Numerical modeling and analysis of the effect of surface groundwater flow and natural convection on the heat exchange of energy pile

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ABSTRACT

The use of renewable energy, particularly shallow geothermal energy, for heating and cooling various spaces during both hot and cold seasons has received considerable attention. Therefore, investigating the natural factors affecting the efficiency of this system, especially the groundwater flow, is of particular importance. The presence of groundwater flow significantly increases the efficiency of shallow geothermal systems. It has been found that the existence of groundwater flow significantly improves the efficiency of the shallow geothermal energy system. However, the assessment of system efficiency under the influence of groundwater flow is often subjected to error and has been inadequately addressed in the literature. In this study, an energy pile was modeled for a period of 90 days using COMSOL Multiphysics software and the finite element method, taking into account surface groundwater flow. The modeling assumes constant soil and inlet fluid temperature. The analysis was carried out for heating and cooling scenarios with various U-shaped pipe existence of groundwater flow. The results indicate that the presence of surface groundwater flow due to natural convection, independent of soil temperature, leads to a significant reduction in system performance.

KEYWORDS

Geothermal energy - Energy pile – Groundwater flow - Numerical modeling – Natural convection

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1. Introduction

Shallow geothermal energy has emerged as a significant and rapidly growing source of renewable energy worldwide. Between the years of 2005 and 2010, the annual growth rate of this sustainable energy source was 16.6% [1]. The most prominent energy geostructures are geothermal boreholes, energy walls, energy tunnels, piles, and groups of energy piles [2]. Among the mentioned cases, energy piles are more popular due to their ability to perform both structural and energy supply functions simultaneously. An investigation of the heat transfer process in energy piles involves various components, including heat transfer within the fluid, pipe, pile, soil, and heat exchange in their interactions. In addition, heat transfer by water between soil pores and the phenomenon of water seepage in the soil must be considered, taking into account the geotechnical characteristics and hydrology of the soil domain. These factors play a significant role in heat transfer in the soil environment [3]. The phenomenon of water flow in soil can be classified into three categories: natural convection, forced convection, and mixed convection. Natural convection is a consequence of temperature fluctuations within the soil domain that affect the density of the fluid present in the soil. Forced convection occurs due to differences in total head between different regions of the soil. In contrast, mixed convection is defined as the simultaneous occurrence of both convection models [4].

The effect of groundwater flow on the behavior of energy piles is still under investigation by researchers, with the aim of providing more detailed analyses of this issue. When there is groundwater flowing near the surface of the earth, it is crucial to consider the temperature of the surface of the earth and natural convection. However, in most previous studies, one or both factors have not been considered. The objective of this research is to examine the impact of surface groundwater flow on the behavior output power of energy pile, while considering the effects of natural convection and the temperature of the ground surface. This is achieved by using the finite element numerical method by COMSOL software.

2. Assumptions and Numerical model

In the model, the dimensions for the length, width, and height were considered as $50D_{ep}\times2L_{ep}\times2L_{ep}$, where D_{ep} is the diameter of the pile and L_{ep} is the length of the pile [5]. The model investigates the effect of surface groundwater flow for heating and cooling with a U-shaped pipe. The basic assumptions of this research are as follows:

- The soil is assumed to be completely saturated, and the water inside the soil pores is incompressible.
- The temperature of the soil and water inside the soil is assumed to be equal.
- The environment is assumed to be completely homogeneous, and the thermal and hydraulic properties are assumed to be unchangeable (isotropic).
- The Brinkman equation is valid for both natural and forced convection modes.

The concrete cover on the pipe is 75 mm, and the distance from the lowest part of the pipe to the end of the pile is 150 mm. In the modeling of energy piles, the tube inside the pile is typically considered insulated up to a depth of 4 meters from the ground surface. This approach is employed to minimize the impact of temperature changes on the ground surface on the system. In order to model the surface groundwater flow, two layers of soil have been utilized: the upper layer of sand (16m thickness) and the lower layer of clay. The velocity of groundwater flow is equal to 5.15×10^{-7} m/s, and its other characteristics change non-linearly in response to temperature, as calculated by COMSOL software.

To determine the boundary conditions, the boundary condition of constant temperature has been employed for the sides and bottom surface of the model and the fluid inlet temperature has been held constant. For the winter season, the temperature of the ground surface and the inlet water flow were assumed to be -1 and 1 °C, respectively. For the summer mode, the temperature of the ground surface and the inlet water flow were assumed to be 36 and 31 degrees Celsius, respectively. Furthermore, the temperature of the ground remained constant at 17 degrees Celsius in both scenarios. The thermal performance of the system has been modeled in each one of the heating and cooling modes for a period of 90 days.

3. Results and discussion

The objective of this study was to compare the output power in three scenarios according to the thermo-hydraulic characteristics of the soil. In the initial scenario, there is no groundwater flow (forced convection) or natural convection in the model. In the second case, there is a groundwater flow, but the effect of natural convection flow is disregarded. In the third case, the simultaneous effect of groundwater flow and natural convection is considered. A model was constructed to investigate the most effective heating and cooling strategies for a building. Figure 1 presents the output power in watts (W) for an energy pile in the cold months of the year for each of these three modes.

