Performance Analysis on Heat Transfer Enhancement of Energy Pile with Nanofluid

You Tian\textsuperscript{1,2,*}, Li Peiyu\textsuperscript{1}
1 School of Civil Engineering, Sun Yat-Sen University, China

2 Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), China

E-mail: youtian@mail.sysu.edu.cn; ORCID: https://orcid.org/0000-0003-2135-3289

Abstract. Energy pile is a novel ground heat exchanger with the pipes buried within building piles. The heat transfer performance of energy piles is essential for the ground source heat pump system's efficiency, economy, and reliability. Nanofluids can improve the convective heat transfer inside the heat exchange pipe and the heat transfer of ground heat exchangers. The improvement of the thermophysical properties of nanofluids has been studied previously. However, only a few research studied the heat transfer performance analysis of a spiral coil energy pile with nanofluids as the heat carrier. Hence, this study will investigate the heat transfer enhancement of the energy pile contributed by a nanofluid. The analytical model of a spiral coil energy pile with seepage and the correlations of thermophysical properties of the nanofluid were employed. The heat transfer capacity, wall temperature, and the outlet temperature of an energy pile under different factors were studied. The results showed that by adopting the nanofluid, the heat transfer of the energy piles increased by 1.21\% - 3.12\%, and the pile wall temperature increased by 0.22 °C - 0.47 °C. The increase in the outlet temperature caused by the nanofluid is more significant than that caused by increasing the spiral pitch. It is also more constant than that caused by increasing the seepage velocity. This work can contribute to improving the heat transfer performance of energy piles.

1. Background

The ground source heat pump (GSHP) is an efficient and clean heating and cooling technology for buildings. It utilizes shallow geothermal energy using ground heat exchangers, including boreholes, energy piles, etc. The energy pile has heat exchanger pipes buried within the building piles, saving the drilling costs and space occupied by boreholes\textsuperscript{[1]}. The heat transfer performance of energy piles is essential to the efficiency, economy, and reliability of the GSHP system\textsuperscript{[2]}.

Therefore, some research focused on the heat transfer enhancement of energy piles, including improving the pipe and pile structures\textsuperscript{[3]}, adding phase change materials\textsuperscript{[4]}, and improving the thermophysical properties of the fluid\textsuperscript{[5]}. 

\textsuperscript{*}Corresponding author.
For improving the thermophysical properties of the fluid, researchers developed nanofluids by suspending nanoparticles in conventional fluids. Meibodi et al.[6] conducted an experiment to study the natural convective heat transfer process of SiO2-H2O nanofluid in a flat plate solar collector. Lotfi et al.[7] analyzed the forced convective heat transfer of nanofluids inside a pipe and validated the accuracy of two-phase models. Diglio et al.[8] numerically studied the borehole with nanofluids as the heat carrier and found that Cu-based nanofluids can reduce borehole thermal resistance by 3.8% when the concentration was 1%. Du et al.[9] reported that CuO/water nanofluid can increase the heat transfer rate by 39.84% for pipes with many elbows. Abdullah et al.[10] analyzed that the outlet temperature of GHE can be improved by 19% and 22% in U-type GHE and spiral GHE for a nanofluid with a volume concentration of 0.1%. However, there is no research on the heat transfer performance analysis of a spiral coil energy pile using a nanofluid as the heat carrier.

Hence, this study investigated the heat transfer enhancement of energy piles contributed by a nanofluid. The analytical model of the spiral coil energy pile with seepage and the correlations of thermophysical properties of the nanofluid will be employed. The heat transfer capacity, wall temperature, and the outlet temperature of an energy pile under different factors will be studied. This work can contribute to improving the heat transfer performance of energy piles.

2. Methodology

The research adopts the finite spiral coil model with seepage to analytically simulate the heat transfer of an energy pile. Besides, the thermophysical properties of nanofluids are calculated based on the analytical correlations proposed by other researchers. The energy pile group model[2] and nanofluid model[3-10] employed here have been validated in previous studies.

