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A novel truncated cone helix energy pile: Numerical and laboratory investigations of thermal performance

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ABSTRACT

As for the cylinder helix energy pile (CyHEP), in order to reduce thermal interference and improve heat transfer efficiency, a novel truncated cone helix energy pile (CoHEP) was proposed in this paper. A 3-D numerical model both considering the dynamic surface condition and the initial soil temperature distribution was developed to investigate its thermal performance, and three main influencing factors (inlet water temperature, water flow rate, cone angle) were studied by the established model. In addition, the laboratory investigation was carried out to verify the accuracy of the numerical model. The results indicate that the heat flux per unit pipe length of the 20° cone angle CoHEP is 6.16% larger than the traditional CyHEP. The whole pipe of CoHEP can be divided into four stages along the flow direction of the pipe length: the entrance stage → the thermal short circuit stage → the small temperature difference stage → the exit stage. During the design of CoHEP, the proportion of the thermal short circuit stage and the small temperature difference stage should be reduced to ensure the overall heat transfer capability. Heat flux per unit pipe length of the CoHEP increases linearly with the inlet water temperature. Increasing the water flow rate can increase the heat flux per unit pipe length of the CoHEP, but it can also reduce the flow time in the pipe, resulting in insufficient heat exchange. As for the cone angle, increasing the cone angle can effectively reduce the radial thermal interference at the upper part of CoHEP and the axial thermal interference. When the system running time is 12 h, as the cone angle increases from 0° to 10° to 20°, the growth rates of heat flux per unit pipe length are 2.54% and 3.53% respectively. Moreover, there must be an allowable maximum cone angle considering the minimum spiral radius of PE pipe, for example, the allowable optimal cone angle is 21° for the model built in the paper.

1. Introduction

Helix energy pile is a new kind of heat exchanger for ground source heat pump [1]. It is usually buried in the building concrete pile foundation, combined with the building structure. Compared with the conventional U-type and W-type energy pile [2–4], helix energy pile has larger heat transfer area under the same depth [5–7]. In addition, helix energy pile can avoid the problem of air accumulation at the top of U-type and W-type ones. As for the traditional helix energy pile, the tube is wound on the cylindrical wall as show in Fig. 1, which is called the cylinder helix energy pile (CyHEP) in this manuscript.

As the geometry of CyHEP is complex, currently the study on it is mainly concentrated in the analytical solution model by doing some simplification. Man et al. [8] proposed infinite length and finite length solid cylindrical heat source model for the CyHEP. And its temperature field expression was derived. However, the models did not consider the impact of the pitch to heat transfer, thus it couldn't analyze the wall temperature change. Zhang et al. [9] proposed the coil heat source model considering the influence of pitch on the basis of the solid cylindrical heat source model. Then the analytic expressions of the finite length and infinite length coil heat source model were derived. The models could help discuss the effect of pitch on heat transfer and calculate the temperature change at the pipe wall. Wang et al. [10] proposed the cylindrical heat source and coil heat source analytical solution model which considered the thermophysical difference between the energy pile and the surrounding soil. And the analytical solution model of CyHEP is further improved. Li et al. [11] established the finite and infinite length spiral heat source model based on the solid cylindrical heat source model and the coil heat source model. The new model considered the complex three-dimensional structure of the CyHEP and was closer to the actual situation.

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Nomenclature

b	pitch in the depth direction (m)
d	the distance between the adjacent tube (m)
L	length of the helix pipe (m)
r	the radius of the helix coil (m)
h	height (m)
τ	the time (s)
C_l	scaling factor of the miniature system (1)
ρ	density (kg m^{-3})
λ	thermal conductivity (W m^{-1} K^{-1})
c	specific heat (J kg^{-1} K^{-1})
T_{in}	inlet water temperature (°C)
V_f	water flow rate (L/h)
u, v, w	the velocity in the x, y, z direction in the Cartesian coordinate system (m s^{-1})
k	turbulent kinetic energy (J)
T	temperature (K)
P	the pressure (Pa)
T_{air}	near-surface air temperature (°C)
$T_{initial}$	initial soil temperature (°C)

