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Laboratory investigations of the thermal performance of an energy pile with spiral coil ground heat exchanger

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ABSTRACT

Spiral coil energy pile is a new type of ground heat exchanger (GHE) used in the ground coupled heat pump (GCHP) system. In this manuscript, a model experimental apparatus of energy pile with spiral coil was set up based on the similarity principle. The experimental investigations of influences of inlet water temperature, intermittent operation mode, spiral pitch and pile material on the thermal behavior of the spiral coil energy pile and soil temperature distribution around it were performed on the experimental apparatus. The experimental results indicate that increasing the inlet temperature contributes to the increase of heat release rate of coil, and the heat release rate increases approximately linearly with the inlet temperature. At the same time, the higher the inlet temperature, the more the heat storage in the pile. For a given inlet temperature, the soil temperature at a level gradually increases from center to outer surface of the pile, and then drops sharply across the outer surface. Under the intermittent operation mode, the soil temperature rise can be stayed effectively by a reasonable intermittent operation control, and thus the performance of GCHP can be improved. As for the spiral pitch, reducing the spiral pitch can increase the total heat release rate of the coil, but also result in the decrease of heat release rate per unit pipe length. Thus, the spiral pitch cannot be reduced unlimitedly and should be optimized through considering the total heat release rate, the heat release rate per unit pipe length, available pile area, and the costs of installation and material. Additionally, increasing the thermal effusivity of pile material can enhance the heat release rate of coil, but also reduce the temperature restoration effect of the soil surrounding the pile. Thus, the selection of pile materials should be overall considered according to the construction requirement of building foundation pile and the heat transfer optimization of energy pile.
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1. Introduction

The new trends in energy savings and greenhouse gas reductions are expecting to explore the utilization of shallow geothermal energy. The most popular way to exploit shallow geothermal energy resources is the ground coupled heat pump (GCHP) system with using ground as a heat source. Because underground temperature is rather constant compared with ambient air temperature, the GCHP could achieve higher efficiency as well as more stable performance compared with traditional air source heat pumps. Thus the GCHP system becomes increasingly popular in commercial and institutional buildings [1–5].

In general, a vertical borehole with ground heat exchanger (GHE) is used as the mainstream of GCHP system. However, the wide application of this type of GCHP technology has been limited by its higher initial cost and substantial land areas required to install the GHE. For this reason, the foundation piles of buildings have been used as part of GHE [6–14] in recent years to reduce the cost of drilling borehole and save the required land area. This innovative idea, utilizing what are usually called "energy piles", has led to notable progress in the field of GCHP systems. It has become particularly attractive because it offers the lower total cost as well as the higher renewable contribution and the lower spatial requirements. In the system's early development, pipes in energy pile were embedded in piles with the configuration of U-tubes, however, the effective heat transfer area was limited in piles and air choking occurred in the turning tips. Hence, a novel configuration of an energy pile with a spiral coil was proposed [15]. The spiral coil configuration has the advantage of more heat transfer area and

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Nomenclature

A	Upper limit of the measuring range (–)
c_p	Mass specific heat of water (J/kg °C)
d	Inside diameter of coil pipe (m)
GHE	Ground heat exchanger (–)
GCHP	Ground-coupled heat pump (–)
L	Length of coil pipe (m)
Q_g	Heat release rate of coil to the soil (W)
q_l	Heat flux per unit pipe length (W/m)
r	Radius (m)
Re	Reynolds number (–)
T_d	Dimensionless soil temperature (–)
T_{in}	Inlet water temperature of coil (°C)
T_{out}	Outlet water temperature of coil (°C)
T_0	Soil initial temperature (°C)
T_g	Soil temperature (°C)
Nu	Nusselt number (–)
ν	Kinematic viscosity (m^2/s)
V_g	Volume flow rate of coil (m^3/s)
z	Depth (m)

Greek letters

ρ	Density (kg/m^3)
θ	Soil excess temperature (°C)
γ	Accuracy grade of test instrument (–)

Subscripts

g	Ground heat exchanger
p	Pressure
in	Inlet
out	Outlet
0	Initial

better flow pattern without air chocking compared with the serial or parallel U-tubes in the pile. In addition, the spiral coil system can reduce the complexity of the pipe connections and decrease the thermal "short-circuit" between supply and return pipes [16]. The schematic diagrams of an energy pile with spiral coil and a conventional energy pile with single U-tube are illustrated in Fig. 1.