2.1. Analytical heat transfer model of a spiral coil energy pile

The analytical heat transfer model of a spiral coil energy pile with seepage is adopted to analyze the heat transfer process around a spiral coil energy pile. The dimensionless soil temperature influenced by the energy pile can be calculated using equation 1. This analytical equation considers the geometry of the coil, the seepage, and the finite depth of the energy pile, with good accuracy. Using the dimensionless soil temperature and heat exchange capacity of an energy pile can be calculated as shown below:

\[
\theta = \frac{B}{16\pi^\frac{7}{2}} \int_0^{\phi_0} \frac{1}{(F o - F o')^\frac{3}{2}} \exp \left[ -\frac{\left[ X - \cos\phi' - S(F o - F o')\right]^2 + (Y - \sin\phi')^2}{4(F o - F o')} \right] \times \exp \left[ -\frac{(Z - B\phi / 2\pi)^2}{4(F o - F o')} \right] d\phi \, dF o'
\]

\[
\theta = \lambda_s \times \frac{T - T_0}{q_l} / q_l
\]

where, \(\theta\), \(B\), \(F o\), \(X\), \(Y\), \(Z\), \(H_1\), \(H_2\), \(S\) are the dimensionless excess temperature, spiral pitch, time, coordinate, depth, and seepage velocity, respectively. \(\lambda_s\) is the thermal conductivity of soil, W/(m·K), \(q_l\) is the heat flux of the energy pile, W/m, and \(T_0\) is the initial soil temperature, °C.

2.2. Thermophysical properties of nanofluid

The CuO-water nanofluid is adopted in this research. Compared to water, the nano CuO particles are added as a suspension increase the fluid's convective and conductive heat transfer inside the pipe. Therefore, the thermophysical properties of the nanofluid are different from the single-phase CuO
particles and water properties. Consequently, the new thermophysical properties can be calculated using Equation 3 to Equation 8.

The density and specific heat are calculated based on Pak and Cho correlations\textsuperscript{[11]}, expressed as Equations 3 and 4.

\[ \rho_{nf} = \varphi \rho_s + (1 - \varphi) \rho_f \] (3)

\[ C_{p,nf} = \varphi C_{p,s} + (1 - \varphi) C_{p,f} \] (4)

The thermal conductivity of the nanofluid is calculated by Equation 5 proposed by Koo and Kleinistrenuer\textsuperscript{[12]}. The first term in Equation 5 represents the static conductivity, and the second term represents the dynamic conductivity enhanced by the Brownian motion. It considers the influence of metal particle size, volumetric concentration, temperature, and the properties of water. The \( f(T, \varphi) \) correlation of CuO-water nanofluid is fitted by experimental data by Xuan and Li\textsuperscript{[13]}.

\[ K_{nf} = \frac{K_p + 2K_{bf} - 2\varphi(K_{bf} - K_p)}{K_p + 2K_{bf} + \varphi(K_{bf} - K_p)} K_{bf} + 5 \times 10^4 \beta \varphi \rho_{bf} C_{p,bf} \frac{\kappa T}{\rho_p d_p} f(T, \varphi) \] (5)

\[ f(T, \varphi) = (1.4315\varphi + 1.0418) \frac{T}{T_0} + 4.0587\varphi - 0.99088 \] (6)

where \( \beta = 0.0455(100\varphi_s)^{-0.80376} \text{ (Cu)} \), \( \kappa = 1.3805 \times 10^{-23} \).

The viscosity of the nanofluid is calculated based on the correlation introduced by Batchelor\textsuperscript{[14]} for calculating the viscosity of nanofluids with spherical nanoparticles, expressed as Equation 7.

\[ \mu_{nf} = (1 + 2.5\varphi + 6.2\varphi^2) \mu_f \] (7)

Nu can be calculated based on the following correlation\textsuperscript{[15]}.

\[ Nu_{nf} = 0.074Re_{nf}^{0.707} \rho_f^{-0.385} \varphi^{0.074} \] (8)

2.3. Case studies

To analyze the contribution of the nanofluid on the heat transfer performance improvement of the energy pile, the heat transfer of a spiral coil energy pile with seepage is investigated. The depth and radius of the energy pile are 50 m and 0.75 m, respectively. The pitch of the spiral tube is 0.75 m. The thermal conductivity, density, and specific heat of soil are 1.74 W/(m·K), 1690 kg/m\textsuperscript{3}, and 1800 J/(kg·K), respectively. The initial soil temperature is 14 °C, and the inlet water temperature is 35 °C. The time step size of the simulation is one month.
The heat transfer performance of an energy pile is affected by some critical factors: the spiral pitch, seepage velocity, and fluid velocity inside the spiral tube. When these factors change, the performance improvement contributed by the nanofluid also varies. Therefore, the contributions of the nanofluid under different spiral pitches, seepage velocities, and fluid velocities will be investigated and compared to the water, as shown in cases 1, 2, and 3. In addition, the contribution of the CuO particle concentration on the convective heat transfer of the nanofluid will also be studied in case study 4. All the parameters of different cases are shown in Table 1.

