

The Modelling of Ground-Coupled Heat Pump Systems

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Abstract: The research on ground-coupled heat pump systems mostly focuses on the modelling of geothermal heat exchanger and some experimental study on system performance. The transient model of geothermal heat exchangers with vertical ground-coupled buried tubes firstly is developed according to conservation of mass and energy in this paper. Then the system model is also established. It consists of two coupled models, one is antifreeze solution loop between the geothermal heat exchanger and a unit, and another is refrigerant loop in heat pump unit. The system performance, such as system cooling capacity, power input and so on, can be predicted according to this model in different layout of geothermal heat exchanger. The experimental result shows that the maximum error of performance factors between predicted and measured data does not exceed percent 10.

Keywords: ground-coupled heat pump systems, geothermal heat exchanger, model

1. INTRODUCTION

The ground-coupled heat pump(GCHP) systems have been utilized in commercial building and residence until late of 1980's because the heat transferring process in geothermal heat exchanger is complicated, and fewer empirical data are available, especially results from systems that have been operating for several years. If the design of geothermal heat exchanger (GHE) is improper, it will bring about unacceptable initial cost. Recently, many reports show the overseas work they have done and obtained results^[1] on this field.

The GCHP systems are paid attentions in China due to advantages of its environmental protection and energy saving and there are some instances of ground source heat pump air-conditioning system in the latest decade. Because there is no relative comprehensive design method on ground-coupled heat pump systems, investigating and summarizing existed project experiences is one of emphases on it.

In the ground source heat pump system, the researches on geothermal heat exchanger are always the difficult and critical problem, meanwhile, it is the core and foundation, which this technology is applied. The existing design methods of geothermal heat exchanger are based on the experimental research from American and European. The domestic research emphases on the ground source heat pump systems are paid on the system performance measure and have obtained the correlative data. However, the conclusion is only fit to some special experimental systems, as a result of knowing less on complicated heat transfer mechanism of heat exchanger in the soil and deficiency in providing basic data, so it is difficult to give a guide for engineering design. Therefore, one of the main objects in this paper is to establish the accurate heat transfer model of geothermal heat exchanger, which coincides with the practical heat transfer process.

It is well known that the performance of ground source heat pump systems is determined by two factors, one is the length and layout of geothermal heat exchanger; another is the matched capability of heat pump units. Under the conditions of giving the layout of geothermal heat exchanger, it is great concerned with the capability of ground source heat pump system in present projects. Therefore, the other subject in this paper is to establish dynamic system models of ground-coupled heat pump, and verify the accuracy of the models by experiments.

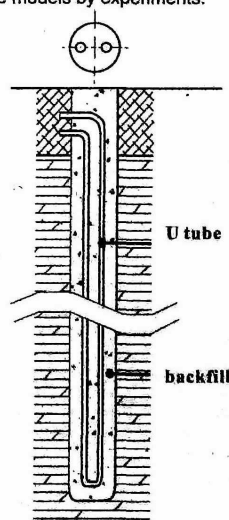


Fig.1 the diagram of vertical GHE with a single U pipe

2. MODEL REVIEW FOR GEOTHEMAL HEAT EXCHANGERS

According to the differences of buried pipes, the GCHPs are classified into two types: horizontal buried pipes and vertical buried pipes. The GHEs with vertical buried pipe usually use U tubes. U tubes are laid vertically in boreholes and backfill are filled in around U tubes so that they contact tightly. There are one or two groups of U tube can be employed in a borehole. The efficiency of GHEs with vertical buried pipe is more high than with horizontal buried pipes, so it is applied extensively in residential and light commercial GCHP systems. The objective to study is the single U pipe GHEs. Fig. 1 shows its installation diagram.

The design of vertical GHEs is complicated by the verity of geological formations and properties that affect thermal performance. Proper identification of material, moisture content, and water movement is an involved process. Even though there is necessary information, it is not arrived accurate design without proper heat transfer model. Therefore One of the approaches to study is to set up simplified model of GHE. There are no model that can be accepted by most researchers until so far.

The existed models are divided into two groups: one is analytical solution model based on the concept of thermal resistance, the other one is numerical solution model based on discrete numerical computation. The first one adopts Kelvin's line heat source or cylinder^[2] theory. This semi-empirical method is simple and can be accepted by engineers easily. Therefore, it is used at present design of GCHP systems. But there are some disadvantages for this method because some simplified assumptions are made^[3] when model is established. Model is too simple and some factors is not considered, especially the variation of cooling and heating load with the time and seasons, the transform and disequilibria between cooling and heating load.

As discussed above, when line source or cylindrical source models are implemented in actual loop design models, further adjustments are necessary to account for the leg-to-leg thermal short-circuiting effects and pipe wall and contact resistances.

In the later phases of the life of a borehole field, where the build up of heat in the far field is of much more significance than the heat distribution local to the borehole, these simplifications are correspondingly insignificant. Correspondingly, in the shorter-term (of the order of hours to weeks) effects local to the borehole, and the influence of the geometry are important.

