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NUMERICAL ANALYSIS OF UNSTEADY HEAT TRANSFER IN U-TUBE GEOTHERMAL HEAT EXCHANGER

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Abstract: This paper presents a numerical model for unsteady heat transfer in geothermal borehole heat exchanger. Heat transfer in the fluid circulating in the pipe is considered as one-dimensional and the governing differential equation is discretized using control volume method. Heat transfer through the pipe wall, grout, and surrounding soil is regarded as three-dimensional and the governing equation is discretized using 3D CVFEM method. The final solution is obtained by simultaneously solving the coupled systems of equations. The numerical solution is verified through comparison with analytical solutions for the cases of simplified geometry and boundary conditions. Overall numerical model is validated through comparison with available experimental results. The abilities of proposed numerical model are demonstrated through analysis of unsteady heat transfer following the step change of inlet fluid temperature where temperature profile of heat transfer fluid along the pipe as well as heat fluxes on the borehole wall and short circuit heat flux are of interest. Finally, the influence of various parameters (velocity and fluid temperature at the inlet, thermal properties of pipe, grout, and soil, shank spacing and groundwater flow) are analysed and the results are systematically presented.
Keywords: geothermal heat pump, borehole heat exchanger, 3D CVFEM

1. INTRODUCTION

Ground source heat pumps are environmentally friendly and energy efficient alternative to conventional air-source heat pumps. The solution with a borehole heat exchanger (BHE) with a U-tube for heat rejection and absorption from the ground provides more efficient operation of the heat pump. The main reason for greater efficiency is the fact that the soil, in relation to the air, has a more favourable temperature for use as a heat source in winter or as a sink in summer. Typical soil temperature profiles, calculated using equation given by Kusuda [1], which illustrates this fact, are given in Figure 1.

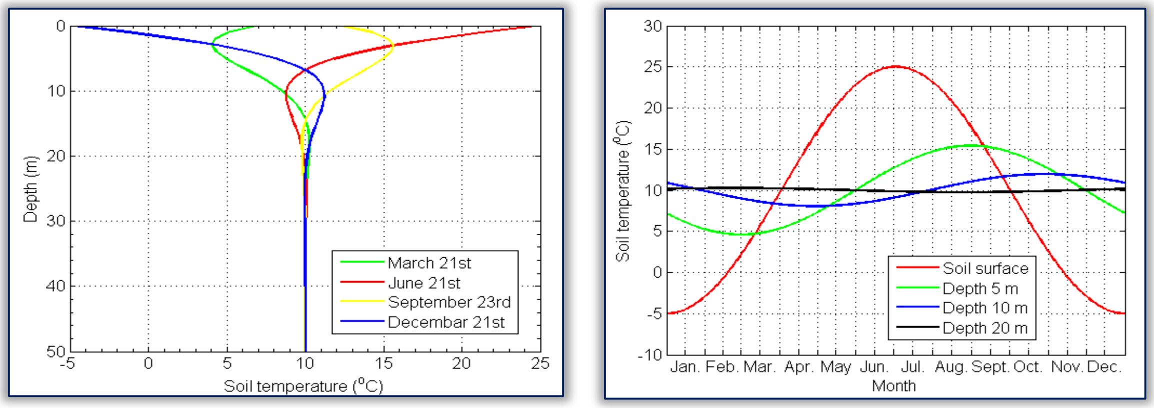

Figure 1. Soil temperature variation with depth during the year

A typical borehole with its horizontal and vertical cross sections is sketched in Figure 2. Heat transfer fluid exchanges heat with the ground by circulating in a U-bended pipe buried in a vertical borehole. U-pipe is usually made of HDPE and has a diameter ranging from 19 mm to 38 mm, while the borehole diameter is in the range from 76 mm to 127 mm. Borehole is backfilled with appropriate grouting material which purpose is to prevent groundwater contamination, and in the same time to improve heat transfer between the pipe and the surrounding soil.