| Case studies | Spiral pitch (b) | Seepage velocity (u) | Fluid velocity (v) | Particle concentration |
|--------------|------------------|----------------------|--------------------|-----------------------|
| 1            | 0.5 m; 1.0 m; 1.5 m | 3×10^{-7} m/s | 0.8 m/s | 5 % |
| 2            | 0.5 m             | 3×10^{-7} m/s; 4×10^{-7} m/s; 5×10^{-7} m/s | 0.8 m/s | 5 % |
| 3            | 0.5 m             | 3×10^{-7} m/s | 0.4 m/s; 0.8 m/s; 1.2 m/s | 5 % |
| 4            | 0.5 m             | 3×10^{-7} m/s | 0.8 m/s | 1 %, 3 %, 5 % |

3. Results and analyses

The contribution of the nanofluid on the heat transfer of energy piles under different factors (spiral pitches, seepage velocities, fluid velocities, and particle concentration) was investigated in this section. The heat transfer of the energy pile, the pile wall temperature, and the outlet temperature of the energy pile are illustrated for the cases using the nanofluid and water.

3.1. Heat transfer of energy pile

The heat transfer of the energy pile using the nanofluid and water under different spiral pitches, seepage velocities, fluid velocities, and particle concentration is shown in Fig. 2. For the different factors, the heat transfer of the energy piles improved by about 1.21 %~3.12 % when the energy piles utilized the nanofluid compared to only water. Specifically, the nanofluid-utilized piles exhibited the following results. When the spiral pitch decreased from 1.5 m to 1.0 m and then to 0.5 m, the heat transfer increased from 1.69 % to 1.71 % and then to 1.74 %. Similarly, when the seepage velocity increased from 3 × 10^{-7} m/s to 4 × 10^{-7} m/s and then to 5 × 10^{-7} m/s, the heat transfer increased from 1.74 % to 1.89 % and then to 2.04 %. Also, when the fluid velocity decreased from 1.2 m/s to 0.8 m/s and then to 0.4 m/s, the heat transfer increased from 1.21 % to 1.74 % and then to 3.12 %. For different particle concentrations, the heat transfer of the energy pile increased slightly when the concentration increased. In the first month, the heat transfer of the energy pile increased by 1.18 %, at a concentration increment of 1 %.
3.2. Wall temperature of energy pile

When the inlet water temperature was maintained at 35 °C, and the initial soil temperature at 14 °C, the wall temperature of the energy pile using the nanofluid (water + CuO particles) and only water under different seepage and fluid velocities are shown in Fig. 3. The pile wall temperature increases by about 0.22 °C–0.47 °C by adopting the nanofluid for different seepage and fluid velocities. For the large seepage velocity or the small fluid velocity, the contribution of the nanofluid is significant. For example, when the seepage velocity increased from $3 \times 10^{-7}$ m/s to $4 \times 10^{-7}$ m/s and then to $5 \times 10^{-7}$ m/s, the pile wall temperature increased from 0.30 °C to 0.32 °C and then to 0.33 °C. Furthermore, when the fluid velocity decreased from 1.2 m/s to 0.8 m/s and finally to 0.4 m/s, the pile wall temperature increased from 0.22 °C to 0.30 °C and 0.47 °C.
3.3. The outlet temperature of the energy pile

The outlet temperature of the energy pile using the nanofluid and water under different seepage velocities and fluid velocities is shown in Fig. 4. Compared to the increase in the spiral pitch, the contribution of the nanofluid to the increase in outlet temperature is more significant. For the energy pile using water as the thermal fluid, when the spiral pitch increased from 1.0 m to 1.5 m, the outlet temperature increased by about 0.24 °C. By contrast, when the fluid changes from water to nanofluid and the spiral pitch is maintained at 1.0m, the outlet temperature increased by about 0.58 °C. In comparison, with the increase in the outlet temperature, the contribution of the nanofluid is relatively constant with time, while the contribution of the seepage increased gradually with time. Using water as the thermal fluid with a decrease in seepage velocity from $4 \times 10^{-7}$ m/s to $3 \times 10^{-7}$ m/s, the outlet temperature increased by 0.10 °C in the first month and by 0.59 °C in the 12th month. When the fluid changes from water to the nanofluid and the seepage velocity is maintained at $4 \times 10^{-7}$ m/s, the outlet temperature increases by about 0.83 °C to 0.61 °C. For different fluid velocities, the contribution of the nanofluid on the heat transfer of energy piles is less noticeable than the contribution of the fluid velocity. The contribution of the nanofluid increased with the decrease in the fluid velocity. When the fluid velocity decreased from 1.2 m/s to 0.8 m/s and then to 0.4 m/s, the outlet temperature increased from 0.45 °C to 0.61 °C and then to 0.96 °C due to the adoption of the nanofluid. For different particle concentrations, the outlet temperature of the energy pile increased by about 0.3 °C, when the concentration increased by about 1 %.
4. Conclusions
This study investigated the heat transfer enhancement of energy piles using a nanofluid. The spiral coil energy pile model with seepage and the thermophysical property correlations of the nanofluid were adopted. The heat transfer capacity, wall temperature, and the outlet temperature of an energy pile under different essential factors were studied. The main conclusions are as follows.

