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An analytical approach to evaluating the effect of thermal interaction of geothermal heat exchangers on ground heat pump efficiency

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ABSTRACT

A semi-analytical model that couples a model outside the borehole with one inside the borehole is proposed. To examine the effect of temperature rise in the soil surrounding a vertical ground heat exchanger on the performance of an associated ground heat pump, the heat pump model should be coupled to the model inside the borehole and the conduction heat transfer model outside the borehole. The running fluid temperature, the borehole wall temperature and the heat load profile are the main coupling parameters between the three models. The results of the analytical model are compared with ones of a finite volume numerical model.

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1. Introduction

Below a certain depth, the ground generally remains warmer than the outside air in winter and cooler in summer. The relatively cool ground may be used as a sink in summer to store the extracted heat from a conditioned space via a ground heat pump (GHP). In winter, the process may be reversed and the heat pump can extract heat from the relatively warm ground and transport it into the conditioned space. Thus, the efficiency of the heat pump, which depends directly on the temperature lift across the heat pump, is enhanced for a GHP.

While the use of geothermal systems is widespread, having had a revival in the 1980s and recently, the sustainability of these systems at their design efficiency is being questioned due to unexpected temperature rises caused by the system itself or adjacent systems. Studies indicate that in many cases these systems are not sustainable or not sustainable at the design efficiency [1,2]. The influence of these systems on each other indicates that there is a limit to the density of development of these systems that can occur in a given region [3]. System parameters, such as heat injection/removal rate and system spacing, affect the potential thermal interaction between geothermal energy systems, and can be prevented by restricting values of some of these parameters. Modeling the heat flows and temperature rise in the soil surrounding the ground heat exchangers (GHEs) is needed to determine their potential thermal interactions and sustainability.

The heat transfer in GHEs is usually analyzed in two separate regions (Fig. 1): the region inside the borehole containing the fluid running in the U-tubes and the grout and the soil region surrounding the borehole. The analysis of the two regions can be coupled by the temperature of borehole wall. If the required amount of heat that is to be delivered to/removed from the soil at the borehole wall is known, the borehole wall temperature can be determined by modeling the region outside the borehole by various available methods. In the heat transfer analysis inside the borehole, the running fluid inlet and outlet temperatures that are needed to deliver/remove a required heat to/from the soil can be evaluated based on the borehole wall temperature. The higher the borehole wall temperature, the higher the inlet temperature of the running fluid should be set in order to deliver a required amount of heat to the ground. The heat pump model can utilize the fluid inlet and outlet temperatures of the GHE that are evaluated via the model inside the borehole, and the dynamic simulation and optimization design for a ground coupled heat pump (GCHP) system can be implemented accordingly. This is the basic idea behind the development of the two-region vertical ground heat exchanger model.

Several analytical models for the heat transfer inside and/or outside the borehole are available [4–8]. The models vary in the way the problem of heat conduction in the soil is solved and the way the interference between boreholes is treated. Kurevija et al. [4] model a GCHP system by using two different solutions; cylinder source solution and line source solution (*L*/*E*). Zeng et al. [5] proposed a model for the line source with finite length in a semi-infinite medium to describe more adequately the heat conduction process in the soil surrounding geothermal heat exchangers. This model can be used as a basis to analyze and calculate the heat con-

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Nomenclature

c_p	specific heat at constant pressure (J/kg K)
COP	coefficient of performance
D_b	distance between boreholes (m)
Fo	Fourier number
h_z	integration variable (m)
H	heating length
$\overline{H}$	dimensionless integration variable
i	time step number
k	soil thermal conductivity (W/mK)
$\dot{m}$	mass flow rate (kg/s)
P	dimensionless parameter
q'	heat flux at borehole wall (W/m^2)
r	radial coordinate (m)
$\overline{R}$	dimensionless parameter
R_{11}	thermal resistance between inlet circulating fluid and borehole wall (mK/W)
R_{12}	thermal resistance between inlet and outlet pipes (mK/W)
R_{22}	thermal resistance between outlet circulating fluid and borehole wall (mK/W)
R^{Δ}	thermal resistance (mK/W)
T	temperature (K)
T'_f	inlet circulating fluid temperature at $z = 100$ m (K)
t	time (s)
Z	dimensionless parameter
z	axial coordinate (m)

