BOREHOLE HEAT EXCHANGER MODELLING: VALIDATION AND SYSTEM PARAMETERS EVALUATION

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Summary The development and validation of a numerical model for the simulation of energy flows and temperature changes in a U-tube borehole heat exchanger is presented. The FlexPDE software package is employed to solve the time-dependent convection-diffusion equation that models the resulting boundary value problem. The model is validated with experimental data and is used to study how various parameters like the U-tube diameter, the ground thermal conductivity and specific heat, affect the exchanger temperature.

INTRODUCTION

Geothermal heat pumps use the ground to reject heat during summer operation or absorb heat in winter operation. A common means of exchanging heat is through vertical ground heat exchangers that mainly consist of a descending and an ascending leg of polyethylene pipe connected at their ends in the ground with a U-joint. A borehole with a diameter of 0.1-0.2m and a common depth of 100 m is drilled in the ground, the heat exchanger is placed in position and the borehole is filled with thermally enhanced bentonite or silica sand. The result is a good contact between the pipe and the ground and therefore a fluid, usually water, circulating in the pipes can be cooled or heated depending on its temperature relative to the adjacent ground. The classic method to model the heat exchange process is through the cylindrical heat source theory proposed by Carslaw and Jaeger [1]. The method is relatively easy to apply and was used by many researchers to model and evaluate the response of ground heat exchangers [2, 3].
With the introduction of the finite element method and software for easy use, a number of researchers have used basic formulae to evaluate the ground heat exchanger performance [4, 5, 6].

PROBLEM FORMULATION

For time-dependent convection-diffusion the representative equation for 3D conduction, but 1D fluid flow, is

$$\frac{\partial \varphi}{\partial t} + u\frac{\partial \varphi}{\partial x} - \frac{\partial}{\partial x}(D\frac{\partial \varphi}{\partial x}) - \frac{\partial}{\partial y}(D\frac{\partial \varphi}{\partial y}) - \frac{\partial}{\partial z}(D\frac{\partial \varphi}{\partial z}) = S, \tag{1}$$

where D is the diffusion coefficient, u is the velocity, φ is the function under consideration, and S is the source or sink term [7]. Applying equation (1) for an incompressible fluid flowing in a pipe with a velocity u and with a convection heat transfer coefficient h in W m^{-2} K^{-1}, we have (for unit volume)

$$\rho c\frac{\partial T}{\partial t} - \rho c u\frac{\partial T}{\partial z} - \frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x}) - \frac{\partial}{\partial y}(\lambda\frac{\partial T}{\partial y}) - \frac{\partial}{\partial z}(\lambda\frac{\partial T}{\partial z}) = \frac{4h}{d_{in}}(T_p - T_f). \tag{2}$$

Here λ is the thermal conductivity of the fluid in W m^{-1} K^{-1}, ρ is the density of the fluid in Kg m^{-3}, c is the specific heat capacity of the fluid in J Kg^{-1} K^{-1} and T is the temperature, with subscripts f, p, i, o denoting fluid, pipe, inlet and outlet respectively. Figure 1 shows the geometry of the problem.
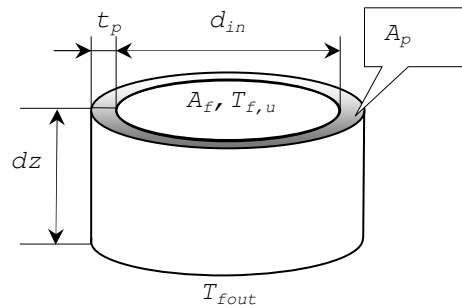

FIGURE 1. Geometry of the problem

The convection heat transfer coefficient h can be estimated as a function of the Nusselt number. Equation (2) can be used for both the tubes of a geothermal heat exchanger with care taken on the sign of u, which in one leg is positive and

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in the other is negative depending on the zero point of the chosen axis system. Applying an energy conservation equation for the pipe (per unit volume), we get:

$$\rho_p c_p \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}(\lambda_p \frac{\partial T}{\partial x}) - \frac{\partial}{\partial y}(\lambda_p \frac{\partial T}{\partial y}) - \frac{\partial}{\partial z}(\lambda_p \frac{\partial T}{\partial z}) = \frac{h}{t_p}(T_f - T_p).$$ (3)

where t_p is the thickness of the pipe. In addition, the heat equation representing the flow in the ground (per unit volume) is given by:

$$\rho_g c_g \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}(\lambda_g \frac{\partial T}{\partial x}) - \frac{\partial}{\partial y}(\lambda_g \frac{\partial T}{\partial y}) - \frac{\partial}{\partial z}(\lambda_g \frac{\partial T}{\partial z}) = 0,$$ (4)

where the subscript g denotes the ground.

