EFFECTS OF GROUNDWATER FLOW DIRECTION ON PERFORMANCE OF GROUND HEAT EXCHANGER BOREFIELD IN GEOTHERMAL HEAT PUMP SYSTEMS USING 3-D FINITE DIFFERENCE METHOD

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ABSTRACT

The effects of groundwater direction on performance of geothermal heat pump systems were analyzed using a 3-D finite difference method with rectangular meshes. Each borehole was approximated by a square column with the actual circular borehole section circumscribing the approximated square section. The fluid temperatures inside each borehole were calculated by discretizing borehole vertically into different segments. Simulations made on various borefield configurations under several loading conditions at different groundwater velocities and directions showed that the percentage variation in leaving fluid temperature was highest for continuous constant load. With a daily operating schedule of 12 hours, the maximum percentage variation was reduced by more than 40%. The introduction of a cyclic load decreased it further but to a much lesser extent. Moreover, the percentage variation generally increased with the scale of the borefield. Hence, a more precise estimation on the groundwater characteristics is necessary when designing a large borefield.

KEYWORDS

Borehole, Borefield, Ground heat exchangers, Geothermal heat pump, Groundwater

INTRODUCTION

Geothermal heat pump systems, employing the ground as a medium for heat exchange to the surroundings through the ground heat exchangers inside the boreholes, provide a higher energy efficiency than conventional air cooled systems. However, the annual unbalanced load when used in tropical or sub-tropical regions will result in a gradual increase in the ground temperature which in turn will reduce the system capacity. The loading per unit length of boreholes has to be reduced in order to maintain the ground temperature within an acceptable level during the entire period of service. This means that the total length of boreholes has to be increased, which implies that a higher installation cost will be incurred. The presence of groundwater helps relieve the increase of ground temperature, thus reducing the installation cost. Analytical models for an infinite line source with groundwater advection (Diao et al. 2004, Carslaw and Jaeger 1959) and for a finite line source with groundwater advection (Claesson and Hellström 2000) had been studied. Performance of the borefield was estimated based on the superposition principle. Some other researchers employed the technique of numerical analysis in their investigations using finite element method (Chiasson et al. 2000) or finite difference method (Niibori et al. 2005, Gehlin and Hellström 2003, Pahud et al. 1996). In all cases, the groundwater direction was assumed to be parallel to one coordinate axis. For a borefield containing more than one borehole, the direction of groundwater may affect the performance of the borefield, especially if the layout and connection configuration of the boreholes are complicated. The understanding of the effect of groundwater flow direction will help set the best orientation for the borefield. Besides, the errors in borefield performance prediction due to wrong estimation of groundwater flow direction can be evaluated. In this paper, a 3-D finite difference scheme will be used to determine the heat transfer in the ground. Emphasis will be made on the effects of groundwater flow direction on the system leaving fluid temperature rise.

SIMULATION

In developing the numerical model, the following assumptions are made:

- The ground is homogeneous and the physical properties of all the materials remain constant within the temperature range investigated;
- The boreholes and the ground have no contact resistance;
- The ground temperature remains unchanged at the top surface and at a distance far away from the borefield boundary;
- Quasi-steady state is maintained inside the boreholes;
- All boreholes are identical and fluid flow rate in each tube of boreholes is the same;
- Groundwater flows uniformly in transverse direction.

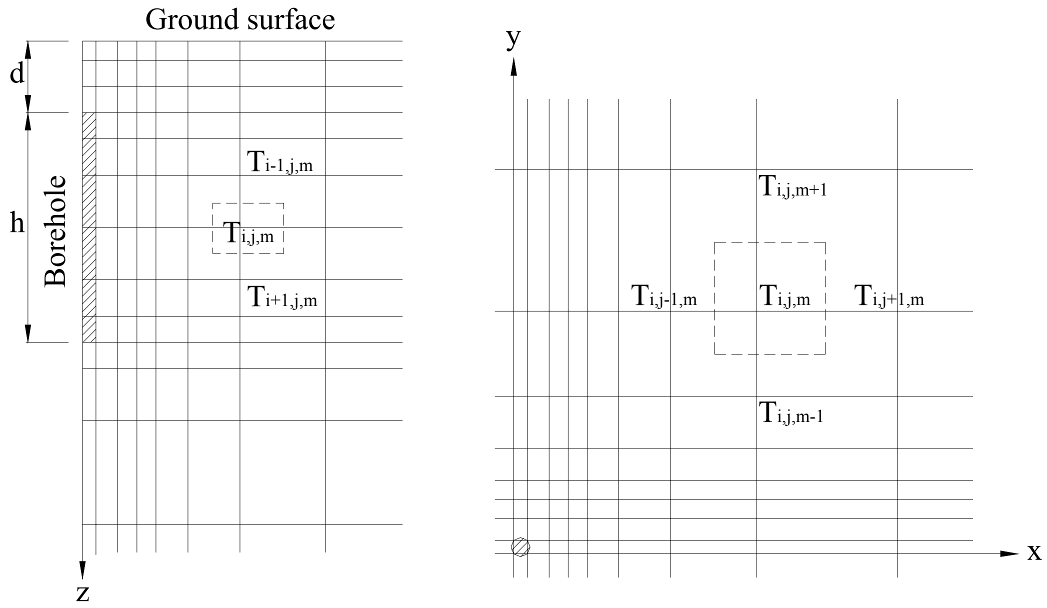

Figure 1 Discretization scheme of ground surrounding borehole

Figure 1 shows the discretization scheme used. The governing differential equation for three-dimensional heat transfer in the ground with a rectangular coordinate system is

