable and renewable energy source from heat transfer by taking the temperature difference between air and subsurface soil. A GHX uses ground as a heat source in winter and a heat sink in summer as sketched in Fig. 1. The basic concept of the GHX is to transfer energy between seasonally changeable atmospheric temperature and constant ground soil temperature at a depth by using circulating fluid in pipes placed within a borehole. To be more exact, a typical thermally enhanced grout filled vertical borehole is excavated in the soil where there is a U-tube with a fluid circulating through, and by this method there will be a heat transfer from soil to structure.

The GHX technology is not new in Europe and has been proven very successful over the years. One of the biggest challenges in this technology is that there is a lack of knowledge of thermal effects of the borehole due to the complicated interactions among soil, grout and turbulent flow, and long term performance of this system once installed in a building [1]. For this reason, dimensioning of the borehole was done empirically in some cases [2]. Furthermore, in order to design the GHX effectively, a deep understanding of the heat transfer from soil to borehole and then from borehole to fluid is necessary. In a borehole three types of heat transfer occur. Total heat transfer can be break down into the soil-grout couple, grout-HDPE (High density polyethylene) pipe couple and HDPE pipe-fluid couple. Moreover, the fluid inside the U-tube moves in a turbulent flow, which is primarily modeled using the K-epsilon and K-omega models [3]. Designing a borehole also needs to collect soil, grout, fluid and geothermal heat pump properties, such as temperature, moisture content and dry density of soils, circulating fluid discharge, circulating fluid type, fluid velocity, and thermal conductivities of soils, HDPE pipe, grout and fluid. Properties of geothermal heat pump capacity and circulating pump are also the key features. Most research that has been done in this field was focused on the understanding of the behavior of a GHX, such as thermal stress/strain, influence of ground water flow on the GHX, energy output differences using different types of U-tube (helical pipe and triple U-tube, etc.), effect of viscoelastic circulating fluid in the GHX, cyclic behavior of the GHX or the heat transfer in turbulent flow, etc. [4–11]. In recent years finite element analysis and experimental test (e.g., impulse response test) have been utilized to understand the complicated thermal behavior of a GHX in heating and cooling circulations [11–16]. Therefore, it is very complicated to design a GHX by taking into account all these factors. In the planning stage of using geothermal energy, a simplified borehole design method might be helpful. The UK Microgeneration

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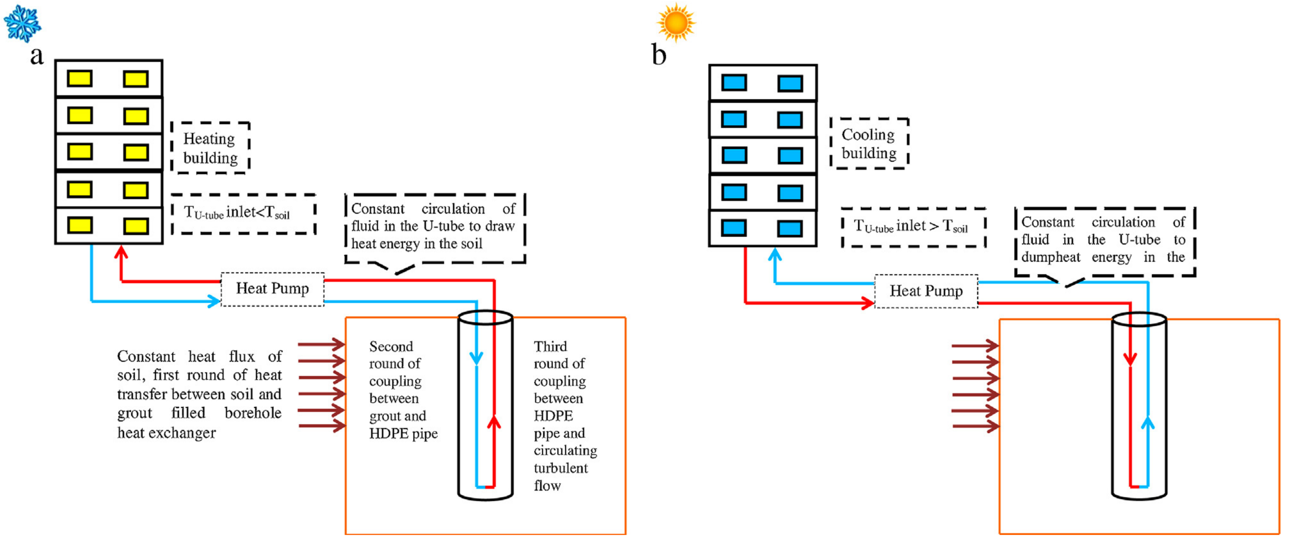

Fig. 1. (a) A schematic diagram of a borehole heat exchanger in winter. (b) A schematic diagram of a borehole heat exchanger in summer.

