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Thermal performance of a double U-tube heat exchanger pile in the presence of coupled thermo-hydro flow

Performances thermiques d'une pile d'échangeurs de chaleur à double tube en U en présence d'un flux thermo-hydraulique couple

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ABSTRACT: Among the available ground source heat pump technologies, geothermal piles have the advantages of less space and initial cost requirements. Thermal design of geothermal piles is mainly based on conductive heat transfer models. Such an approach completely ignores the interaction between temperature and pore fluid flow within the ground. This research investigates time-dependent performance of a geothermal pile considering coupled thermal and hydraulic flow in the ground. A 20-m-long, double-tube geothermal pile is modelled using commercially available finite element software. Pile-soil heat transfer analyses, which account for thermally induced natural convection and groundwater flow along with conduction, are performed. For a constant inlet fluid temperature, power output for different values of groundwater flow velocity is compared with that obtained using a conduction model. Results show, for a GWF velocity of 1×10^{-5} ms^{-1}, 62% increase in power output in comparison to conduction model alone. Analysis results further demonstrate that the consideration of coupled thermo-hydro flow can positively influence the long-term performance of ground-anchored shallow geothermal energy harvesting systems.

KEYWORDS: Heat transfer; coupled flow; geothermal energy; groundwater flow; thermal performance

1 INTRODUCTION

Rapid industrialization and exponential growth in the living standard of any civilization steadily increases the energy demand. Keeping up with the enhanced energy demand while limiting the carbon footprint poses a significant challenge to the science and engineering community in the present global context. There is an apparent mismatch between the need, availability, and utilization of different sustainable energy resources. Adequate harvesting and proper utilization of different renewable energy forms (e.g., solar, geothermal, wind, and tidal energy resources) can minimize such a gap. Heating and cooling of buildings contribute towards a major portion of energy demand in residential and commercial facilities (Lund and Boyd 2016). The ground source heat pump (GSHPs) technology is proven to be efficient for partially meeting such building energy demands and, therefore, such a technology can help in reducing the use of traditional energy sources.

However, the initial cost of installing the traditional GSHP systems (e.g., geothermal boreholes and geothermal wells) is high because a dedicated borehole needs to be drilled solely for this purpose. Consequently, there is a rather long payback period for the stakeholder to start getting benefits from this technology (Brandl 2006, Cecinato and Loveridge 2015). Reduction in the installation cost and increase in the system's efficiency to minimize payback time can be viable solutions to this problem. Geothermal piles, for which heat carrying fluid circulation tubes are embedded in piles used as foundation element, eliminate the requirement of drilling boreholes that are not otherwise utilized in building construction. Furthermore, depending on the diameter of the geothermal pile, more than one circulation tube may as well be used for enhancing pile thermal performance. (Huttrer 1997, Brandl 1998). While geothermal boreholes have been in use for almost seven decades, energy harvesting through geothermal piles is a relatively new and less explored (especially in terms of long term energy harvesting performance) concept (Spitler 2005, Amis and Loveridge 2014).