Greek symbols

θ	cone angle (°)
Re	Reynolds number
Pr	Prandtl number
ε	turbulence energy dissipation rate (1)
η	molecular viscosity coefficient (N s m^{-2})
η_t	turbulent viscosity coefficient (N s m^{-2})
η_{eff}	effective viscosity coefficient (N s m^{-2})
$\sigma_k, \sigma_\varepsilon, \sigma_T$	turbulent Prandtl number of k, ε and the temperature T

Superscript

CyHEP	cylinder helix energy pile
CoHEP	truncated cone helix energy pile
f	fluid
p	pipe
s	soil
t	top surface of pile
b	bottom surface of pile
min	miniature system
pro	prototype system

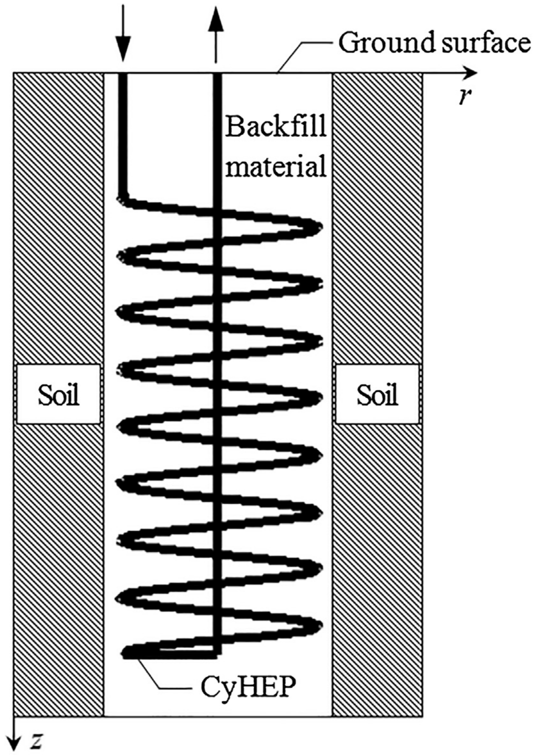

Fig. 1. Cylinder helix energy pile (CyHEP).

By analysis we can find that although the analytic solution models are very convenient they are always given a certain assumption which results in differences with the actual situation. Few analytical solution models consider the flow of water inside the exchanger and they just set a constant unit length of heat transfer for the CyHEP. It is also considered that the initial temperature of the soil is uniform which just does not match the actual situation. Moreover, almost all the analytical solution models do not consider the dynamic environment parameters above the soil surface.

In addition to the analytical solution models, some researchers have also studied the numerical solution models of the CyHEP. Bezyan et al. [12] established the three-dimensional numerical heat transfer model of CyHEP and the heat transfer performance under different pitch is simulated and analyzed. The commercial FLUENT 6.3.26 was used to conduct the simulation. Similarly, the initial soil temperature was assumed to be uniform and the boundary temperature was also assumed to be a constant value. Jalaluddin et al. [13] studied the heat transfer and pressure drop characteristics of CyHEP by three-dimensional numerical simulation via the computational fluid dynamics software ANSYS FLUENT 14.5. Xiang et al. [14] established a new practical numerical model for the CyHEP. The model was simplified from the three-dimensional model and it included one-dimensional transient sub-model of the fluid domain and one-dimensional transient sub-model of the solid domain. The two sub-models were solved by sequential computing algorithm. Through the analysis we can find that the three-dimensional numerical solution model of the CyHEP is complex. Researchers always make a certain simplification which will lead to the deviation from actual situation. For example, most of the models did not consider the nonuniformity of the initial soil temperature and the dynamic environment parameters above the soil surface. Some researchers simplified the complex three-dimensional model into one-dimensional or two-dimensional model to make simulation easier.

Although the CyHEP has the characteristics of large heat transfer area and large heat transfer, the results of Park et al. [15,16] show that the traditional CyHEP has a close distance between the adjacent tubes axially which leads to a serious thermal interference phenomenon. Even when the pitch is small enough, the relative heat transfer efficiency is lower than the U-type ground heat exchanger. Park et al. [17,18] also studied the thermal performance of energy pile equipped with coil-type and W-type heat exchange pipe experimentally and numerically. They found that the heat exchange rate per pipe length was not directly proportional to the pipe length because the tight coil pitch caused thermal