Certification Scheme [17] provided look-up tables to estimate how much heating power available from borehole heat exchangers in different ground conditions. In this paper a new and simple graph method is presented based on climate and subsurface soil conditions in the state of Louisiana. The graph method could give a quick solution to the fundamental questions of geothermal energy use, such as the total borehole length needed for the peak HVAC load demand of a small building or an apartment. The findings were validated using commercially available software packages GLD 2012 and GLHEPRO, respectively [18,19]. A real house cooling system was designed as an example using the simplified method, and results were verified by the two commercial software programs. This method has significantly reduced the need of background knowledge and made the design simpler and faster. The result found from this method can be used as a basis of an elaborate design. These graphs were produced for northern Louisiana soils using its long-term measured ground temperature data, and may provide as well useful information for projects in other states with similar ground temperature and thermal properties of ground soils.

There are many types of GHXs that are available in practice, and among them the most popular one is the closed-loop vertical heat exchanger. In this paper only grout filled vertical heat exchanger is discussed. Unlike in southern Louisiana, dense sands and stiff clays dominate the subsurface soil layers in northern Louisiana, where pile foundation is not necessary for many one or two-story houses. For the use of geothermal energy, installation of typical grout filled borehole outside the building premise is an important option.

2. Fundamental parameters for the geothermal heat exchanger design

One of the most important parameters for geothermal heat exchanger design is the ground soil temperature. It remains constant beyond the depth of 9.14 m (30′) throughout the year based on the US Environmental Protection Agency [20]. From Fig. 2, the ground soil temperature in northern Louisiana can be taken as 18.33 °C (65 °F). In the north, ground water table is lower than in the south. As such, the soils are considered partially saturated. This assumption implies that less heat transfer occurs in the heat exchanger borehole in northern Louisiana than in the south, as soils with higher moisture contents have more heat transfer from soil to borehole [21–23]. Other important factors that influence the energy output from a geothermal heat exchanger system include the inlet and outlet fluid temperature gap, U-tube orientation in a borehole, number of U-tubes in a borehole, grout thermal conductivity, U-tube diameter, circulation pump power, flow rate in a U-tube, bore hole spacing and use of optional cooling tower, etc. [24,25].

Nowadays it's almost a convention to use a heat pump in the GHX system to increase the coefficient of performance (COP). Refs. [27,28] suggested that, for cooling, a temperature gap ranging from 11.11 °C (20 °F) to 16.7 °C (30 °F) above the undisturbed ground water temperature might be needed, and for heating a gap ranging from 5.55 °C (10 °F) to 11.11 °C (20 °F) below the undisturbed ground water temperature might be needed. In the design for northern Louisiana, the U-tube inlet fluid temperature was taken as 35 °C (95 °F) and the outlet fluid temperature as 7.22 °C (45 °F). To circulate the fluid, a 1492 W (2 HP) circulation pump is adopted with an efficiency of 85% considered in the design found from software package GLD 2012 [18]. To minimize the energy costs of heat pump and circulation pump, the system was designed such that it had a variable fluid speed depending on thermal load demand. Again to ensure turbulent flow in the U-tube all the time, a minimum flow velocity was taken 0.61 m/s (2 fps) and the design discharge was taken 11.99×10^{-4} m^3/s (19 gpm). It was over 0.76×10^{-3} m^3/s (12 gpm), as presented in Table 1, which was suggested by commercial software package GLHEPRO in the simulation [19]. In the design no antifreeze solution was considered as it is highly unlikely that water is frozen in the U-tube in Louisiana. Generally in areas where temperature goes below freezing point one needs to use methanol/ethanol with water in the U-tube [25].

In the research presented in this paper, it was assumed that a standard dimensional ratio (SDR 11) type of U-tube (40 mm in diameter) was placed in each borehole with a diameter of 0.25 m (10 in.). As presented in Table 1, three types of U-tube placement are available for use as illustrated in Fig. 3. For the research conducted, the pipe placement in the middle one was selected. In the design, the shank spacing (c/c distance between two ends of U-tube) was taken 0.05 m (0.17′). In Louisiana the GHX is a cooling

Table 1
The minimum flow rate in pipes with different sizes [26].

Pipe size (m)	Minimum flow rate $\times 10^{-3}$ (m^3/s)	Pipe size (m)	Minimum flow rate $\times 10^{-3}$ (m^3/s)
0.019	0.25	0.038	0.76
0.025	0.38	0.051	1.14
0.032	0.57	0.076	2.52