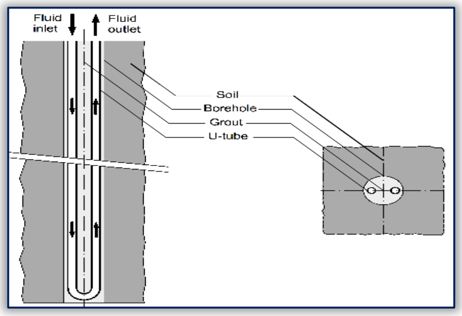

Figure 2. Vertical and horizontal cross section of BHE

Geothermal systems with U-tubes require special attention during the design phase because of unsteady heat exchange between the fluid circulating in the pipe and the surrounding soil. Otherwise, design mistakes can impair the long-term efficiency of the system. An exhaustive review of simulation models of BHE can be found in the book by Sarbu and Sebarchievici [2]. The general conclusion on pros and cons of analytical and numerical models is as follows:

- Analytical models are attractive because of computational efficiency that facilitates their incorporation into a design and simulation program. On the other hand, they are based on a number of simplifying assumptions, mainly regarding the geometry of BHE, that compromise the accuracy of the solution.
- Numerical models offer more general and accurate representation of unsteady, three-dimensional heat transfer process in GHE. They are able to take into account the geometric details of BHE, different thermal properties of involved materials (fluid, pipe, grout and soil), three-dimensionality of the heat transfer process, complex boundary conditions etc. All listed advantages are at the cost of computer time that hinders their integration into a design and simulation program.

The focus of our research interest is unsteady heat transfer in a borehole heat exchanger and analyse of various influencing parameters. Only a fully discretized three-dimensional numerical scheme offers the possibility of more comprehensive consideration of non-stationary nature of heat transfer.

2. MATHEMATICAL MODEL AND NUMERICAL SOLUTION

BHE consists of two subdomains: the first is the heat transfer fluid, while the other includes the pipe itself, grout and surrounding soil. Assuming that the heat transfer in the fluid can be considered as one-dimensional in the downstream direction of the flow (coordinate s), the corresponding energy equation is reduced to:

$$\rho_f c_f \frac{\partial T_f}{\partial t} + \rho_f c_f \frac{\partial}{\partial s}\left(\mathrm{v}_f T_f\right) = \frac{\partial}{\partial s}\left(k_f \frac{\partial}{\partial s} T_f\right) + \frac{4h}{d_{p,i}}\left(T_{wall} - T_f\right) \quad (1)$$

where ρ_f, c_f, k_f and v_f are density, specific heat, conductivity and flow velocity of the fluid, T_f and T_{wall}, are temperatures of the fluid and of the inner pipe wall, $d_{p,i}$ is the inner diameter of the pipe and h heat transfer coefficient.

Assuming three-dimensional heat transfer through the pipe wall, grout and soil and possibility of advective heat transfer due to the groundwater flow, the corresponding energy equation has the form:

$$\rho c \frac{\partial T}{\partial t} + \rho_w c_w u \frac{\partial T}{\partial x} + \rho_w c_w v \frac{\partial T}{\partial y} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) \quad (2)$$

where ρ, c, k and T without subscripts are density, specific heat, thermal conductivity and temperature of the pipe, grout or soil and ρ_w, c_w, u and v are density, specific heat and corresponding components of the two-dimensional groundwater flow field.

Equation (1) is discretized using CVM, while equation (2) is discretized using CVFEM. Domain of equation (2) is divided along the depth in a number of layers. Since the U-tube has two legs, this results in twice the number of CV for fluid, i.e. for the domain of equation (1). Due to its sweepability, domain of equation (2) is meshed by triangular prism and control volumes are constructed around each node of the mesh, in accordance with the requirements of CVFEM approach. The discretized equations (1) and (2) are solved iteratively and simultaneously: the solutions are coupled through the source term on the right side of equation (1) and the boundary condition on the pipe wall for equation (2), in a way that preserves the continuity of heat flux on the mutual interface.

A computer program that flows the above-mentioned procedure is written in Fortran 90 and results are post-processed and plotted in Matlab.