Majority of the currently used methods for energy performance design of geothermal piles were initially developed for geothermal boreholes. Several analytical models that quantify pile-soil heat exchange are influenced by the infinite line source (ILS) model that considers only conduction. The finite line source model, finite solid and hollow cylindrical-source model, spiral line model and, infinite hollow cylindrical-source models are few examples of such models (Ingersoll et al. 1954, Carslaw and Jaeger 1959, Eskilson 1987, Zeng et al. 2002, Li and Lai 2012, Ghasemi-Fare and Basu 2013, Ozudogru et al. 2015). Nevertheless, conduction alone may not define complete heat transfer process in a two-phase porous medium like soil that consists of soil (solid) particles and fluid-filled pore space. In the recent past, researchers adopted analytical, numerical, and experimental approaches to explore the influence of natural convection on pile-soil heat exchange (Diao et al. 2004, Banks 2012). Kramer et al. (2015) and Ghasemi-Fare and Basu (2018) reported large-scale experiments on a laboratory scale heat exchanger pile. These studies concluded that the thermally induced natural convection has a non-negligible effect on pile-soil heat exchange in coarse-grained soil. In comparison to analyses considering purely conductive heat transport in saturated ground, numerical heat transfer analyses considering both conduction and natural convection demonstrate a 12% increase in power output and a 7% increase in the temperature difference between inlet and outlet fluid temperature (Ghasemi-Fare and Basu 2015, Ghasemi-Fare and Basu 2018, Ghasemi-Fare and Basu 2019). Field and numerical thermal response tests (TRTs) on water-filled borehole heat exchangers (BHEs) demonstrated up to 50% reduction in borehole thermal resistance when compared to the case with grout-filled boreholes in which natural convection is missing (Gehlin et al. 2003, Gustafsson and Westerlund 2010, Gustafsson et al. 2010, Gustafsson and Westerlund 2011, Choi and Ooka 2016, Spitler et al. 2016, Johnsson and Adl-Zarrabi 2019). Note that none of the above studies considered groundwater flow (GWF). However, literature contains numerical studies that explored sole influence of GWF on thermal efficiency of geothermal heat exchangers (Shi et al. 2010, Molina-Giraldo et al. 2011, Raymond et al. 2011, Shang et al. 2011, Vasilyev et al. 2014, Le Lous et al. 2015, Yang et al. 2015, Bidarmaghz et al. 2016, Angelotti et al. 2018, Li et al. 2018, Stylianou et al. 2019). While much of such research focuses on quantifying the effect of GWF on temperature distribution in soil, only a few quantifies the impact of GWF on thermal power output from a ground-coupled heat exchanger. Most of the published research separately consider natural convection (i.e., temperature-induced buoyant flow of pore fluid) and forced convection (i.e., advection through GWF) in the ground. For a specific range of hydraulic parameters, the individual effect of these heat transport mechanisms (i.e., natural and forced convection) on pile-soil heat transfer may not be significant. Nevertheless, their combined action may significantly contribute to heat transport in the ground near a geothermal heat exchanger. Research presented in this paper fills this knowledge gap through thermal performance analysis of a geothermal pile under consideration of different modes of heat transport in the ground.

2 PROBLEM FORMULATION

Three-dimensional finite element simulations are performed for a geothermal pile with two U-shaped circulation tubes to study pile-soil heat exchange. The finite element (FE) model considers heat transport through three major components of the pile-soil heat exchange system – circulation fluid, concrete pile, and saturated ground.

3 MODEL AND BOUNDARY CONDITIONS

A 40×40×30 m^3 soil domain with a centrally placed 650-mm-diameter and 20-m-long geothermal pile is modelled in COMSOL Multiphysics® (Comsol 2008). Concrete pile and PVC (polyvinyl chloride) heat circulation pipes are modelled as solid domains with only conductive heat transport, whereas soil is modelled as a porous domain in which coupled heat transfer (i.e., conduction, natural convection, and advection through GWF) is considered. A constant-temperature (equal to initial ground temperature) boundary condition is enforced at the bottom and side boundaries. The ground surface is modelled as a convective boundary. Groundwater flow, with different values of constant average velocity, is considered along the x-direction (Figure 1).