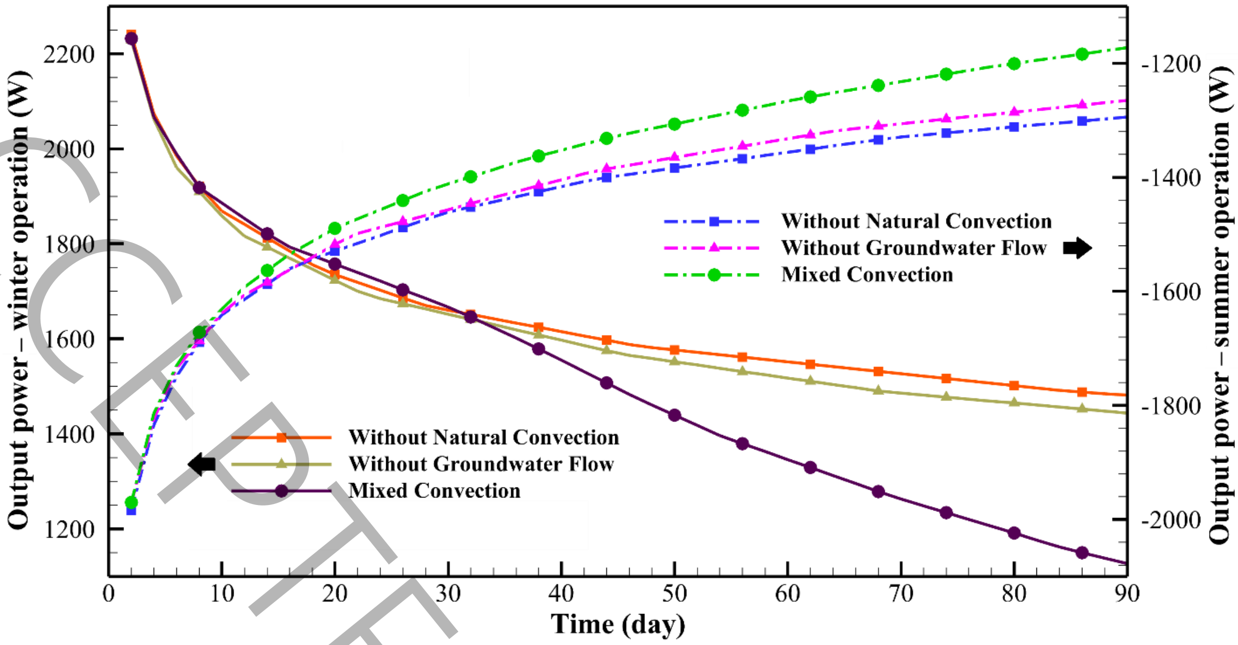

Figure 1- Output power of energy pile in different scenarios for winter and summer operation

As illustrated in Figure 1, during winter operation, when groundwater flow is considered to be without natural convection, as anticipated, the output power is enhanced in comparison to the scenario where there is no groundwater flow. The observed improvement in performance and increase in heat exchange rate reached approximately 2.6% on the 90th day. However, when the natural convection flow is considered, the output power is found to decrease significantly from the 30th day. The reduction in output power is observed to reach more than 27% on the 90th day for the U-shaped pipe. This phenomenon can be attributed to the continuous natural convection caused by the temperature difference between the ground surface and the soil domain, which completely alters the direction of the flow within the soil domain. This results in the transfer of ground surface temperature to the interior of the soil, which subsequently leads to a decrease in soil temperature. It is noteworthy that this phenomenon occurs exclusively in the upper sand layer, with the lower clay layer remaining largely unaffected due to its low permeability. It can be demonstrated that a reduction in the temperature of the existing soil domain will result in a reduction in the output power of the energy pile.

This also applies to the 90 days of the summer season. The negative effect of the presence of surface seepage in the hot seasons of the year is also significant. Not considering the natural convection flow can cause a significant impact on the thermal performance of the energy pile. Figure 1 shows the output power of an energy pile over time with summer performance. As illustrated in Figure 1, the presence of groundwater flow without natural convection enhances the output power of the energy pile in a manner analogous to the winter performance. However, when the effect of natural convection flow is taken into account, the output power declines once more. On the 90th day, the output power drop reaches 10% in comparison to the state without groundwater flow.

4. Conclusion

In this research, numerical modeling and COMSOL software were employed to investigate the effect of natural convection flow and surface seepage in a sand-clay double-layered soil, in different seasons and conditions, on a 28-meter-long energy pile, U-shaped piping, and over a period of 90 days. The constructed model was validated against previous studies and subsequently employed for analysis. The following paragraph presents the most significant findings of this research:

- At low groundwater flow velocity, the natural convection flow induced by the ground surface temperature can influence the velocity and direction of groundwater flow. The impact of natural convection flow caused by the temperature of the ground surface can have a considerable effect on the thermal performance and output power of the energy pile.
- In cold seasons, the natural convection flow can reduce the output power of the energy pile by 27%. This reduction in output power is 10% in the hot seasons of the year.

5. References

[1] J. Fadejev, R. Simson, J. Kurnitski, F. Haghighat, A review on energy piles design, sizing and modelling, Energy, 122 (2017) 390-407.

[2] S.M. Fattahian, M.A.Kiani Fordoei, M. Oliaei, Numerical investigation of the factors affecting the output power from heat exchanger piles, Civil Engineering Sharif. (2021). (In Persian)

[3] A.K. Sani, R.M. Singh, T. Amis, I. Cavarretta, A review on the performance of geothermal energy pile foundation, its design process and applications, Renewable and Sustainable Energy Reviews, 106 (2019) 54-78.

[4] O. Ghasemi-Fare, P. Basu, Influences of ground saturation and thermal boundary condition on energy harvesting using geothermal piles, Energy and Buildings. 165 (2018) 340–351.

[5] Y. Lou, P. fei Fang, X. yu Xie, C.S.A. Chong, F. yuan Li, C. yang Liu, Z. jin Wang, D. yong Zhu, Numerical research on thermal response for geothermal energy pile groups under groundwater flow, Geomechanics for Energy and the Environment. 28 (2021).