The other one is numerical solution model based on discrete numerical computation. The finite element method or finite difference method is adopted to solve the underground temperature response and to analyse heat transfer. Numerical models of conduction around the borehole accordingly have advantage of being able to account for the complexities of the geometry but the disadvantage of being computationally more expensive and are

therefore more suitable for modelling on shorter time scales.

3. MODELING OF VERTICAL GHE WITH A SINGLE U PIPE

3.1 quasi-three-dimensional models in a borehole

The thermal property of backfill in a borehole and the geometrical size of borehole have important effects on the capacity of GCHP system in short time scales. In existing one-dimensional and two-dimensional models, it is impossible to gain the change of fluid temperature in U tubes with boreholes depth and heat short-circuit between two U pipes due to making a number of simplifying assumptions. The most significant of these is the assumption of the so-called "equivalent diameter" approximation that treats the two legs of the U-tube as a single pipe co-axial with the borehole so that a solution such as the 'cylinder heat source' solution may be applied. Therefore there are error between predicted value by model and actual measured results.

The group of project takes some innovative study on model of GHEs and develops a new model named as quasi-three-dimensional models on the basis of two-dimensional models. In this model, the change of fluid temperature along the borehole depth and the convective heat transfer of fluid in the direction of axis must be accounted for, but conductive heat transfer of solid inside the borehole along the direction of axis is still considered negligible in order to keep the model concise.

$$\left. \begin{aligned} \Theta_1(Z) &= \cosh(\beta Z) \\ &\quad - \frac{1}{\sqrt{1-P^2}} \left[1-P \frac{\cosh(\beta) - \sqrt{\frac{1-P}{1+P}} \sinh(\beta Z)}{\cosh(\beta) + \sqrt{\frac{1-P}{1+P}} \sinh(\beta)} \right] \sinh(\beta Z) \\ \Theta_2(Z) &= \frac{\cosh(\beta) - \sqrt{\frac{1-P}{1+P}} \sinh(\beta)}{\cosh(\beta) + \sqrt{\frac{1-P}{1+P}} \sinh(\beta)} \cosh(\beta Z) \\ &\quad + \frac{1}{\sqrt{1-P^2}} \left[\frac{\cosh(\beta) - \sqrt{\frac{1-P}{1+P}} \sinh(\beta)}{\cosh(\beta) + \sqrt{\frac{1-P}{1+P}} \sinh(\beta)} - P \right] \sinh(\beta Z) \end{aligned} \right\}$$

$$\text{Here, } \Theta = \frac{T_f(z) - T_b}{T'_f - T_b}, \quad Z = \frac{z}{H}, \quad P = \frac{R_{12}}{R_{11}},$$

$$\beta = \frac{H}{Mc\sqrt{(R_{11} + R_{12})(R_{11} - R_{12})}}$$

C—specific heat of fluid,

M—qualitative flow rate of fluid in a U pipe,

R_{11} —heat resistance from the wall of U pipe to the borehole wall^[5],

R_{12} —heat resistance between two pipes,

T_b —wall temperature of solid at the borehole wall,

H—depth of a borehole,

T_f —the inlet temperature of fluid.

3.2 the analysis of transient temperature field outside the borehole

To analyze heat transfer around a borehole the approaches is that U pipe and overall backfill in a borehole usually can be thought as a line heat source laid in semi-unlimited medium, and to determine the wall temperature. The recommended model abroad to calculate heat resistance outside a borehole is the model of infinite line heat source. It is a one-dimensional model. The borehole depth and the influence of earth surface being the boundary is ignored in it and it will result in larger errors when dealing with longer-term transfer problems.

The temperature response of finite line heat source in semi-unlimited medium is achieved by utilizing Green's function. It solve the contradiction between operational precision and calculating time. the formula can be expressed as^[7]:

$$\Theta = \int_0^1 \left[\frac{\operatorname{erfc} \left(\frac{\sqrt{R^2 + (Z-H')^2}}{2\sqrt{Fo}} \right)}{\sqrt{R^2 + (Z-H')^2}} - \frac{\operatorname{erfc} \left(\frac{\sqrt{R^2 + (Z+H')^2}}{2\sqrt{Fo}} \right)}{\sqrt{R^2 + (Z+H')^2}} \right] dH'$$

Here,

$$Z = \frac{z}{H}, \quad H' = \frac{h}{H}, \quad R = \frac{r}{H}, \quad Fo = \frac{a\tau}{H^2},$$

$$\Theta = \frac{4k\pi(t - t_0)}{q_l}$$

4. WATER-WATER HEAT PUMP MODEL

Reciprocating vapor compression heat pumps and chillers have been the target of a number of simulation models. Hamilton^[7] presented a classification scheme for air conditioning equipment with two extremes. At one end of the spectrum are equation-fit models, called "functional fit" models by Hamilton, which treat the system as a black box and fit the system performance to one or a few large equations. At the other end are deterministic models, called "first principle" models by Hamilton, which are detailed models based on applying thermodynamic