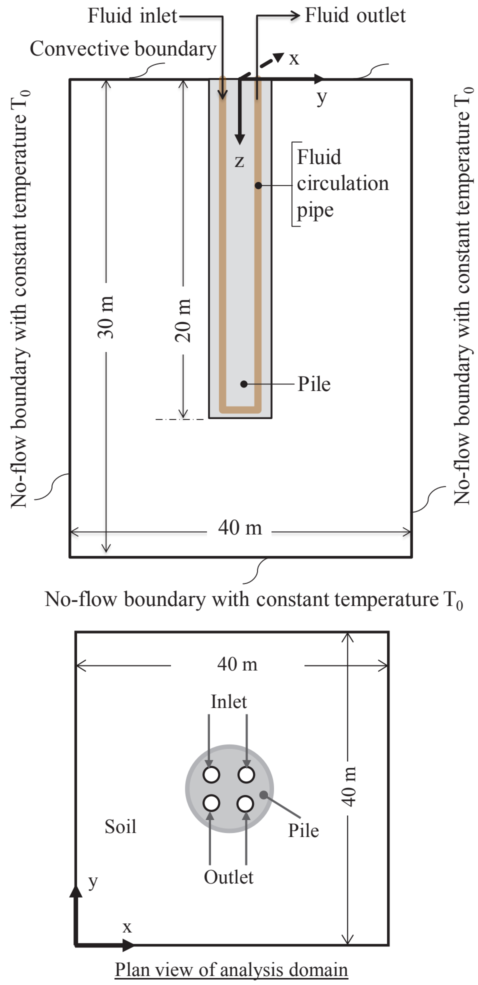
3.1 *Governing physics and FE modelling*

Coupled heat and pore fluid flow is modelled following the laws of mass, momentum, and energy conservation. Considering the incompressible heat carrier fluid (within circulation tubes) with a constant average circulation velocity u_{cf}(ms^{-1}), the momentum and mass balance equations for the circulation fluid are expressed as

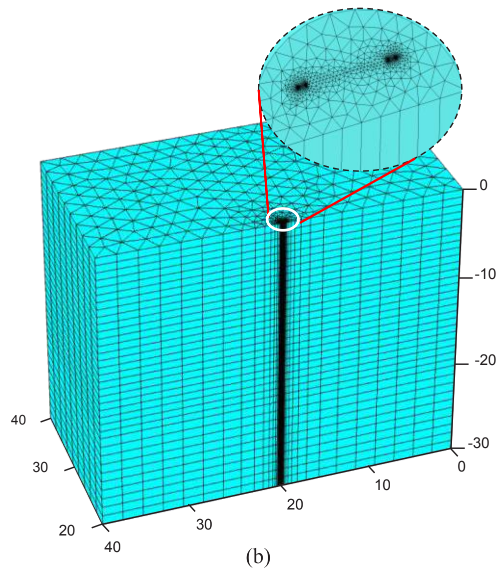
$$\rho_{cf}\frac{\partial u_{cf}}{\partial t} = -\nabla P - f_D\frac{\rho}{2d_h}u_{cf}\left|u_{cf}\right| \tag{1}$$

$$\nabla . u_{cf} = 0 \tag{2}$$

where ρ_{cf} (kgm^{-3}) is density of circulation fluid, t(s) is time, f_D is Darcy friction factor, P (Nm^{-2}) is pressure field, and d_h (m) is the mean hydraulic diameter of fluid circulating tube.



(a)



(b)

Figure 1. Analysis domain with a geothermal pile (a) problem geometry and boundary conditions, (b) FE mesh

The energy balance inside the circulation tubes can be mathematically expressed as

$$\rho_{cf} A_t C_{pcf}\left(\frac{\partial T_2}{\partial t} + u_{cf}.\nabla T_2\right) = A_t k_{cf} \nabla^2 T_2 + f_D \frac{\rho A_t}{2 d_h} |u_{cf}|^3 + Q_{wall} \tag{3}$$

where A_t (m^2) is the available cross-sectional area of fluid circulation pipe, T_2 is fluid temperature, C_{pcf} ($JkgK^{-1}$) and k_{cf} ($Wm^{-1}K^{-1}$) are, respectively, specific heat capacity and thermal conductivity of the heat carrier fluid. Q_{wall} is the amount of radial heat transfer to concrete.

$$Q_{wall} = (hZ)_{eff}(T_2 - T_c) \tag{4}$$

where T_c is concrete temperature and $(hZ)_{eff}$ is the coefficient of convective heat transfer, which depends on film resistance of circulating fluid and shape and size of the heat circulation tubes. The concrete pile temperature is computed using the equation of conductive heat transport in solid.

$$(\rho C_P)_c \frac{\partial T_c}{\partial t} = k_c \nabla^2 T_c \tag{5}$$

where ρ_c is concrete density, C_{Pc} ($JkgK^{-1}$) and k_c ($Wm^{-1}K^{-1}$) are heat capacity and thermal conductivity of concrete, respectively.

