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Thermal capacity effects in borehole ground heat exchangers

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ABSTRACT

A one-dimensional transient ground heat exchanger model is proposed to account for fluid and grout thermal capacities in borehole ground heat exchangers with the objective of predicting the outlet fluid temperature for varying inlet temperature and flow rate. The standard two-pipe configuration is replaced with an equivalent geometry consisting of a single pipe and a cylinder core filled with grout. Transient radial heat transfer in the grout is solved numerically while the ground outside the borehole is treated analytically using the cylindrical heat source method. The proposed model is validated successfully against analytical solutions, experimental data, a three-dimensional transient numerical model, and TRNSYS's Type 451.

For a typical two-pipe configuration, it is shown that the fluid outlet temperature predicted with and without borehole thermal capacity differs by 1.4, 0.35, and 0.23 °C after 0.1, 0.2 and 1 h, respectively. Annual simulations are also performed over an entire heating season (5600 h) with a 6 min time step. Results show that the outlet fluid temperature is always higher when borehole thermal capacity is included. Furthermore, the difference in fluid outlet temperature prediction with and without borehole thermal capacity increases when the heat pump operates infrequently. The end result is that the annual COP predicted is approximately 4.5% higher when borehole thermal capacity is included.

1. Introduction

Closed-loop ground coupled heat pump systems rely on ground heat exchangers (GHE) to reject or extract heat from the ground. A schematic representation of such a heat exchanger is shown in Fig. 1. It consists of a borehole in which a U-tube pipe is inserted. The borehole is usually filled with a grout to enhance heat transfer and protect underground aquifers. In general, the depth of the borehole (L) is approximately 100 m and its diameter is usually in the 10–15 cm range. High density polyethylene (HDPE) pipes are typically used for the U-tubes. The inside diameter of these pipes is approximately 25 mm. The center-to-center distance between these pipes varies from cases where the pipes are touching each other in the center of the borehole to cases where the pipes are touching the borehole wall on opposite sides. These two cases are often referred to as the A and C configurations [1]. In the B configuration (shown in Fig. 1), the pipes are equally distanced from each other and from the borehole wall.

Heat is transferred from the fluid circulating in the pipes to the ground. The borehole can experience a variety of flow rates ranging from no flow to full flow conditions and any flow in between if the system is equipped with a variable flow pumping system. At full flow, the residence time, i.e., the time required for the fluid to travel from the inlet to the outlet, is of the order of a few minutes. The difference between the inlet (T_i) and outlet (T_o) temperatures is typically around 5 °C. Inlet conditions (either temperature or flow) variations do not lead to instantaneous changes in the outlet conditions. This is due to two main reasons. First, the residence time of the fluid in the borehole induces a delay. Second, any changes at the inlet are dampened by the fluid and grout thermal capacities.

Ground heat exchangers can be modeled in two distinct regions: from the fluid to the borehole wall, and from the borehole wall to the far field. Ground models have been the subject of many investigations including a comparison exercise [2]. The present study concentrates on the inside of the borehole. A one-dimensional transient borehole model is proposed to account for fluid and grout thermal capacities. The objective is to accurately predict the outlet fluid temperature for varying inlet conditions so that borehole thermal capacity can be accounted for in energy simulation programs. The borehole model is coupled here to a ground model which is based on the cylindrical heat source method.

2. Review of previous studies

Some of the important pioneering works can be attributed to Eskilson [3] and Hellström [4]. Using spatial superposition, Hellström developed a 3D simulation model for borehole thermal energy storage systems. The model was implemented in the

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Nomenclature

c	specific heat (kJ/kg K)
D	half the center-to-center distance between pipes in the U-tube configuration (m)
D_b	borehole diameter (m)
D_{eq}	diameter of the equivalent pipe (m)
D_p	diameter of U-tube pipes (m)
dt	time step (s)
Fo	Fourier number ($Fo = \alpha_{gd} t / r_{bore}^2$)
G	G-factor in CHS method
h	film coefficient (W m^2/K)
int	integer figure
IT	internal time, number of intermediate calculations during each *TI*
k	thermal conductivity (W/m K)
L	borehole length (m)
$\dot{m}$	mass flow rate (kg/s)
NI	number of calculations done in the numerical borehole model during each *RT*
q'	rate of heat transfer per unit length at the equivalent pipe wall (W/m)
q''	heat flux imposed at the inner pipe wall (W/m^2)
r	radial distance from the borehole center (m)
r_b	borehole radius (m)
r_{eq}	equivalent pipe radius = $D_{eq}/2$ (m)
r_p	pipe radius of the U-tubes pipes (m)
$R_{b,ss}$	steady state borehole thermal resistance for real single U-tube borehole geometry (K/W)
RT	residence time, given by Eq. (5) (s)
t	time (s)
t_{res}	residence time (s)
T	temperature (°C)
TI	time increment, the time between two step changes in inlet conditions (s)
T_i	inlet fluid temperature to the borehole (°C)
T_m	mean fluid temperature = $(T_i + T_o)/2$ (°C)
T_o	outlet fluid temperature from the borehole (°C)
T_{req}	temperature at r_{eq} (°C)
u	fluid velocity (m/s)