(1) For the different factors (spiral pitches, seepage and fluid velocities), the heat transfer of the energy piles increased by about 1.21% ~ 3.12% using the nanofluid.

(2) For different seepage and fluid velocities, the pile wall temperature increased by about 0.22°C – 0.47°C using the nanofluid.

(3) The increase in the outlet temperature caused by the nanofluid is more significant than that caused by the increase in the spiral pitch and is more constant than that caused by the increase in the seepage velocity.

(4) The heat transfer performance is enhanced with the decrease in the spiral pitch, the increase in the seepage velocity, the decrease in the fluid velocity, and the increase in the particle concentration of the nanofluid.

5. Acknowledgments
The authors gratefully acknowledge the funding support from Guangdong Basic and Applied Basic Research Foundation (2021A1515011739 and 2020A1515110391) and Sun Yat-Sen University (2021qntd15).

References
[1] You S, Cheng X, Guo H, et al. In-situ experimental study of heat exchange capacity of CFG pile geothermal exchangers. Energy and buildings, 2014, 79: 23-31.
[2] You T, Li X, Cao S, et al. Soil thermal imbalance of ground source heat pump systems with spiral-coil energy pile groups under seepage conditions and various influential factors. Energy Conversion and Management, 2018, 178: 123-136.
[3] Huang G, Yang X, Liu Y, et al. A novel truncated cone helix energy pile: Modelling and investigations of thermal performance. Energy and Buildings, 2018, 158: 1241-1256.
[4] Du T, Li Y, Bao X, et al. Thermo-Mechanical Performance of a Phase Change Energy Pile in Saturated Sand. Symmetry, 2020, 12(11): 1781.
[5] Rostami S, Aghaei A, Hassani Joshaghani A, et al. Thermal–hydraulic efficiency management
of spiral heat exchanger filled with Cu–ZnO/water hybrid nanofluid. Journal of Thermal Analysis and Calorimetry, 2021, 143: 1569-1582.

[6] Meibodi S S, Kianifar A, Niazmand H, et al. Experimental investigation on the thermal efficiency and performance characteristics of a flat plate solar collector using SiO2/EG–water nanofluids. International Communications in Heat and Mass Transfer, 2015, 65: 71-75.

[7] Lotfi R, Saboohi Y, Rashidi A M. Numerical study of forced convective heat transfer of nanofluids: comparison of different approaches. International Communications in Heat and Mass Transfer, 2010, 37(1): 74-78.

[8] Diglio G, Roselli C, Sasso M, et al. Borehole heat exchanger with nanofluids as heat carrier. Geothermics, 2018, 72: 112-123.

[9] Du R, Jiang D D, Wang Y, et al. An experimental investigation of CuO/water nanofluid heat transfer in geothermal heat exchanger. Energy and Buildings, 2020, 227: 110402.

[10] Kapıcıoğlu A, Esen H. Experimental investigation on using Al2O3/ethylene glycol-water nanofluid in different types of horizontal ground heat exchangers. Applied Thermal Engineering, 2020, 165: 114559.

[11] Pak B C, Cho Y I. Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles. Experimental Heat Transfer an International Journal, 1998, 11(2): 151-170.

[12] Koo J, Kleinstreuer C. A new thermal conductivity model for nanofluids. Journal of Nanoparticle research, 2004, 6(6): 577-588.

[13] Xuan Y, Li Q. Heat transfer enhancement of nanofluids. International Journal of heat and fluid flow, 2000, 21(1): 58-64.

[14] Batchelor G K. The effect of Brownian motion on the bulk stress in a suspension of spherical particles. Journal of fluid mechanics, 1977, 83(1): 97-117.

[15] Duangthongsuk W, Wongwises S. An experimental study on the heat transfer performance and pressure drop of TiO2-water nanofluids flowing under a turbulent flow regime. International Journal of Heat and Mass Transfer, 2010, 53(1-3): 334-344.