Heat transport in the soil domain is represented as Eq. 6. The second term in Eq. 6 signifies the convective component of heat transport in soil. The flow of pore fluid is modelled using the Brinkman equation (Eq. 7) and mass balance equation (Eq. 8) that consider temperature-dependent change in the mass density ρ_f of the pore fluid.

$$\left(\rho C_\rho\right)_{eff} \frac{\partial T}{\partial t} + \rho_f C_{\rho_f} \vec{v} \cdot \hat{\nabla} T - k_{eff} \hat{\nabla}^2 T = 0 \tag{6}$$

$$\frac{\rho_0}{n}\left[\frac{\partial \vec{v}}{\partial t} + (\vec{v}.\hat{\nabla})\frac{\vec{v}}{n}\right] = -\hat{\nabla}P + \hat{\nabla}\left[\frac{\mu}{n}\left\{\hat{\nabla}\vec{v} + (\hat{\nabla}\vec{v})^T - \frac{2}{3}(\widehat{\nabla.\vec{v}})I\right\}\right] - \frac{\mu}{K}\vec{v} - \frac{C_F \rho_0 \epsilon}{K^{\frac{1}{2}}}|\vec{v}|\vec{v} + F_B \tag{7}$$

$$\rho_f \hat{\nabla} \vec{v} = 0 \tag{8}$$

where ρ (kgm^{-3}) is mass density, C_ρ ($JkgK^{-1}$) is specific heat capacity, k ($Wm^{-1}K^{-1}$) is thermal conductivity, T (K) is temperature field in soil respectively, and $\vec{v}$(ms^{-1}) is velocity vector and subscripts s and f are for soil and pore fluid, respectively, μ (Pas) is the dynamic viscosity of water, K (m^2) is intrinsic permeability of porous media, C_F is Forchheimer coefficient and F_B is the body force. Following Boussinesq's approximation, F_B is affected by temperature variations. Numerical solutions for temperature and pore fluid velocity fields inside soil domain are obtained by coupling the momentum balance and energy conservation equations. Table 1 lists the input parameters and their values used in the finite element analyses (FEAs) presented in this paper.

Table 1. Input parameters for FEAs of double U-tube geothermal pile

Parameters	Value	Unit
Global parameters		
Initial ground temperature	20	°C
Test duration	30	days
Constant inlet temperature	41	°C
Ambient air temperature	25	°C
Coefficient of convective heat transfer	1	$Wm^{-2}K^{-1}$
Heat carrying fluid		
Flow rate	0.25	kgs^{-1}
Dynamic viscosity	2.2	mPa s
Thermal conductivity	0.41	$W\,m^{-1}\,K^{-1}$
Specific heat capacity	3455	$J\,kg^{-1}\,K^{-1}$
Density	1060	$kg\,m^{-3}$
Circulation pipes		
Thermal conductivity	0.390	$W\,m^{-1}\,K^{-1}$
Specific heat capacity	1100	$J\,kg^{-1}\,K^{-1}$
Effective density	234.1	$kg\,m^{-3}$
Pipe inner diameter	40	mm
Pipe wall thickness	3	mm
Shank spacing	300	mm
Concrete pile		
Thermal conductivity	1.5	$W\,m^{-1}\,K^{-1}$
Specific heat capacity	1000	$J\,kg^{-1}\,K^{-1}$
Density	2500	$kg\,m^{-3}$
Diameter	65	cm
Length	20	m
Tube distance	30	cm
Ground		
Thermal conductivity	3.2	$W\,m^{-1}\,K^{-1}$
Specific heat capacity	800	$J\,kg^{-1}\,k^{-1}$
Bulk density	1907	$kg\,m^{-3}$
Porosity	0.41	m
Permeability	1×10^{-9}	m^2