Greek Letters

α	thermal diffusivity (m^2/s)
β	dimensionless parameter
Θ_1	dimensionless temperature of inlet circulating fluid
Θ_2	dimensionless temperature of outlet circulating fluid
θ	dimensionless temperature
ρ	density (kg/m^3)
τ	time (s)

Subscripts

0	initial
ave	average
b	borehole
f	circulating fluid
f1	inlet circulating fluid
f2	outlet circulating fluid
H	high
L	low
out	outlet
rev	reversible

duction of the vertical boreholes for their long-term operation in GCHP systems. Lamarche and Beauchamp [6] propose an analytical model that yields results very similar to the tabulated numerical ones proposed in the literature. The analytical results of their study are valuable due to the flexibility of analytical methods when evaluating lengths of ground heat exchangers. Yang et al. [7] propose a two-region analytical solution model, which divided the heat transfer region of vertical U-tube GHE into two parts at the boundary of borehole wall, to simulate the heat transfer process of a single vertical GHE used in GCHP system.

Koohi-Fayegh and Rosen [9] study the heat flows in the soil surrounding boreholes in the long run. They present a numerical model for the region outside the borehole and assume a periodic heat flux at the borehole wall. Care must be taken when using a heat flux boundary condition in models for outside the borehole since the temperature of the ground to rise infinitely without a stop in

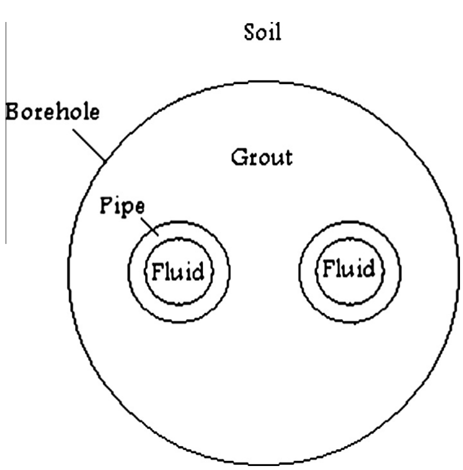

Fig. 1. Cross-section of a vertical ground heat exchanger (GHE). The fluid is ascending in one pipe and descending in the other.

system operation [10]. In reality, if the temperature of the soil surrounding a borehole becomes close to or higher than the inlet temperature of the circulating fluid exiting the heat pump, the system will not be able to deliver the desired heat to the ground and will automatically stop operating until the heat around it is dissipated away and the soil temperature drops to a lower value. In order to overcome such a limitation when modeling the system, the running fluid temperature needs to be evaluated according to the borehole wall temperature and the system heat load to insure that it is in the range where heat pump operation is possible. This is done by coupling the heat transfer model outside of the borehole to the one inside the borehole.

In a recent study, Koohi-Fayegh and Rosen [11] use an analytical solution to the heat transfer problem inside the borehole to evaluate the temperature of the circulating fluid along the borehole length. This solution is then used to calculate the heat delivery/removal along the borehole caused by the temperature difference between the circulating fluid and the borehole wall temperature. The heat delivery/removal calculated from the model inside the borehole is implemented as the heat boundary condition in the analytical line source with finite length as well as in a three-dimensional finite volume model [12] and the results are compared [13]. The limitation of this study is that the temperature of the soil at the borehole wall is assumed to be steady throughout the whole operation time and, therefore, the solution is only able to make valid estimations of temperature variations in the soil surrounding the boreholes when they are low. This only occurs for lower-than-typical heat flux on the borehole wall. When determining how thermal interaction between two operating GHEs can affect their performance, the effect of the transient borehole wall temperature on their heat delivery strength and inlet fluid temperature becomes an important factor. Furthermore, in the analytical model presented in this study, the heat flux on the borehole wall is assumed to be constant whereas in real systems this heat flux varies in accordance to the building heat load.

The overall objective of this paper is to study the performance of geothermal heat pumps due to “Thermal pollution” in the soil

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