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The heat transfer analysis and optimal design on borehole ground heat exchangers

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Abstract

The paper makes heat transfer analysis on borehole ground heat exchangers (GHEs) of ground-coupled heat pump system, for one thing, the thermal transmission on two cases including sing U-tube and double U-tubes inside borehole are illustrated, for another, the heat transfer characteristics outside borehole are presented based on the mathematical model, it is meaningful to obtain the analytical solution of temperature response in the underground medium. The relevant analysis lays a firm foundation for the optimal design of borehole GHEs because it can provide theoretical guidance for the calculation and design. In addition, some factors which can exert influences on the heat exchange performance of GHEs are pointed out, such as the arrangement of boreholes GHEs, the type of circulating liquid and so on. Afterwards the impacts degrees of these factors are studied according to simulation. It is necessary to optimize the design of borehole GHEs because in such a way can the size of GHEs be reduced so that the initial cost of the system is lowered, this is favourable for the application of ground-coupled heat pump technology.

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Keywords Ground-coupled heat pump; Ground heat exchangers; Borehole; U-tube; Influential factors;

1. Introduction

The ground-coupled heat pump (GCHP) technology adequately utilizes underground medium as the cooling source and heating source respectively in summer and in winter, this system consists of ground heat exchangers (GHEs), heat pump unit and indoor air-conditioner. GHEs usually can be divided into horizontal GHEs and vertical GHEs in the light of arrangement [1]. In spite of easy construction and installation for horizontal GHEs, it should be admitted that the performance is easily affected by ambient outside climate, another obvious shortcoming is large land area needed for burying heat exchange tubes. Therefore vertical GHEs are most widely applied and the schematic diagram for the whole system is shown in Fig.1.

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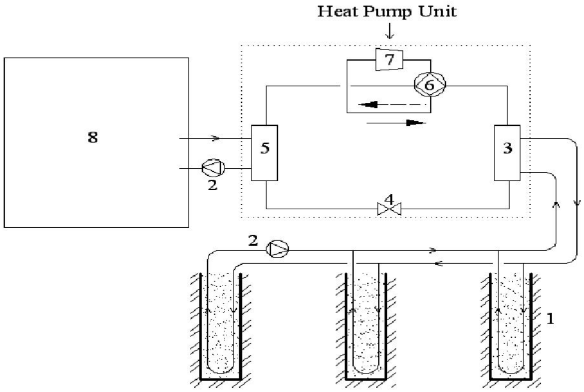


1.Ground heat exchangers 2.Circulating water pumps 3.Heat exchanger 4.Throttling valve 5. Heat exchanger 6.Four-way directional control valve 7.Compressor 8.Building

Fig.1 Schematic diagram of ground-coupled heat pump system

2. Heat transfer equations inside and outside borehole

2.1 Inside borehole

As far as single U-tube is concerned, circulating liquid flows along U-tube to release or absorb heat, considering there are two tubes then if the heat flux for them are respectively q_1 and q_2 , T_{f1} and T_{f2} denotes the average temperature of liquid respectively inside two tubes [2], T_b is the mean temperature of tube. In addition, R_{11} and R_{22} can be regarded as thermal resistance respectively between every tube and circulating liquid for two tubes, and R_{12} stands for thermal resistance between two tubes. Accordingly, the relevant equations are obtained as follows [3]:

$$\begin{cases} T_{f1} - T_b = R_{11}q_1 + R_{12}q_2 \\ T_{f2} - T_b = R_{12}q_1 + R_{22}q_2 \end{cases} \quad (1)$$

Because double U-tubes implies two groups of U-tubes are installed in parallel, thereby there are totally four branch tubes and two inlets and two outlets for circulating liquid flowing through tubes. q_1, q_2 , q_3 and q_4 are severally heat flux of four branch tubes, T_{f1} ,T_{f2}, T_{f3} and T_{f4} respectively indicates the mean temperature of liquid inside every branch tube, R_{ij} (i=j) is the thermal resistance from liquid to tube and R_{ij} (i≠j) shows the thermal resistance between every two branch tubes. The energy equations are listed in Eq.(2):

$$\begin{cases} T_{f1} - T_b = R_{11}q_1 + R_{12}q_2 + R_{13}q_3 + R_{14}q_4 \\ T_{f2} - T_b = R_{21}q_1 + R_{22}q_2 + R_{23}q_3 + R_{24}q_4 \\ T_{f3} - T_b = R_{31}q_1 + R_{32}q_2 + R_{33}q_3 + R_{34}q_4 \\ T_{f4} - T_b = R_{41}q_1 + R_{42}q_2 + R_{43}q_3 + R_{44}q_4 \end{cases} \quad (2)$$

2.2 Outside borehole

In virtue of the fact that the depth is long meanwhile the diameter is short for borehole thus the ratio of length to diameter is large, the borehole GHEs can be deemed to be a line source emitting heat continuously [4], it is significant to exhibit the expression of the temperature response induced by GHEs to comprehend the heat transfer essence during the period of running of GCHP system, a method entitled as Green function [5,6] was proposed to depict the temperature response caused by instantaneous heat point source in infinite space and the corresponding equation is given in Eq.(3).

$$G(x,y,z,\tau;x',y',z',\tau')=\frac{1}{8\left[\sqrt{\pi a(\tau-\tau')}\right]^3}\exp\left[-\frac{(x-x')^2+(y-y')^2+(z-z')^2}{4a(\tau-\tau')}\right] \quad (3)$$