Two different types of mesh are used to discretize the model. Heat carrier fluid is modelled as a one-dimensional line element. A structured mesh is used for the PVC circulation tube, concrete pile, and the soil surrounding it. Structured mesh is selected to minimize the computational time without affecting the accuracy of the result. Figure 1(b) shows the FE mesh for half of the analysis domain. The convergence and stability of the model were checked for different element sizes and time intervals. Optimal mesh size and time step are chosen based on results obtained from several trial FE simulations.

4 RESULTS AND DISCUSSION

Circulation fluid is injected (at a constant temperature = 41 °C) through both the inlet pipes. The fluid flow domain inside the soil is switched off for simulation of solely conduction behaviour. The soil permeability value is kept constant for simulations considering GWF and temperature induced fluid flow. The fluid temperature difference ΔT [= $(T_{in}-T_{avg})$; T_{avg} is an average of temperature at the two outlet points] between the inlet and outlet points at the end of 30 days is 0.97 °C when only conduction is considered as heat transport medium in the soil, whereas ΔT rises to 1.13 °C when natural convection is considered along with conduction. This temperature difference is 1.17 °C, 1.43 °C and 1.59 °C, respectively, for GWF flow velocity equal to 1×10^{-6} ms^{-1}, 5×10^{-6} ms^{-1}, and 1×10^{-5} ms^{-1}. For the analysis cases of coupled thermo-hydro flow in saturated ground, T_{avg} reaches a constant value within a short duration after the thermal operation starts (Fig. 2). However, for the analysis case considering solely conduction in the ground, the average T_{avg} keeps on increasing with the duration of pile thermal operation. Figure 3 shows power output (defined as total amount of heat rejection divided by the pile length) obtained for different analysis cases. At the end of one month of thermal operation, a steady increase in power output is noted, in comparison to purely conductive heat transport, when coupled physics is considered;

power out increases by 20%, 46%, and 62.8% for v = 1×10^{-6} ms^{-1}, 5×10^{-6} ms^{-1}, and 1×10^{-5} ms^{-1}, respectively. Unlike the case of pure conduction, for which the power output steadily decreases with thermal operation time, power output reaches a stable value in case of convection in soil. Such performance offers the promise of sustainable energy harvesting through geothermal piles. However, the consideration of natural convection does not make a noticeable difference in pile thermal performance for GWF velocity $v \geq 5\times10^{-6}$ m/s. The power output ratio plotted in Figure 4 represents the ratio of power output considering the coupled physics to the power output for pure conduction. While consideration of natural and forced convection in saturated ground is important in thermal performance assessment of geothermal piles, the consideration of natural convection plays an important role only for small GWF velocity $v \leq 5\times10^{-5}$ ms^{-1} (Fig. 4).

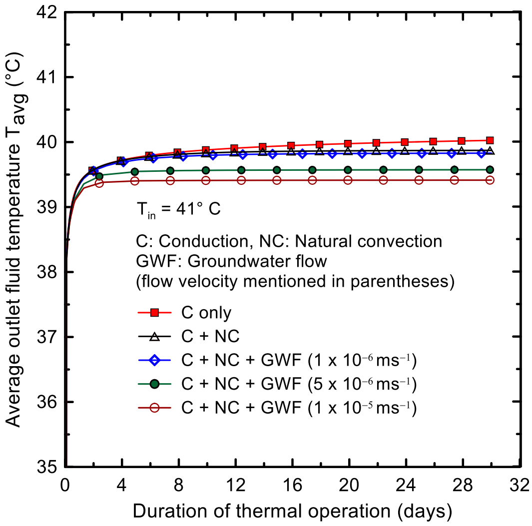


Figure 2. Average fluid outlet temperature for different combinations for heat transfer modes in saturated ground

