Geothermics 77 (2019) 75–82

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Experimental investigations of the heat load effect on heat transfer of ground heat exchangers in a layered subsurface

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ARTICLE INFO

Keywords:
Ground source heat pump system
Ground heat exchanger
Laboratory investigation
Ground stratification
Heat load

ABSTRACT

To experimentally investigate the effect of heat loads on the thermal performance of vertical ground heat exchangers (GHEs) in a layered subsurface, a series of experiments were conducted using a testing box filled with sand and clay. Temperature distributions during the operation and recovery periods were different in the layered subsurface, where materials with high thermal diffusivities (e.g. sand) excel in both heat transfer and recovery. With more heat transferred from tubes, the sand and clay located close to the tubes showed drastic temperature variations along the length of tubes, especially around the interface between layers. The thermal interference could enhance the layered thermal distribution in the stratified underground, especially in materials with low thermal diffusivities. Moreover, if the applied power increased by four times, the proportion of the temperature difference between sand and clay to the sand temperature increased from 12.9% to 32.7%, which indicated a more severe thermal stratification. Therefore, it is recommended to consider the effect of ground stratification for multi-GHEs with considerable thermal injection and severe thermal interference, especially in materials with low thermal diffusivities.

1. Introduction

Since the buildings consume approximately 40% of the total world energy annually, the application of renewable energy in buildings is highly recommended due to its energy efficiency and environmental friendliness (Omer, 2008a). Geothermal energy is one of the leading sustainable energies utilised by over 80 countries worldwide, while more than half (55.2% in the year 2014) of its direct application is for the ground source heat pump (GSHP) systems (Lund and Boyd, 2016). As one of the most energy-efficient approaches used in buildings (Omer, 2008b), GSHP systems remove the waste heat away from the buildings to the ground through the ground heat exchangers (GHEs). The GHE system plays an important role in achieving an efficient performance of GSHP system, and its efficiency can be greatly influenced by the operational and geological factors (Han and Yu, 2016).

The thermal performance of GHE system is largely affected by the heat injection or extraction of the ground, which were determined by the heating and cooling demands, system operating modes and borehole layouts (Qian and Wang, 2014). For a cooling-dominated building, the accumulative ground injection brought by the thermal imbalance of building demands could increase the fluid temperature, and further deteriorate the system cooling efficiency and shorten the system lifespan (Li et al., 2018a). Since the ground temperature drift depends primarily on the annual heat imbalance between heating and cooling loads, it is efficient to limit the thermal drift effect by rebalancing the heat loads rather than installing more boreholes (Capozza et al., 2015). Moreover, the discontinuous operation mode can alleviate the system thermal performance deterioration effectively (Cui et al., 2008). The increase of the recovery time can decrease temperatures and thermal radius, and increase the heat transfer rate of GHEs (Cao et al., 2015), which becomes more significant in material with low soil thermal conductivity (Baek et al., 2017). Besides the load demands and patterns, the thermal interaction among boreholes also showed non-negligible impacts on the ground temperature variation, especially for long-term operations (Bernier et al., 2008). Yuan et al. (2016) observed that the heat transfer performance of each GHE in a bore-field remain almost the same, however, the central boreholes were less effective due to the severe thermal interference influence once the thermal interference emerged. Lazzari et al. (2010) studied the long-term performance of GHE system with different layouts, the simulation results showed that the performance deterioration was nearly negligible for a single GHE while became significant for the infinite square GHE field.