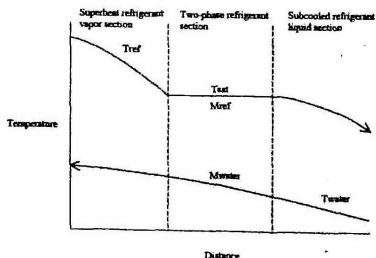


Fig. 2 Temperature profile of the counter-flow concentric tube condenser

laws and fundamental heat and mass transfer relations to individual components.

A heat pump unit consists of compressor, condenser, expansion valve and evaporator. The model presented in this report uses deterministic models of each heat pump component. Each component is simulated to a very detailed level. For example, to simulate the real heat transfer process in the condenser, the condenser itself is analysed as three heat exchangers connected in series corresponding to the three phases of the refrigerant (see Fig.2). Evaporator model is also be obtained in the same method. Compressor and thermostatic expansion valve model are presented by applying lumped parameter method. Heat pump model is composed of four components model by connecting with heat and heat and mass conservation relations. After initial value of three variables, just like evaporating temperature condensing temperature and refrigerant quality is assumed, the calculation begins. if the prespecified error tolerance is beyond limited value, initial value is modified and the process continues until the condition is attained.

When the component's size and input parameter are given, we can simulate outlet temperature of cooling water and chilled water and the performance of heat pump.

5.SYSTEM MODEL FOR GCHP

The system of water-water GCHP consists of three loops: water or antifreeze solution loop, the refrigerant loop in heat pump unit and water loop on side of air conditioning room. So the GHE model, heat pump model and the user load model through the relations of mass and energy conservation, couples the system model. The simulating approaches is summarized below.

1. Specify the length and layout of GHE, physical properties of underground soil and plastic buried pipes.
2. Specify component geometry of condenser and evaporator and compressor characteristics and expansion valve.
3. Input variables and parameters:
The ground loop——initial temperature, flow rate, specific heat of water or antifreeze solution
Water loop on side of user load——room cooling load, returning temperature, specific heat of water
Refrigerant loop in heat pump unit——refrigerant charge
4. Call heat pump model and simulate the capacity of heat pump, outlet temperature of cooled and cooling water at initial moment.
5. Call GHE model and simulate outlet fluid temperature of GHE at first moment.
6. Call load model and simulate the cooled water temperature as inlet temperature of unit at first moment.
7. Call heat pump model and simulate the capacity of heat pump, outlet temperature of cooled and cooling water at next moment.
8. Repeat step 5 to 7 and can calculate the COP of heat pump, outlet temperature of cooled and cooling water at any moment until the simulation time is to up.

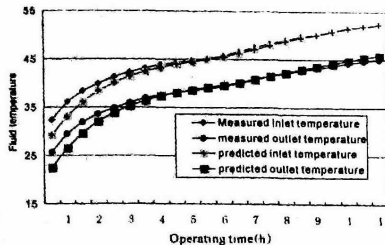


Fig.3 Measured vs. predicted fluid temperature of a GHE

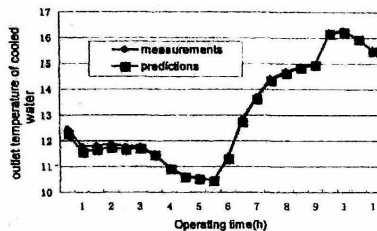


Fig.4 Measured vs. predicted outlet water temperature in heat pump unit outlet

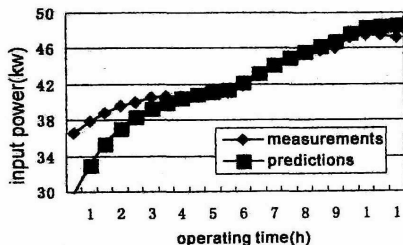


Fig.5 Measured vs. predicted power of a compressor

6.RESULTS AND DISCUSSION

Comparisons between predictions of the model and corresponding measurements on the experimental facility were made to determine the accuracy and limitations of the transient system model.

Fig.3 through Fig.5 illustrate comparisons between the experimental measurement and model predictions for GHE and heat pump unit.

Above results shows that the error of inlet and outlet fluid temperature, compressor power and cooled water outlet temperature are both bigger for a GHE inlet in initial about three hours and then gradually decrease after that. This illustrates that this system model don't fit to simulate the performance of heat pump system in a short time interval.

This is mainly because the heat transfer of GHE in boreholes is thought as steady-state heat transfer approximately. The relative error between simulations and measurements included compressor power, fluid temperature in the outlet of GHE, cooled water and so on does not exceed 10% by a larger number of individual tests. This show the model is invalid.

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