Finally, the power flow in the tubes, which is constant, as constant is the fluid flow velocity, is defined through a specified difference between the entering and exiting fluid temperature. Note that at the bottom of the pipe where the "U"-connection is, the mean temperatures of the fluid of the two legs of the pipe are considered to be equal.

RESULTS AND CONCLUSIONS

First, the system of equations (2)–(4) is solved by the Finite Element Method using the FlexPDE software. To validate the results of the theoretical formulation a real case is then tested for various tube diameters in a 100 m borehole in Cyprus. Figure 2(a) shows a good agreement between the simulated and the experimental results for a 25 mm diameter. Then, the validated model is used to study how various factors, such as the U-tube diameter, the variation of the ground thermal conductivity and specific heat and the borehole filling material affect the temperature of the inlet and outlet fluid. For example, figure 2(b) demonstrates that the smaller the pipe diameter the hotter the fluid is during the exchanging process.
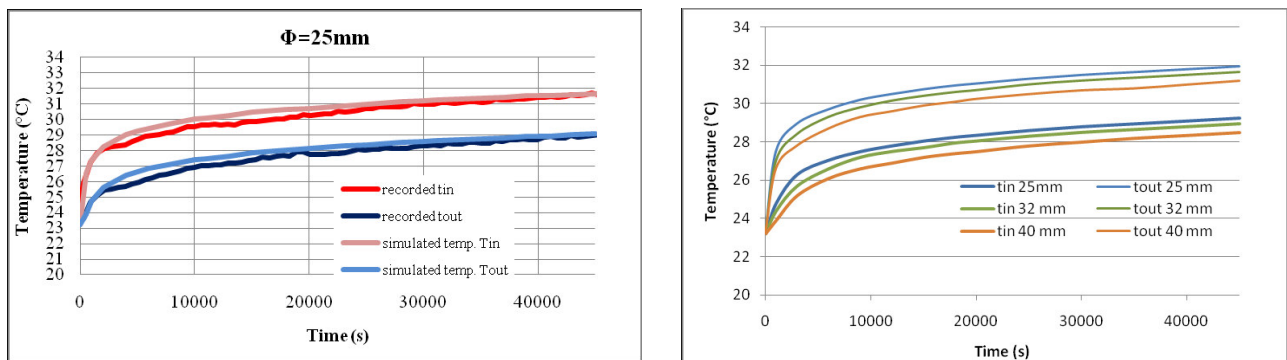

FIGURE 2. (a) Comparison of the simulated fluid temperature to the actual recorded temperatures for 25mm-tube, (b) Difference in input and output temperature in heat exchanger with tube diameters of 25 mm, 32mm and 40 mm, showing that the bigger diameters maintain lower temperatures for a given flow and power input.

Moreover, it is shown that the lower the soil specific heat the higher the increase of the tube temperature. Finally, it is concluded that the choice of the borehole filling is of great importance, showing specifically that bentonite is an insulator and better not be used unless required by regulations; sand and soil appear to be much better filling choices.

References

[1] Carslaw H. S. & Jaeger J. C.: Conduction of heat in solids. Claremore Press, Oxford, 1946.

[2] Mei V. C. & Emerson C. J.: New approach for analysis of ground-coil design for applied heat pump systems. *ASHRAE Transactions* **91**(2B):1216-1224., 1985.

[3] Deerman J. D. & Kavanaugh S. P.: Simulation of vertical U-tube ground coupled heat pump systems using the cylindrical heat source solution. *ASHRAE Transactions* **97**(1):287-295, 1991.

[4] Nam Y., Ookaa R. & Hwanga S.: Development of a numerical model to predict heat exchange rates for a ground-source heat pump system. *Energy and Buildings* **40**(12):2133-2140, 2008.

[5] Cui P., Yang H. & Fang Z.: Numerical analysis and experimental validation of heat transfer in ground heat exchangers in alternative operation modes, *Energy and Buildings* **40**(6): 1060-1066, 2008.

[6] Schiavi L.: 3D Simulation of the Thermal Response Test in a U-tube Borehole Heat Exchanger, Proc. COMSOL Conference, Milan, 2009

[7] Heinrich J. C. & Pepper D. W.: Intermediate finite element method: Fluid flow and heat transfer applications, Taylor & Francis, Philadelphia, PA, 1999.