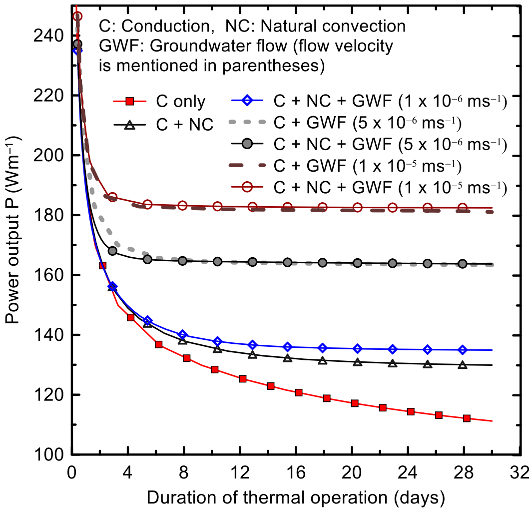


Figure 3. Variation of power output with the duration of thermal operation

Considering different physics of heat transfer inside saturated soil, Figure 5 shows the total amount of heat injection into ground with time. At the end of 30 days of thermal operation, around 8% more (when compared to purely conductive heat transport) heat is injected into soil mass in presence of natural convection. This increase is about 44% in the presence of GWF with a velocity equal to 1×10^{-5} ms^{-1}. Heat rejection performance of the pile improves in the presence of coupled thermo-hydro flow in saturated ground. Therefore, convective heat transport facilitates enhanced thermal performance of a geothermal pile.