$$\rho c_{eff}\frac{\partial T}{\partial t} = k_{eff}\nabla^{2}T - \rho c_{w}\left(V\cos\theta\frac{\partial T}{\partial x} + V\sin\theta\frac{\partial T}{\partial y}\right) + qs \qquad (1)$$

Here, each borehole is represented by a square column with the cross section circumscribed by the borehole radius. The borehole temperature is evaluated by averaging the four corner temperatures of the square section.

The borehole loading per unit length, qb, can be determined by

$$qb = \sum_{u=1}^{Nt}\frac{T_{f,u} - T_{b}}{R_{u}} \qquad (2)$$

R_u can be calculated from formulae derived by previous worker (Hellström 1991). The variation of fluid temperature (and consequently the borehole loading) along each tube with prescribed borehole temperature profile, tube connection and borehole connection configurations can be estimated by discretizing eq. (2) along the borehole and all the grid fluid temperatures can be solved simultaneously by using an iterative method. The source term at each corner point of borehole will be equal to one quarter the borehole loading multiplied by a load factor (taken as 1.047 by calibrating the simulated ground temperature with the cylindrical source model).

The percentage variation (PV) of borehole system leaving fluid temperature rise over entire groundwater direction range is defined as

PV = [(Maximum leaving fluid temperaure rise –
minimum fluid temperature rise)x100]/
Mimumum fluid temperature rise (3)

PV represents the maximum percentage error for the leaving fluid temperature rise due to wrong estimation of the groundwater flow direction. Several borefield configurations (at 5-m borehole spacing and all parallel connected) and load profiles are simulated. Table 1 shows the corresponding values used for various parameters.

Four loading profiles with identical peak cooling load are tried for particular borefield configurations:

1. Continuous constant load;

2. Constant load with a daily operating schedule of twelve hours;
3. Annual periodic load with a zero minimum load and a daily operating schedule;
4. Annual periodic load with (peak cooling load/peak heating load) = 4 and a daily operating schedule.

DISCUSSIOIN AND RESULT ANALYSIS

Figures 2 and 3 show the change of PV with groundwater velocity under different loading profiles for 1x2 and 2x2 borefield

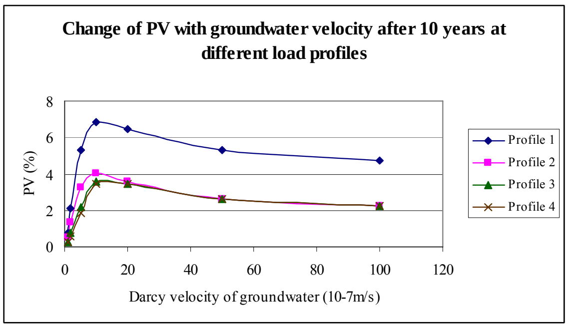

Figure 2 Change of PV with groundwater velocity after 10 years for 1x2 borefield

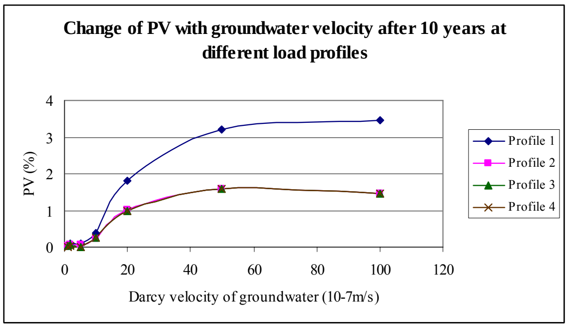

Figure 3 Change of PV with groundwater velocity after 10 years for 2x2 borefield

Figure 2 is typical for non-square borefields. PV increases with increase in Darcy velocity of groundwater until it reaches a maximum, and decreases with further increase in Darcy velocity. For square borefields as shown in Figure 3, the trend depends on the loading profile. For a constant continuous load, PV generally increases with increase in Darcy velocity of groundwater. For other loading profiles, the trend is similar to that for non-square borefields except that PV decreases only slightly after it reaches the maximum. Nevertheless, for square borefields, the directional effect is negligible for a groundwater velocity less than 10^{-6}m/s.

It can be observed that PV depends on the loading profiles, and is highest for a constant continuous load. With a daily operating schedule of 12 hours, the maximum PV is reduced by more than 40%. By replacing the constant load with an annual periodic load (approximated by a sine curve) with a zero minimum load, the maximum PV is decreased further but to a much lesser extent. The provision of a heating period (peak cooling load/peak heating load = 4) in the load cycle has insignificant effect compared to the case with zero heating load.