In the process of analyzing heat transfer from GHEs to surrounding underground medium, the first step is to ignore the thermal transmission along depth direction i.e. z-axis and only takes x and y directions into account, there is no doubt this is a two-dimensional problem involved Eq.(4) as the formula of temperature response.

$$t_{l,i}=\frac{q_l}{4\pi a\rho c}\int_{(-x^2-y^2)/4a\tau}^{-\infty}\frac{\exp(m)}{m}dm \quad (4)$$

The three-dimensional problem i.e. x, y, and z directions are all considered, actually the depth of any borehole is finite therefore three-dimensional case is approximately to actual circumstance, on these grounds Eq.(5) reflects the accurate expression of temperature response of finite model, $r^2=x^2+y^2$.

$$t_{l,f}=\frac{q_l}{4\pi k}\int_0^h\left\{\frac{erfc\left[\frac{\sqrt{r^2+(z-z')^2}}{2\sqrt{a\tau}}\right]}{\sqrt{r^2+(z-z')^2}}-\frac{erfc\left[\frac{\sqrt{r^2+(z+z')^2}}{2\sqrt{a\tau}}\right]}{\sqrt{r^2+(z+z')^2}}\right\}dz' \quad (5)$$

3. The analysis on every parameter exerting influence on determining size of GHEs

The building area of the project is nearly 18000m^2, and the height is about 36 m contains eight floors, the heat extracted from indoor space is discharged into underground, borehole GHEs not only take on building cooling load but also be responsible for power of heat pump unit, in contrast, when heating for building is carried out, the heat will be absorbed from underground medium then combined with power of heat pump unit to heat building [7]. The building load and borehole GHEs load every month and the cumulative load with the time of borehole GHEs can be demonstrated in Table 1 respectively.

Table 1 The building load, borehole GHEs load every month and the cumulative load for borehole GHEs in a year

Month	Building Load (kWh)	Ground Heat Exchangers Load (kWh)	Ground Heat Exchangers cumulative load (kWh)
January	219119.5	-164340	-164340
February	158057.6	-118543	-282883
March	85941.76	-64456.3	-347339
April	0	0	-347339
May	0	0	-347339
June	-62615.5	75138.62	-272201
July	-168058	201669.1	-70531.4
August	-132425	158909.8	88378.34
September	-28758.5	34510.18	122888.5
October	0	0	122888.5
November	77182.34	-57886.8	65001.77
December	205377.4	-154033	-89031.3

At present the tubes with both diameter 25mm and 32mm respectively are adopted to be installed into borehole to form GHEs [8], The space between tubes, arrangement style of boreholes [9], thermal conductivity of backfill material [10], type of circulating liquid, element of underground medium, distance between boreholes and the minimum temperature of circulating liquid entering heat pump unit are those factors which should be investigated to optimize the design for the borehole GHEs.

4. Conclusions

The heat transfer model are described in detail for both inside borehole and outside borehole; the whole heat transfer process is complex because U-tube, circulating liquid, backfill material, underground medium and so on are respectively one part during heat exchange period, there is no denying the fact that the research provide theoretical guideline for actual GCHP projects. Combined with an actual project which apply GCHP technology as air-conditioning system to fulfil cooling and heating, every parameter that has impact on performance of heat transfer of borehole GHEs are analyzed when different values or cases selected for them are taken into consideration, this is favourable to optimize the design for GHEs then lower the initial cost of the system. The paper not only elaborates theoretical knowledge but also cover actual application function, it is obvious that the research of this paper is significant to promote the further development of GCHP technology.

References

[1] Jia Li, Fang Zhaohong, Qian Xinghua. *Advanced Heat Transfer*. 2nd ed. Beijing: Higher Education Press; 2006.

[2] Zhang Yaozhong, Diao nairen. The energy consumption analysis for variable flow control system of ground heat exchanger. *Energy Conservation*. 2011; 348: 86-89.

[3]Zeng H Y, Diao N R, Fang Z H. Heat transfer analysis of borehole in vertical ground heat exchanger. *International Journal of Heat and Mass Transfer* 2003; 46(12):1203-1211.

[4] Zeng H Y. A finite line-source model for boreholes in geothermal heat exchangers. *Heat Transfer-Asian Research* 2002; 31(7) :558-567.

[5] H.S. Carslaw, J.C. Jeager. *Conduction of Heat in Solids*.2nd ed. Oxford: Oxford Press, 1959

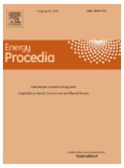
[6] Min Li, Alvin C.K. Lai. Heat-source solutions to heat conduction in anisotropic media with application to pile and borehole ground heat exchangers. *Applied Energy* 2012; 96: 451-458.

[7]Mirko Morini, Michele Pinelli, Pier Ruggero Spina, Mauro Venturini. Optimal allocation of thermal electric and cooling loads among generation technologies in household applications. *Applied Energy* 2013; 112:205–214.

[8] Georgios A. Florides, Paul Christodoulides, Panayiotis Pouloupatis. Single and double U-tube ground heat exchangers in multiple-layer substrates. *Applied Energy* 2013; 102:364-373.

[9] Cui Ping. Simulation Modeling and Design Optimization of Vertical Ground Heat Exchanger. *Building Energy & Environment* 2010; 29(5):50-54.

[10] Richard A. Beier.Transient heat transfer in a U-tube borehole heat exchanger. *Applied Thermal Engineering* 2014; 62: 256-266.



Biography

Wenke Zhang: Male. Ph.D candidate of the department of building services engineering of the Hong Kong Polytechnic University, the research area is ground source heat pump technology, and have finished a certain amount of research work in terms of calculation and optimization on ground heat exchangers.