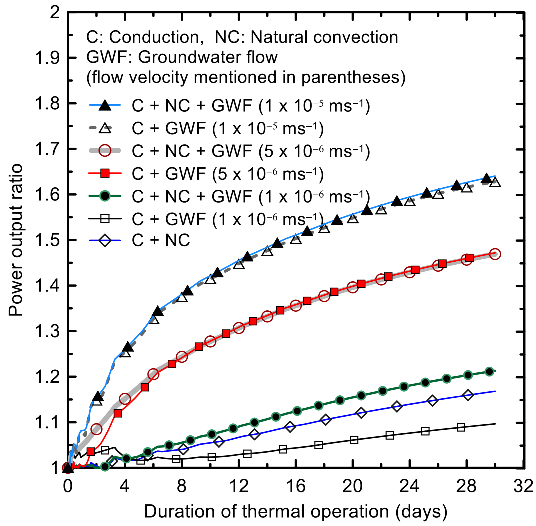


Figure 4. Power output ratio with the duration of thermal operation

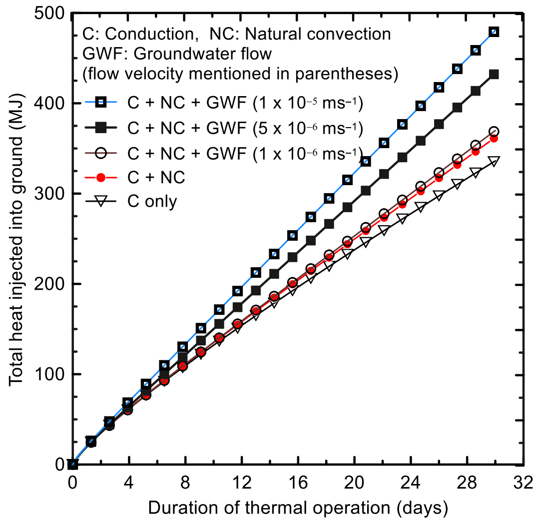
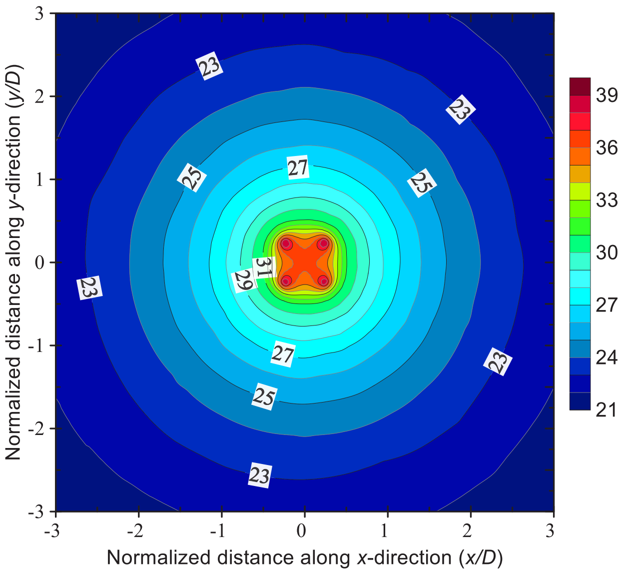
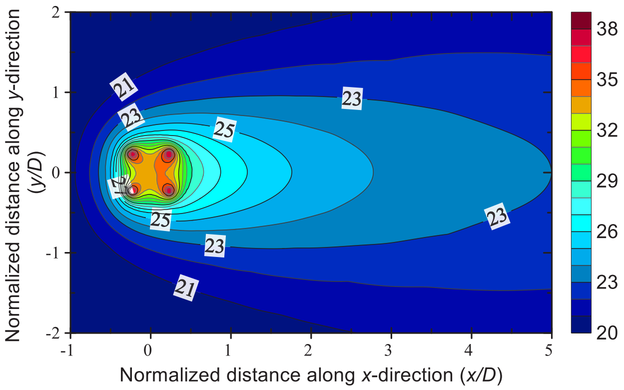


Figure 5. Total heat injected into ground with duration of thermal operation for different groundwater velocity

Figure 6 shows isotherms in the ground at the plan passing through centre of geothermal pile for conduction alone and with a GWF velocity of 5×10^{-6} ms^{-1}. Temperature is evenly distributed around the geothermal pile in case of conduction alone, and the influence zone is $4D$ from the centre of the geothermal pile. However, in the presence of GWF, temperature is unevenly distributed, and the zone of influence is more ($\approx 6D$) in the direction of GWF, while it is just $2D$ in the direction normal to the GWF. This can help in deciding the arrangement of geothermal piles if more than one geothermal pile is working as part of a group.



(a)



(b)

Figure 6. Temperature contours near geothermal pile zone (a) conduction only (b) Coupled condition with GWF velocity 5×10^{-6} ms^{-1}

5 CONCLUSIONS

The potential effect of coupled thermo-hydro flow on thermal efficiency of geothermal pile is investigated through advanced pile-soil heat exchange analyses. Power output of a double U-tube geothermal pile considering only conduction in soil and that considering natural convection and groundwater flow are examined. The temperature difference ΔT increases with an increase in GWF velocity. A considerable increase (= 62.8%) in power output (at the end of 30 days) is observed, when compared to the conductive mode of heat transfer only, for GWF velocity of 1×10^{-5} ms^{-1}. At low GWF velocity ($\approx 1\times10^{-6}$ ms^{-1}), power output with and without consideration of natural convection differ by around 10%. The effect of natural convection diminishes at GWF velocity $v > 5\times10^{-6}$ ms^{-1}. For purely conductive heat transfer in the ground, there is a steady reduction in thermal power output with time of pile thermal operation. Nevertheless, in the presence of coupled thermo-hydro flow, especially in the case of large GWF velocity, power output quickly attains a steady-state. Therefore, adequate consideration of coupled thermo-hydro flow is important for long term performance assessment of geothermal piles in saturated ground.

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