Figure 4 shows the change of PV at a Darcy velocity of 10^{-5}m/s under a constant load with a daily operating schedule of 12 hours per day with the number of boreholes in x-direction having different borefield shapes (square, 1:2 and 2:3).

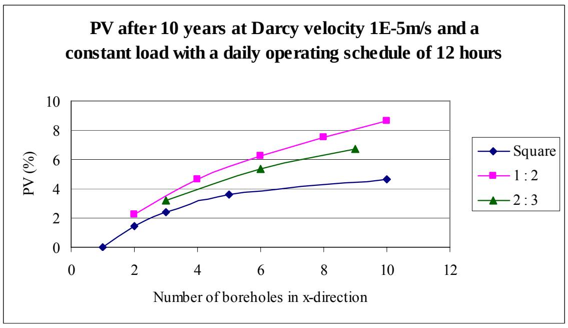

Figure 4 PV of various borefields after 10 years with groundwater velocity 10^{-5}m/s and a constant load with a daily operating schedule of 12 hours

It can be noted that PV is generally increased with the scale of the borefield. From Figure 3, the maximum PV with daily operating schedule is only slightly higher than that with Darcy velocity being 10^{-5}m/s (less than 10%). Hence, it can be anticipated that the maximum PV for a 10x10 borefield will be around 5%. However, from Figure 2, the maximum PV with a daily opreating schedule can be 40% higher than that with a Darcy velocity being 10^{-5}m/s. Hence, the maximum PV can reach 12% for a 5x10 borefield and 10% for a 6x9 borefield. The range of groundwater flow direction between the maximum and minimum fluid leaving temperatures does not always equal the full groundwater direction range (45° for square borefield and 90° for non-square borefield). Indeed for a 2x2 borefield, the maximum and minimum fluid leaving temperatures occur within a range of 15° of groundwater flow direction, while for 1x2 borefield with a very high groundwater flow velocity, the range is 60°.

The leaving fluid temperature rise affects the design length of boreholes very much. In fact, a 10% decrease in the leaving fluid temperature rise can result in more than 15% decrease in the borehole length (assuming the same allowable maximum leaving fluid temperature), resulting in a tremendous reduction in the installation cost.

CONCLUSION

The effects of groundwater flow direction on the performance of ground heat exchangers in geothermal heat pump systems were analyzed. Simulation results showed that square borefields were less likely to be affected by groundwater flow direction, especially if the groundwater flow velocity was less than 10^{-6}m/s. For non-square borefields, PV reached a maximum at a particular groundwater flow velocity. In all cases, PV depended on the loading profiles and the scale of borefields. For large non-square borefields, PV could exceed 10% with a daily load schedule. This could lead to a substantial difference in the design borehole length, and consequently the installation cost.

Hence, in designing a large borefield, especially if it is to be used in sub-tropical regions where the annual load is unbalanced, the precise estimation of groundwater flow direction can help decide the proper setting of the borefield in order to get the best performance. Conversely, an inaccurate evaluation of the groundwater flow direction can substantially derate the capacity of the borefield.

NOMENCLATURE

k	Thermal conductivity, mK/W
Nt	Number of tubes in each borehole
PV	Percentage variation of leaving fluid temperature rise
qs	Source term, W
qb	Borehole loading per unit length, W/m
R	Thermal resistance coefficient of tubes inside borehole, mK/W
T	Ground temperature, K
t	Time, s
U	Tube designation inside borehole
V	Darcy velocity of groundwater, m/s
x	Coordinate axis dimension, m
y	Coordinate axis dimension, m
ρc	Volumetric heat capacity, J/m^3K
∇^2	Laplacian operator
θ	Groundwater direction relative to x-axis

Subscript

b	Borehole surface
eff	Effective wet ground properties
f,u	Fluid at tube u
u	Tube designation inside borehole
w	Groundwater

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Table 1 Corresponding values of various parameters used for simulation

Parameter	**Value**	**Parameter**	**Value**
Insulated length of borehole, m	5	Effective length of borehole, m	110
Borehole diameter, m	0.055	U-tube outer radius, m	0.016
U-tube inner radius, m	0.013	Distance between tube and borehole centre, m	0.03
Number of discretization segments along borehole	20	Effective ground thermal conductivity, W/mK	3.5
Number of tubes inside borehole	2	Effective ground volumetric heat capacity, J/m^{3}K	2,160,494
Fluid mass flowrate inside tube, kg/s	0.2	Groundwater volumetric heat capacity, J/m^{3}K	4,190,000
Peak applied load per borehole, W	4000	Fluid volumetric heat capacity, J/m^{3}K	4,190,000
Pipe thermal conductivity, W/mK	0.4	Fluid thermal conductivity, W/mK	0.614
Grout thermal conductivity, W/mK	1.3	Fluid dynamic viscosity, kg/ms	0.00086