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Small-scale lab analysis of the ground freezing effect on the thermal performance of a Flat-Panel ground heat exchanger

Jingyu Cao[a], Michele Bottarelli[b,*], Marco Bortoloni[c], Gang Pei[a]

[a] *Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230027, China*
[b] *Department of Architecture, University of Ferrara, Via Quartieri 8, Ferrara 44121, Italy*
[c] *TekneHub Laboratory, University of Ferrara, Via Saragat 13, Ferrara 44122, Italy*

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ABSTRACT

Shallow ground heat exchangers are increasingly studied due to their advantages in cost and long-term energy performance stability when coupled with heat pumps for space heating and cooling. As for borehole heat exchangers, the backfilling material affects significantly the operating efficiency of the whole system, mainly driven by the low thermal diffusivity of the soil. To enhance the heat transfer, the mixing of the backfilling material with phase change materials (PCMs) is a novel strategy still partially investigated, especially with regards of the heat pump on/off cycling. This study presents the results of experimental tests carried out at lab-scale to analyse the performance of a shallow Flat-Panel ground heat exchanger (FGHE) coupled with water-sand mixture. Firstly, the comparison between FGHEs coupled with dry sand and water-sand mixture is performed; then, the impact of latent heat resulting from freezing is further studied in three on/off operating modes. A maximum of 31.6% increment in heat transfer efficiency is observed in wet conditions and for the highest on/off frequency. Therefore, coupling FGHE with water-sand mixture enhances the heat transfer, especially in icing interval and when combined with a suitable on/off operating frequency.

1. Introduction

Ground coupled heat pumps (GCHPs) have been widely used as a sustainable energy technology for heating and cooling of buildings due to its high efficiency (Omer, 2008; Zhai et al., 2011; Sarbu and Sebarchievici, 2014). It is particularly useful in cold and humid regions because it can avoid the frosting problem affecting air source heat pumps; therefore, significant energy consumption can be saved (Bayer et al., 2012; Self et al., 2013; Soni et al., 2015). In GCHP systems, the ground heat exchangers (GHEs) works as a key component and could be roughly classified into vertical and horizontal types according to their arrangement (Soni et al., 2015). In the vertical solution, GHEs are installed into boreholes drilled up to hundreds meters deep to exploit the great heat storage capacity of the ground and higher temperatures (Li and Lai, 2015; Rivera et al., 2015; Cao et al., 2017). This type has been widely utilized for high-rise buildings; however, initial costs and install and maintenance difficulties are significant drawbacks of this technology (Soni et al., 2016). On the contrary, the horizontal installation type has remarkable advantages because the heat exchanger is placed few meters deep in shallow ground (Gabrielli and Bottarelli, 2016). Unlike the stable geothermal source in borehole systems, the shallow ground source may mainly serve as a temporary solar energy buffer, as a consequence of the close dependence on environmental conditions. Even if the seasonal weather conditions affect the performance of horizontal GHEs, at the same time they can avoid ground thermal drifts after long-term operation, that on the contrary affect the vertical GHEs. Therefore, increasing attention has been devoted to the horizontal GHEs in recent years, particularly in field of compact GCHP systems (Chalhou et al., 2017; Han et al., 2017; Hua et al., 2017).

Anyway, the low thermal diffusivity of the ground impacts heavily on the GHE size, and therefore on the installation costs. Enhancing the thermal properties of the backfilling material has been considered an effective solution, especially with regard of the heat conductivity (Erol and François, 2014; Kim et al., 2017). Besides, taking into account the on/off operating mode of normal heat pump system, the usage of phase change materials (PCMs) in the ground close to the GHEs can improve the on-time heat transfer capability (Farida et al., 2004) by using the off-time as thermal buffer recovery. This strategy has been studied since 1996 and in different conditions (Rabin and Korin, 1996; Lei and Zhu, 2009; Wu, 2011). Closer examination was carried out by Wang et al. by adopting PCMs as grout to improve the heat capacity of soil. The variation of heat transfer characteristic of borehole heat exchanger was

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* Corresponding author.
E-mail address: michele.bottarelli@unife.it (M. Bottarelli).

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Nomenclature

C	Specific heat [kJ/kg °C]
$\dot{Q}$	Heat transfer rate [kW]
T	Temperature [°C]
$\dot{V}_g$	Volume flow rate [m^3/s]

Greek letters

ρ	Density [kg/m^3]

Subscripts

A	Box A
B	Box B
g	Working fluid
0 ~ 6	Temperature probes

evaluated by a 3-dimensional numerical heat transfer simulation. The results show that the land area can be reduced effectively with PCMs as backfilling; however, the heat transfer improvement is needed due to the low conductivity of the selected PCMs (Wang et al., 2014). Li et al. proposed a shape-stabilized phase change backfilling material for U-tube heat exchanger. It referred to a mixture of decanoic acid and lauric acid. The shape-stabilized PCM backfilling could improve the heat exchange capability up to 37% and showed significant influence on heat pump coefficient (Li et al., 2016). Qi et al. tested the performance of vertical GHE coupled with four backfilling materials, including soil, paraffin RT27, acid and enhanced acid PCM. The efficiency improvement was analysed on the basis of its small thermal effects radius and consistent temperature in the phase change process (Qi et al., 2016).