3. VERIFICATION AND VALIDATION

Verification of numerical solution is done through comparison with the available analytical solutions. First, the numerical solution for steady state heat transfer in the fluid circulating in the pipe is compared with well-known analytical solutions for the case of constant temperature and constant heat flux at the pipe wall. The solution for unsteady heat transfer in the fluid is verified by comparison with the analytical solution given by van Genuchten and Alves [3]. The solution for unsteady heat transfer in the soil surrounding the borehole is verified by comparison with the analytical solution by Carslaw and Jaeger [4] for an infinite cylindrical heat source. The solution for unsteady heat transfer in the soil surrounding the borehole, in the presence of groundwater flow is verified by comparison with the analytical solution developed by Diao [5] for an infinite moving line heat source. Numerical solution for steady state heat transfer in the borehole is verified in an indirect way, by comparing the calculated numerical thermal resistance of the borehole with values that are obtained using the model of Paul, Gu and O'Neal, cylindrical heat source and multipole model. The solution for steady state heat transfer in a coupled system consisting of heat transfer fluid, U-tube and grout is verified by comparison with the analytical solution given by Eskilson and Claesson [6]. Very good agreement of numerical and analytical solutions in all of those cases assures that the equations are solved in the right way.

Model validation is performed by comparing the numerical results with the results of measurements on installations at Oklahoma State University. The first installation [7] is of the laboratory scale, which permits independent measurements of thermal characteristics of grouting material and wet sand surrounding the borehole. Numerically calculated variation of water temperatures at the outlet of U-tube as well as the temperature variation of the sand at different positions are in very good agreement with measured values, both, in the case of continuous operation of the circulating pump and electric heater, and in the case of interruption of work for a period of two hours. The second installation [8] consists of three BHE of the average depth of 75 m. In this case, the numerical solution for the variation of water temperature at the outlet is in good agreement with measured values, both, in the short period of time during one on-off cycle of the heat pump, and for long term simulation of 18 months. Good agreement between numerical solution and experimental measurements assures that the physical process is modelled using the right equations.

4. RESULTS OF NUMERICAL SIMULATIONS

A very good agreement between the numerical solutions and the available analytical solutions and measurements on experimental installations indicates that the proposed numerical model can be successfully used for the analysis of transient heat transfer in geothermal exchangers with U-tubes.

Thermal behaviour of the borehole following the sudden change of the inlet fluid temperature is analysed using the proposed numerical model. By means of simulation, it is possible to follow a distinct unsteadiness of the process at the very beginning, right after the sudden change of inlet temperature. For example, it is possible to observe in the simulation that the change of temperature at the outlet does not occur immediately, but with a delay, which depends on the flow velocity.

