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Computer simulation of borehole ground heat exchangers for geothermal heat pump systems

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Abstract

Computer simulation of borehole ground heat exchangers used in geothermal heat pump systems was conducted using three-dimensional implicit finite difference method with rectangular coordinate system. Each borehole was approximated by a square column circumscribed by the borehole radius. Borehole loading profile calculated numerically based on the prescribed borehole temperature profile under quasi-steady state conditions was used to determine the ground temperature and the borehole temperature profile. The two coupled solutions were solved iteratively at each time step. The simulated ground temperature was calibrated using a cylindrical source model by adjusting the grid spacing and adopting a load factor of 1.047 in the difference equation. With constant load applied to a single borehole, neither the borehole temperature nor the borehole loading was constant along the borehole. The ground temperature profiles were not similar at different distances from the borehole. This meant that a single finite difference scheme was not sufficient to estimate the performance of a borefield by superposition. The entire borefield should be discretized simultaneously. Comparison was made between the present method and the finite line source model with superposition. The discrepancies between the results from the two methods increased with the scale of borefield. The introduction of time schedule revealed a discrepancy between the load applied to the ground heat exchanger and that transferred from the borehole to the ground, which was usually assumed to be the same when using analytical models. Hence, in designing a large borefield, the present method should give more precise results in dynamic simulation.

Keywords: Ground source heat pump; Ground heat exchanger; Borehole; Borefield; Thermal resistance

1. Introduction

Geothermal heat pump systems, employing the ground as media of heat exchange with the surrounding through ground heat exchangers, offer higher energy efficiency and lesser environmental impact than air-cooled systems. Vertical ground heat exchangers (with U tubes installed inside boreholes) are most common, requiring lesser land field. Fig. 1 shows the general arrangement of a borehole ground heat exchanger and pipe connection in a borefield. However, drilling of deep boreholes involves a high initial cost, which hinders the application of such systems. To reduce cost, precise system design becomes very important.

Various design tools have been developed. The simplest ones are the line source model from Ingeroll et al. [1] and the cylindrical source model from Carslaw and Jaeger [2]. Both models assume infinite length for borehole, and no steady state occurs. Hart and Couvillion [3] proposed an equation for the ground temperature around a line source in terms of a power series of the ratio of radial distance and far field distance. The definition of far field distance depended on the radius of the borehole. IGSHPA [4] adopted the line source model but developed formulae to approximate the exponential integral appearing in the line source solution. Hellstrom [5] applied a numerical inversion technique to solve the inverse Laplace transform of the governing differential equation for one-dimensional transient heat conduction equation in polar coordinates and developed an alternative form for the cylindrical source solution. Hikari et al. [6] derived simplified forms for the

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Nomenclature

a_g	thermal diffusivity of ground (m^2/s)
b_{uv}	centre to centre distance between tube u and v in a borehole (m)
Cf	$=\pi r_{pi}^2 \rho_f c_f/\Delta t$ (W/mK)
c_f	specific heat capacity of fluid (W/kg K)
d	depth of borehole top from ground surface (m)
di	centre to centre distance between tube and borehole (m)
dx	ground grid spacing in x direction (m)
dy	ground grid spacing in y direction (m)
dz	ground grid spacing in z direction (m)
H	length of borehole (m)
h	heat transfer coefficient (W/m^2)
k	thermal conductivity (W/mK)
M	mass flow rate of fluid inside tube of borehole (kg/s)
M_{total}	total mass flow rate of fluid through a borefield (kg/s)
m1	exponent used in Eq. (3)
N	number of tubes inside each borehole
N_{bore}	number of boreholes in a borefield
nz_{bore}	number of ground grid points along borehole depth
Pr	Prandtl number
Q	applied load to a borefield (W)
Q_{bf}	load transferred from borefield to ground (W)
qb	borehole loading per unit length (W/m)
q_{fact}	load factor to be multiplied in calculating the source term
qs	source term in the finite difference equation (W)
qt	tube loading per unit length inside borehole (W/m)
q_{x+}	heat load into control volume of ground from downstream x direction (W)
q_{x-}	heat load into control volume of ground from upstream x direction (W)
q_{y+}	heat load into control volume of ground from downstream y direction (W)
q_{y-}	heat load into control volume of ground from upstream y direction (W)
q_{z+}	heat load into control volume of ground from downstream z direction (W)
q_{z-}	heat load into control volume of ground from upstream z direction (W)
$\overset{o}{R}_{uv}$	thermal interference coefficient between tube u and v according to Eq. (A.1) (mK/W)
$\overset{o-}{R}_{uv}$	element of inverse matrix of $\overset{o}{R}_{uv}$ between tube u and v (W/mK)
$\overset{\Delta}{R}_{uv}$	thermal interference coefficient between tube u and v according to Eq. (3) (mK/W)
Rb_{bf}	thermal resistance of entire borefield (mK/W)
Re	Reynolds number
$\overset{*}{Rnf}_{uv}$	thermal interference matrix element between tube u and v according to Eq. (9) at no fluid flow (W/mK)
$\overset{\Delta}{Rnf}_{uv}$	thermal interference coefficient between tube u and v according to Eq. (6) at no fluid flow (mK/W)
Rp	thermal resistance between fluid and grouting inside borehole (mK/W)
Rpnf	thermal resistance between fluid and grouting inside borehole at no fluid flow (mK/W)
r_b	borehole radius (m)
r_{max}	margin from borefield boundary beyond which the ground temperature was assumed unchanged (m)
r_{pi}	inner radius of tube (m)
r_{po}	outer radius of tube (m)
T	ground temperature (K)
Tb	Borehole temperature (K)
$\overline{Tb}$	average borehole temperature of entire borefield (K)
Tf	fluid temperature at boundary of control volume inside borehole (K)
Tfl	fluid temperature at centre of control volume inside borehole (K)
T_{in}	fluid temperature entering a borefield (K)
T_{out}	fluid temperature leaving a borefield (K)
t	time (s)
t_{max}	maximum time encountered in the analysis (s)

Greek symbols

Δx	length of control volume of ground in x direction (m)
Δy	length of control volume of ground in y direction (m)
Δz	length of control volume of ground in z direction (m)
Δt	discretization time step (s)
μ	dynamic viscosity (kg/ms)
ρ	density (kg/m^3)
σ	$=(k_b-k_g)/(k_b+k_g)$

Subscripts

b	borehole
f	fluid
g	ground
i, j, m	ground discretization step designation in z, x and y directions
p	tube inside borehole
u, v	tube designation inside borehole

Superscripts

n	discretization step designation in time