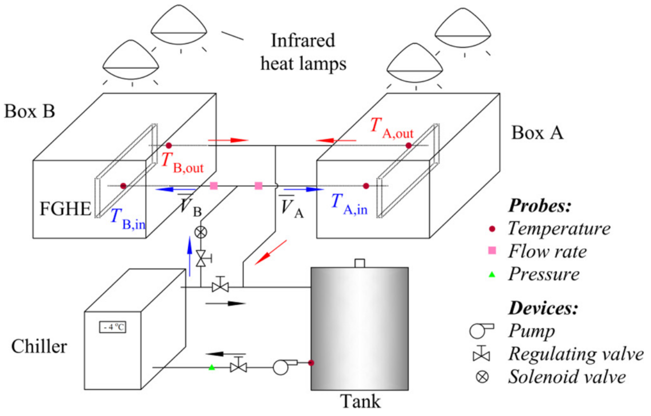
Though several analyses were done about this topic, they were mainly limited in the field of vertical system, and few literatures were related to horizontal GHEs. Bottarelli et al. studied the effect of PCMs on the performance of a horizontal and shallow Flat-Panel GHE, whose flat shape and its edgeways installation into a narrow trench well adapts to similar applications (Bottarelli et al., 2015a,).

However, the significant cost increment caused by the large amount of PCMs, their low heat conductivity and environmental impact are still unsolved problems for GCHPs. To avoid them, Eslami-nejad and Bernier proposed to utilize latent heat from groundwater freezing. Based on this low-cost PCM, 38% of the borehole depth can be reduced for the same heat pump system (Eslami-nejad and Bernier, 2012). Yang et al. built a two-dimensional heat transfer model to study the effects of soil freezing on underground temperature variations of soil around GHEs. It further proved that the soil freezing lessened the soil temperature drop, increased the temperature difference and finally helped to shorten the length of GHE (Yang et al., 2015). Particularly, Gan et al. preliminarily simulated the effect of soil freezing on the heat exchanger performance of horizontal GHE. The significant increase in the specific heat extraction resulting from soil freezing was observed and it could be beneficial for continuous operation of a heat pump (Gan, 2013). Recently, a three-dimensional model was used by Zheng et al. to simulate the effect of latent heat from groundwater freezing; results confirm that exploitation of latent heat through groundwater freezing is economically attractive with low electricity price (Zheng et al., 2016).

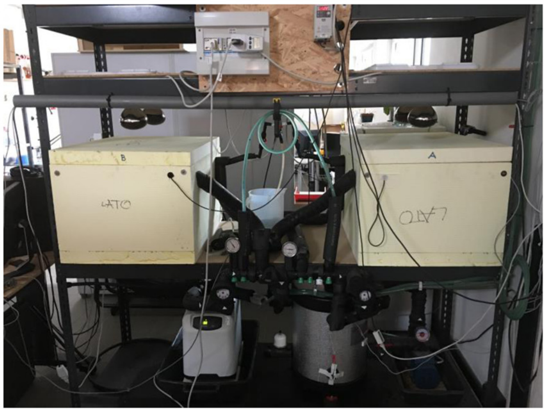
To further explore this potential benefit for horizontal GHEs, we experimentally analyse in this study the usage of water as PCM backfilling material of the sand filling the trench containing a Flat-Panel ground heat exchanger (FGHE), similar to what was studied by Bottarelli et al. (2015a). The use of water as a phase change material applies to GCHPs operating with water/glycol mixture as the working fluid. The thermal behaviour of it is significantly related to the heat transfer capability of the FGHE. Though numerical analysis on the FGHE coupled with PCMs was carried out (Bottarelli et al., 2015a,b), the experimental approach had still to be investigated, such as the short-term heat transfer behaviour of the FGHE.

2. Experimental set-up

An original test rig installed at the TekneHub laboratory of the University di Ferrara (Italy) has been revamped to evaluate the thermal performance of FGHE coupled with shallow water-sand mixture for heat pump systems. As depicted in Fig. 1, the test rig is composed of two insulated boxes A and B, made by 6 cm thick extruded polystyrene (XPS) with a thermal conductivity of 0.04 W/mK. The top thermal insulating layer can be removed. A plastic tub is placed inside the insulating box and the interstice between them (6 cm) is filled with sawdust to furtherly reduce heat loss. As shown in Fig. 2, a FGHE is located in the middle of each box and installed into a trench with aluminium walls. The tub and the trench volume (i.e. the soil volume) are initially filled by dry sand. Three samples were taken in order evaluate the dry sand properties. The density and porosity were experimentally measured to be on average of 1515 kg/m^3 and 0.36, respectively. The average specific heat capacity equal to 952 J/kgK was estimated by means of a differential scanning calorimeter (DSC) at the Istanbul Technical University. Finally, the soil thermal conductivity



(a) Set up



(b) Test rig

Fig. 1. Test rig and probes.