Numerical Study on Ground Heat Exchange System

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ABSTRACT

Ground-coupled heat system has attracting attention as a promising renewable energy technology due to its improving energy efficiency and eco-friendly mechanism for space cooling and heating. Contact between heat exchanger pipe and surrounding porous soil is a passage for thermal interaction in geothermal exchange system. Forced convection of fluid flow inside the pipe causes mechanical deformation and hydraulic change in surrounding material. Conversely, ground water flow in porous material can change heat exchange rate of the system. This thermal interaction between heat exchange pipe and the surrounding soils governs short-long performance of underground heat exchanger. However, both complexity of turbulent flow coupling thermal-hydraulic phenomena and very long aspect ratio of the pipe make it difficult in direct modeling of fluid flow inside the pipe.

In this study, one-dimensional pipe-flow element is proposed to model convective heat transfer between fluid flow inside the pipe and surrounding material, and also advective and conductive heat movement of the fluid inside the pipe. Proposed pipe-flow element is connected to pre-developed FEM code for THM phenomena for porous continuum media. Developed numerical code is applied to Thermal Response Test for estimating equivalent thermal conductivity of surround material, Thermal Performance Test for evaluating heat transfer rate to the surrounding ground. Also effect of ground water flow to thermal performance of heat exchanging system is investigated. Numerical results show that the developed code can successfully model this very complex behavior of coupled THM phenomena.

1. INTRODUCTION

Ground-source heat pump systems have become increasingly popular for heating and cooling applications because of their higher energy efficiency compared with conventional systems. In closed-loop heat pump systems, heat rejection/extraction is accomplished by circulating a heat exchange fluid through the pipe buried in boreholes.
Three-dimensional numerical analysis of fluid flow phenomena in ground heat exchanger system has a severe difficulty in numerical modeling of geometry due to very large aspect ratio around the pipe compared to surrounding media. Therefore, many numerical simulations ignored thermal transfer in the deep direction, and conducted simplified two-dimensional numerical analyses (Yavuzturk et al., 1999). However, three-dimensional numerical analysis has advantages considering heat transfer in deep direction around the borehole, multi-layered ground, geothermal gradient, thermal-fluid flow inside the pipe, thermal short circuit between pipes in up and down directions, appropriate upper and lower areas of analysis, etc (Diersch et al. 2011). So far, direct thermo-hydro numerical analysis for fluid flow inside the pipe is very difficult, since theoretical and numerical approach for turbulent flow is still in progress. Furthermore, numerical simulation with previous theories requires excessive computation time to obtain reliable and stable results.

In this study, instead of performing direct numerical analysis of the fluid flow inside the pipe, the pipe is considered as a one-dimensional element using convective thermal equation from experimental results to emulate heat exchange between the pipe and surrounding soils. Developed pipe element is combined with FEM numerical simulator for THM (Thermo-Hydro-Mechanical) phenomenon. Numerical analyses were performed for TRT (Thermal Response Test) to estimate the thermal conductivity of the ground, TPT (Thermal Performance Test) to evaluate thermal performance of ground heat exchanger system, and explore effect of groundwater flow on thermal performance.

2. Finite element formulations

2.1 Numerical formation of pipe element

A one-dimensional finite element was developed to simulate thermo-hydro behavior of the heat exchanger pipe. Pipe element models a change in temperature in the longitudinal direction, but cross-sectional temperature distribution of the pipe is assumed to be the same (Cengel & Ghajar, 2012)

\[
q_i = h(T_i - T_f)
\]

Fig. 1 a) Heat exchanger between heat pipe and surrounding soil, b) Temperature changes of the fluid inside the pipe by convection under a constant influx by external heat
One-dimensional assumption of the pipe makes sense due to high slenderness ratio of the heat pipe compared to surrounding media and ignorable temperature change inside the pipe in the radial direction. Sequentially connecting one-dimensional pipe elements makes possible to replicate the arrangement of the underground heat pipes, and closed-loop of the pipe elements can simulate fluid circulation of the heat pipe to model fluid temperature change inside the pipe and its effect on the surrounding media. Developed pipe element has two degrees of freedom; fluid temperature inside the pipe \(T_f\), temperature of the surrounding soil \(T_s\). Material properties of the pipe elements are cross-sectional area of the pipe, fluid velocity, density, specific heat, and thermal insulation.

Law of energy conservation includes conductivity fluid flow inside the pipe \(q_s\), deformation and fluid transfer (advection) by the energy flux \(J_s\), the convective flow of the fluid in the pipe \(q_i\), and an internal source \(f_s\), for example, TRT test.

\[
\frac{d}{dt} \left[ \left( -\frac{\partial T}{\partial x} + \frac{\partial J_s}{\partial x} \right) \cdot A + g_s \cdot P \cdot dx + f_s \cdot Adx \right] = \rho \cdot c_p \cdot dT \cdot dx \cdot A \tag{1}
\]

\[
\rho \cdot c_p \cdot A \cdot \frac{dT}{dt} = -\frac{\partial J_s}{\partial x} \cdot A + g_s \cdot P + f_s \cdot A
\]

where, \(J_s = \rho \cdot E \cdot \dot{u}_p, \frac{\partial J_s}{\partial x} = \rho \cdot c_p \cdot \dot{u}_f \frac{\partial T}{\partial x}\)

\(g_s = h \cdot (T_s - T)\)

This can be summarized as follows.

\[
\rho \cdot c_p \cdot A \frac{dT}{dt} + \rho \cdot c_p \cdot A \cdot \dot{u}_f \frac{dT}{dt} - h \cdot P \cdot (T_s - T) - f_s \cdot A = 0 \tag{2}
\]

Galerkin formulation is applied to energy conservation equation of the pipe element.

\[
\int_s \left[ w^p \cdot \rho \cdot c_p \cdot A \frac{dT}{dt} ds + \int_s \left[ w^p \cdot \rho \cdot c_p \cdot A \cdot \dot{u}_f \frac{dT}{ds} ds - \int_s w^p \cdot h \cdot P \cdot (T_s - T) ds - \int_s w^p \cdot f_s \cdot A ds \right] = 0 \tag{3}
\]

After time integration of Galerkin formulation for the given time interval, and a finite element code is developed for that equation.