Currently, there are a number of studies available to investigate the thermal behavior of spiral coil energy piles. Cui et al. [15] developed the ring coil heat source model to investigate transient heat transfer around spiral coil energy piles. They evaluated and discussed the influence of the coil pitch and locations on specific solutions. Man et al. [16,17] presented a solid cylindrical source model of pile foundation to consider both the radial dimension and the heat capacity of the borehole or pile. Expressions of the analytical solution are derived for 1- D and 2-D new models by means of the Green's function method. Go et al. [18,19] presented a novel hybrid design algorithm for spiral coil energy piles that considered groundwater advection using an analytical model. The accuracy of the analytical model was verified for its design application using a finite element numerical model, and the effect of groundwater advection on the design results was investigated. Park et al. [20,21] presented an experimental and numerical case study of the heat transfer behavior around the helical ground heat exchanger. The indoor thermal response tests were conducted in homogeneous dry sand, and then were numerically simulated based on simple finite element analyses considering heat exchange between circulating fluid and surrounding soil. Li et al. [22,23] presented several analytical solutions to the heat conduction problem in infinite or semi-infinite anisotropic media with line, spiral-line or cylindrical-surface heat source, new temperature response functions were also derived for pile ground heat exchangers with spiral coils and for borehole GHEs with single or double U-shaped tubes. Zhang et al. [24–27] illustrated the existing heat transfer models, and considered the ring coil model as the most realistic standard relation to the heat transfer analysis and computation of pile foundation GHEs with buried coils. Also they developed a new mathematical model for describing the heat transfer of energy pile considering groundwater seepage effects. Lee et al. [28,29] conducted experiments and simulations on the thermal performance of coil-type GHE when applied to the foundation (vertical installation) and bottom(horizontal installation) of the same building. The effective thermal conductivity of GHE was measured to analyze its basic thermal performance. Park et al. [30] suggested an efficient spiral coil source model that considered the effects of three-dimensional shape and radial dimension effect by using Green's function. Zarrella et al. [31] conducted a comparative study of spiral coil and triple U-tube configurations inside a foundation pile using field tests and numerical analysis. The results showed that the spiral coil energy pile provided better thermal performance than the triple U-tube configuration, there was an increase of about 23% at peak. Park et al. [32] examined

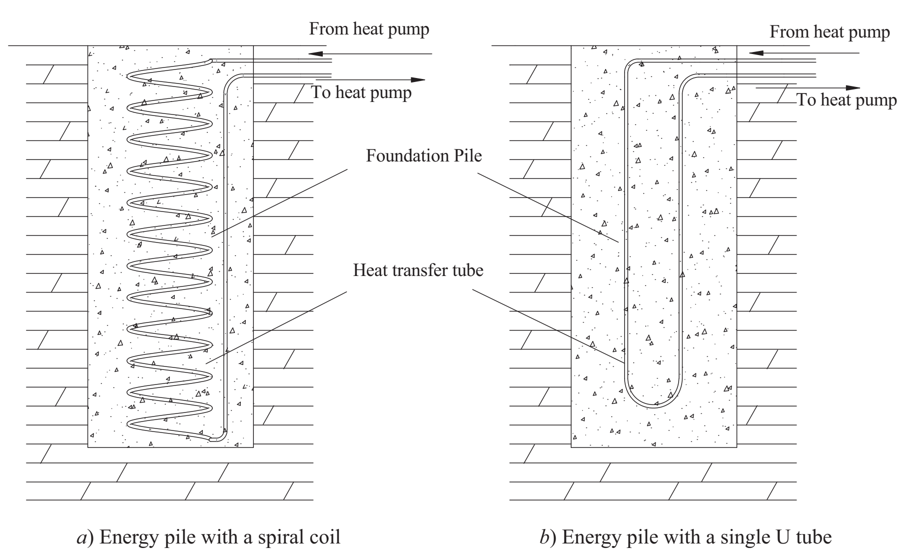

Fig. 1. Schematic diagrams of energy piles with spiral coil and a single U-tube.

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