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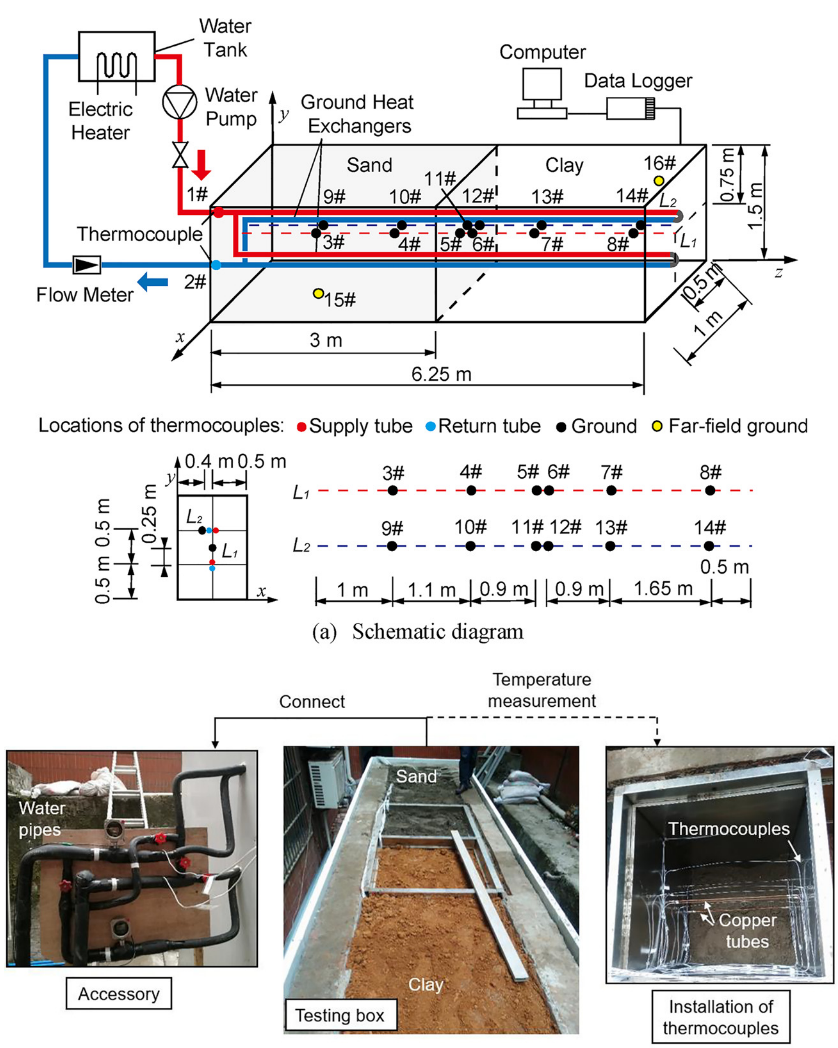
https://doi.org/10.1016/j.geothermics.2018.08.011
Received 21 May 2018; Received in revised form 9 August 2018; Accepted 30 August 2018
0375-6505/

Nomenclature

A	Heat transfer area (m^2)
$C_{p,\,f}$	Specific pressure heat capacity of the fluid (J/kg °C)
k_s	Thermal conductivity of sand (W/m °C)
k_c	Thermal conductivity of clay (W/m °C)
m_f	Mass flow rate of the fluid (kg/s)
P	Electric power (W)
q	Heat transfer rate (W)
q^*	Heat transfer rate per unit area (W/m^2)
q^*_{radial}	Radial heat transfer rate per unit area (W/m^2)
q^*_{axial}	Axial heat transfer rate per unit area (W/m^2)
Q_g	Ground heat injection or extraction (W)
R_k	Thermal resistance (°C/W)
t	Time (s)
ΔT	Temperature difference (°C)
T_0	Initial ground temperature (°C)
T_g	Ground temperature (°C)
T_{in}	Temperature of water flowing into the tubes (°C)
T_{out}	Temperature of water flowing out of the tubes (°C)
Δx_s	Distance between two points in sand (m)
Δx_c	Distance between two points in clay (m)
θ	Temperature increase (°C)

On the other hand, the thermal performance of the GHE system is strongly dependent on the soil type (texture, mineralogical composition) (Leong et al., 1998). Since the typical depth of vertical GHEs ranges widely from 15 to 180 m (ASHRAE, 2011), the ground stratification effect has aroused extensive interests. Lee (2011) conducted numerical simulations with different ground compositions, and the ground layers had negligible effects on the long-term fluid temperature predictions. However, based on a small-scale laboratory apparatus, Li et al. (2018b) found the numerical models with layered and equivalent thermal properties gave similar water temperatures while different thermal exchange and ground temperature distributions along the depths of tubes. The varied thermal exchange rates along the length of GHEs were also observed in a practical five-layer subsurface (Luo et al., 2014) and even within the individual strata (Olfman et al., 2014). If the homogeneous subsurface assumption was adopted in models with strong heterogeneity, the ground temperatures would be overestimated or underestimated by up to 25% due to the excessive simplification (Abdelaziz et al., 2014; Perego et al., 2016). The inaccuracy brought by the homogeneous model became more pronounced at the soil interface, and it increased with the increasing Fourier number and decreasing



(a) Schematic diagram

(b) Photos

Fig. 1. (a) Schematic diagram and (b) Photos of the experimental rig used in this study.