2.2 Modification of energy balance equation for porous media

Energy balance for the porous media was developed, and it is modified to consider heat convection due to installed pipe element. Energy balance equation can be expressed using enthalpy balance, but it is easy to express using internal energy
(Olivella etc., 1996; Lewis etc., 1998). Solid, liquid, and gas phase of the porous material are considered to derive the equation using generalized balance equation.

\[
\frac{\partial}{\partial t}\left[(1-\phi)\rho_s E_s + \phi S_i \rho_i E_i + \phi(1-S_i)\rho_g E_g\right] + \nabla \cdot i - c
\]

\[
+ \nabla \cdot \left[(1-\phi)\rho_s E_s \hat{u} + \phi S_i \rho_i E_i \hat{u} + \left(\rho_s^w g + i_s^w\right) E_s^w + \left(\rho_i^w q + i_i^w\right) E_i^w + \left(\rho_g^w q + i_g^w\right) E_g^w\right] = -q_s
\]

where, \( E_s \) is specific internal energy of solid phase of the porous media, and energy transfer due to heat conduction is evaluated using Fourier’s law \((i_{c} = -\lambda \nabla T)\).

3. Numerical results

3.1 Thermal performance tests

Thermal performance test (TPT) performs in order to evaluate thermal performance of heat exchanger systems (Miyara, 2010). After maintaining a constant inlet temperature of the pipe, outlet temperature of the pipe is monitored to calculate total amount of heat transfer into the ground. It is divided with the depth of the borehole to calculate heat exchange rate (or heat transfer rate).

\[
q = \frac{\rho_f C_f A_f u_f (T_{in} - T_{out})}{L}
\]

Initial heat exchange rate shows very high value due to temperature difference between pipe fluid and surrounding soil. With time, temperature increase of surrounding soil due to thermal convection from circulating fluid lowers heat exchange rate, and then converges to a constant value.
Fig. 2 Temperature evolution around the heat pipe in TPT simulation \( (\lambda = 1.0 \frac{W}{m \cdot K}) \), a)

Analysis domain, b) Temperature distribution after 30 hours in U-type geothermal exchanger, c) b) Temperature distribution after 30 hours in W-type geothermal exchanger (Red=30°C, Blue=10°C)

W-type heat exchanger pipe expects higher heat exchange rate compared with U-type heat exchanger pipe, because of longer contact time with the pipe and surrounding soil. W-type heat exchanger shows 80% higher efficiency initially, and 40% higher efficiency in long term, than that of U-type heat exchanger.
Fig. 3 Evolution of fluid temperature in the pipe and heat exchange rate with time in TPT simulation ($\lambda = 1.0 \frac{W}{m \cdot K}$, $u_f = 1.0 m/s$), a) Change of fluid temperature inside the pipe in U-type exchanger, b) Temperature difference between in-let and out-let fluid in U-type exchanger, c) Evolution of heat exchange rate in U-type and W-type exchangers, d) Ratio of heat exchange rate of W-type to U-type exchanger

3.2 Effect of groundwater flow on thermal performance

Groundwater flow in the vicinity of the heat exchanger involves thermal conduction and advection. Increase in groundwater velocity decrease borehole resistance, so it enhances performance of heat exchanger (Wagner, 2013). The amount of energy transferred by conduction and advection can compare with Péclet number (Domenico and Palciauskas, 1973), and higher groundwater velocity increases Pe and heat exchange rate (Fujii et al. 2005). Barcenilla et al further. (2005) conducted the effect of groundwater flow on the correction of the equivalent thermal conductivity in vertical ground heat exchanger.
In the long-term performance evaluation of geothermal systems, ground water flow (Pe = 0.04) decrease thermal gradient and improve the thermal performance continuously. In the absence of ground water flow, the flow rate inside the heat pipe does not affect the performance significantly. However, flow velocity under groundwater flow almost linearly increases the performance. Flow rate inside pipe requires pump power consumption, so it is necessary to determine the proper flow rate (Jun, 2009).
Fig. 5 Effect of fluid velocity inside the pipe and groundwater velocity (Pe=0.0, 0.04) on the performance of ground heat exchange system, a) Evolution of heat exchange rate with time @ pipe fluid velocity=1m/s, b) Change of heat exchange rate due to pipe flow and groundwater flow velocities

4. CONCLUSIONS

One-dimensional pipe-flow element developed to model convective heat transfer between fluid flow inside the pipe and surrounding material. Suggested pipe element is connected to pre-developed FEM code for THM phenomena for porous continuum media.

Numerical simulation on thermal response test showed that W-type heat exchanger shows almost 40% higher efficiency in long term behavior due to longer
contact time with the pipe and surrounding soil during circulating of fluid inside the pipe. Ground water flow in geothermal exchange system improves the thermal performance, and flow velocity under groundwater flow almost linearly increases the performance.

REFERENCES