Subscripts

bore	associated with the borehole wall
eq	associated with the equivalent diameter pipe
f	fluid
gd	ground
gt	grout
i	internal, inlet
n	north neighbor
o	external, outlet
p	associated with the U-tube pipes
real	associated with the real U-tube configuration
r_{eq}	associated with the equivalent pipe wall
s	south neighbor
∞	associated with far field

Superscript

0	value at preceding time step

Greek letters

α	thermal diffusivity (m^2/s)
δr	radial distance between two control-volume faces (m)
Δr	radial increment (m)
Δt	time step (s)
ρ	density (kg/m^3)

TRNSYS [5] simulation program by Hellström et al. [6]. However, the thermal capacity of the borehole is not included in the model. When there is flow in the borehole, the fluid temperature is evaluated using the borehole wall temperature and a steady-state thermal resistance. For no flow conditions, the fluid temperature is set equal to the borehole wall temperature.

Eskilson's model calculates the average borehole wall temperature in a bore field using numerically generated *g-functions*. It is important to note that the borehole thermal capacity is not accounted for in the original *g-functions* and that heat transfer to the ground is applied at the borehole wall. Therefore, if only the heat transfer rate in the fluid is known, then one has to evaluate the time it takes for a heat impulse in the fluid to reach steady-state at the borehole wall in order to properly use *g-functions*. This time has been evaluated by Eskilson to be equal to $t_b = 5r_b^2/\alpha_g$, where r_b is the borehole radius and α_g is the thermal diffusivity of the grout material. For typical boreholes, t_b is of the order of 3–6 h [7].

Wetter and Huber [8] modeled the transient behavior of a single borehole with a double U-tube configuration. This 2D model was implemented in TRNSYS as Type 451. It accounts for grout and fluid thermal capacities. In the radial direction, heat transfer is simulated numerically from the borehole center up to a distance of two meters where the boundary temperature is evaluated using Kelvin's line-source solution. The four-pipe geometry is transformed into a single pipe of equivalent diameter centrally located in the borehole. The grid spacing is non-uniform in the radial direction with one grid point located in the equivalent annulus representing the grout. In the axial direction, the computational domain is subdivided

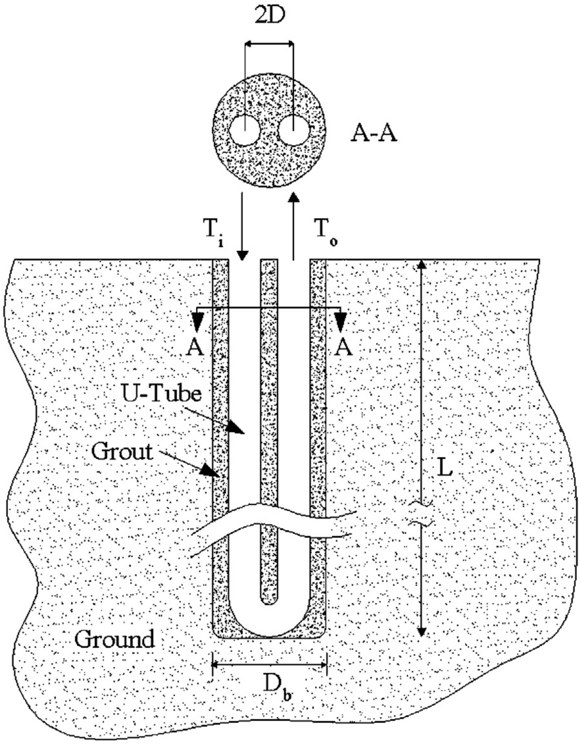

Fig. 1. Schematic representation of a typical single U-tube ground heat exchanger.