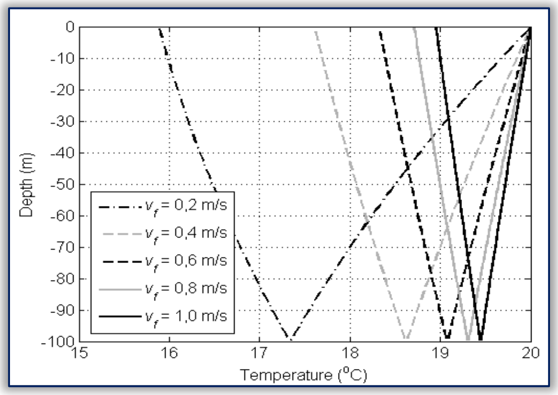

Figure 3. Fluid temperature profile along U-tube for different flow velocities

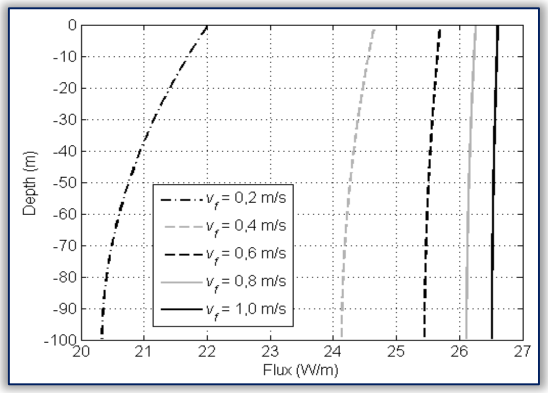

Figure 4. Borehole wall heat flux profile for different velocities

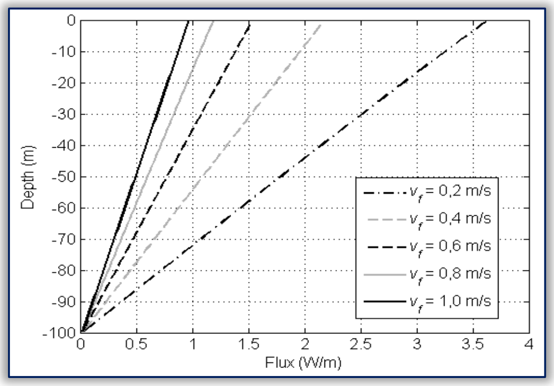

Figure 5. Short circuit heat flux profile for different velocities

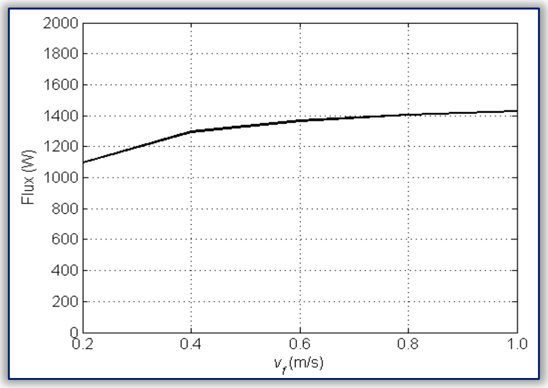

Figure 6. Borehole wall heat flux vs. fluid velocity

Results of simulation after 48 hours indicates that the fluid temperatures, the heat flux at the borehole wall, and the short circuit heat flux gradually approach the steady state values. The temperature profile along the U-tube is nonlinear at lower flow rates, and practically linear with higher (Figure 3). Flux at the borehole wall increases with the flow rate. At lower flow rates this flux decreases non-linearly with depth (Figure 4), while it is virtually uniform with depth at higher flow rates. Short circuit heat flux has a linear profile with depth at all fluid flow rates - it has the highest values at the surface and is equal to zero at the bottom of the borehole (Figure 5).

Analysis of the influence of different parameters on the heat exchange is performed using the proposed numerical model. For example, it is obtained that in order to increase the capacity of BHE it makes sense to increase the heat transfer fluid flow rate only up to a certain limit (Figure 6). In addition, it is observed that temperature difference of the fluid and the undisturbed ground significantly influences the capacity of BHE. In order to increase the capacity of BHE, it is reasonable to increase the thermal conductivity of the pipe or grout, or to increase the distance between the pipe legs. Simulations have also shown that groundwater flow has a desirable effect and that steady state conditions are reached earlier with higher groundwater velocities.

5. CONCLUSION

The paper describes, in brief, the extensive research, which included mathematical and numerical modelling of unsteady heat transfer in the geothermal heat exchangers. Numerical model includes the assumption that the heat transfer is one-dimensional in the fluid, and three-dimensional through the pipe wall, grout, and soil. Verification and validation of the model through comparison with available analytical and numerical solutions have shown that those assumptions are reasonable. The proposed numerical model is capable of capturing the details of unsteady three-dimensional nature of heat transfer in BHE. Some of the conclusions regarding the influence of different parameters on heat transfer process in BHE, which are obtained through numerical simulations are highlighted in the article.

Note

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References

[1] Kusuda, T., Achenbach, P.R. (1965). Earth Temperature and Thermal Diffusivity at Selected Stations in the United States. National Bureau od Standards, Washington DC.
[2] Sarbu, I., Sebarchievici, C., Ground-Source Heat Pumps: Fundamentals, Experiments and Applications. Academic Press, Cambridge, 2015.
[3] van Genuchten, M.Th, Alves, W.J. (1982). Analytical solutions of the one-dimensional convective-dispersive solute transport equation, Technical Bulletin No. 1661, United States Department of Agriculture, Washington DC.
[4] Carslaw, H.S., Jaeger, J.C. (1947). Conduction of Heat in Solids. Clarendon Press, Oxford.
[5] Diao, N., Li, Q., Fang, Z. (2004). Heat transfer in ground heat exchangers with groundwater advection. International Journal of Thermal Science, vol. 43, no. 12, pp. 1203-1211.
[6] Eskilson, P., Claesson, J. (1988). Simulation model for thermally interacting heat extraction boreholes. Numerical Heat Transfer, vol. 13, no. 2, pp. 149-165.
[7] Beier, R.A. (2014). Reference data sets for vertical borehole ground heat exchanger models and thermal response test analysis. Geothermics, vol. 40, no. 1, pp. 79-85.
[8] Hern, S.A. (2004). Design of an experimental facility for hybrid ground source heat pump systems. M.Sc. thesis. Oklahoma State University, Stillwater.

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