ARTICLE IN PRESS

Applied Thermal Engineering xxx (2014) 1–7

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Numerical analysis of a novel ground heat exchanger coupled with phase change materials

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HIGHLIGHTS

- Coupling of a flat-panel ground source heat exchanger (GHE) with PCMs.
- The mixture of soil and PCMs is assumed as a backfill material for the GHE.
- Numerical simulation of heat transfer in soil with realistic boundary conditions.
- PCMs allow better working fluid temperatures mitigating the soil's thermal depletion.
- Potential increase in the COP of a ground coupled heat pump.

ARTICLE INFO

Article history:
Received 14 June 2014
Received in revised form
29 September 2014
Accepted 7 October 2014
Available online xxx

Keywords:
Ground-coupled heat pump
Ground heat exchanger
Flat-panel
Phase change materials
Numerical model
Underground thermal energy storage

ABSTRACT

Thermal energy storage with phase change materials (PCMs) is a functional strategy to minimize the sizing of air conditioning systems and reduce their primary energy consumption. This approach is well known in ground-coupled heat pump applications (GCHP), especially with use of borehole ground heat exchangers (GHEs). However, this is seldom investigated for coupling with shallow horizontal GHEs that are usually considered to be less effective for GCHP applications, due to faster depletion of the stored thermal energy as a result of the seasonal energy balance.

In order to make shallow GHEs more effective, mixing PCMs directly with backfill material for a flat-panel type GHE is presented in this study. The application has been evaluated through numerical modelling to solve transient heat transfer using effective heat capacity method. Yearly performance has been simulated by taking into account the estimated energy requirement for an assumed residential building located in Northern Italy. According to hourly time series boundary conditions and annual performance, the simulation results show that employment of PCMs is able to smooth the thermal wave in the ground, improve the coefficient of performance of the heat pump (COP) and if suitably sized, prevent thermal depletion in winter by charging the PCMs naturally in summer with a shallow GHE.

1. Introduction

Ground-coupled heat pumps (GCHPs) have been regarded as a sustainable energy technology for space heating and cooling in commercial, industrial and residential buildings, as well as a profitable solution when correctly designed. Coupling a heat pump with the ground is obtained by means of ground heat exchangers (GHEs), which can be installed vertically or horizontally. In the horizontal installation, the heat exchangers are placed in shallow diggings a few metres deep in soil, as opposed to the vertical solution where the heat exchangers are installed in boreholes drilled down up to a hundred metres deep. Owing to their different depths of installation, the vertical solution exploits a real geothermal

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http://dx.doi.org/10.1016/j.applthermaleng.2014.10.016
1359-4311/

source, while for the horizontal one, the ground source may mainly serve as a solar energy buffer. However, the weakest link in a GCHP system is the GHE, because the heat transfer in the ground is mainly conductive and its thermal diffusivity is low. This means that the ground thermal response is much slower than the heat pump requirement, resulting in thermal waves being transmitted into the ground through the GHEs by means of a circulation loop. This may cause lower coefficient of performance of a GCHP, because the heat pump has to lower its evaporation temperature in winter or increase its condensation temperature in summer to obtain the required heat flux. But, the heat pump usually operates in an alternate on/off mode, so it would be interesting to apply ground thermal storage to suppress the thermal wave by use of the off-time thermal buffer to maintain on-time heat flux requirement.

Employing Phase Change Materials (PCMs) is an effective measure to store thermal energy [1,2] and it may also be considered as an effective method to smooth the thermal wave generated from operation of a GCHP [3,4]. In this study, we propose to mix the PCMs directly with backfill material in a trench containing a flat-panel GHE. The backfill material could be also contained in a shell close to the GHE. There is little research reported in literature about this idea [5–8], and the performance has not yet been investigated for shallow GHEs. Use of the PCMs incorporated with GHEs may be able to meet some instantaneous high heat flux demand by a GCHP, thus reducing the sudden heating or cooling thermal wave upon the ground. Therefore, the peak operation temperature in the heating/cooling mode of a GCHP could be raised/lowered for a given size of GHE. In other words, the GHE size could be reduced for a given peak operation temperature. Moreover, the depletion of the latent heat due to the PCMs solidification/melting could be recharged during the summer/winter season, which therefore achieves the seasonal ground thermal storage.

2. Methodology and numerical simulation

The coupling between the GHE and PCMs is here assumed to occur by mixing water and micro-encapsulated paraffin with the soil, and use the mixture as a backfill material for the trench containing a flat-panel GHE. Due to different solidification/melting temperatures, water in the mixture is devoted to prevent depletion of heat in the low temperature situation (heating season in winter), whereas micro-encapsulated paraffin is required for the high temperature situation (cooling season in summer). The numerical approach was simplified by considering the heat conduction problem of an equivalent solid to the supposed mixture, and to solve it numerically by means of a commercial software (COMSOL Multiphysics, V4.4).

The model is implemented in a 2D domain with time-varying boundary conditions to study the temperature distribution in the ground and at the surface of GHE, by solving the equation:

$$\rho_{eq} c_{eq} \frac{\partial T}{\partial t} = \nabla \cdot (\lambda_{eq} \nabla T) \tag{1}$$

where ρ_{eq}, c_{eq} and λ_{eq} are the equivalent density, specific heat and heat conductivity of the mixture, which can be calculated as the mass weighted average properties of the mixture at the given temperature. In addition, the latent heat of fusion is considered in c_{eq}. To represent those thermo-physical properties during the phase change, some specific relationship are implemented as an evolution of what is reported in Ref. [9]. In the reported approach, the PCM problem was numerically treated as a simple porous media, which is composed of the two phases of the same material (e.g., solid ice and liquid water). The specific heat capacity c was defined to consider the latent heat of fusion h^{SL} by means of a normalized Dirac's pulse $D(T)$, expressed in K^{-1}. Moreover, the phase change between the liquid phase (L) and the solid one (S) are expressed in Ref. [9] as a function of a dimensionless variable $H(T)$ which is the volumetric fraction of the liquid phase in a PCM, ranging between 0 and 1 with respect to the temperature changing around the melting point (T_m). These functions were introduced to moderate the switching between solid ($H(T_m - \Delta T) = 0$) and liquid phases ($H(T_m + \Delta T) = 1$).

In the present study, because of working with two different PCMs ($n = 2$) and considering only heat conduction, we simplified the porous media heat transfer as a heat conduction problem of an equivalent solid domain. Here, the solid matter is considered as a mixture between soil and the two PCMs, in accordance with the respective mass ratio r_i supposed between each PCM and the soil (G). As a consequence and in variation of a previous work [9], two different functions $H_i(T)$ were assumed as mass ratio of each specific PCM considered, and similarly two different functions $D_i(T)$ were used. The $H_i(T)$ and $D_i(T)$ functions for water and micro-encapsulated paraffin are given in Fig. 1, with evidence of their melting points.

Finally, the equivalent overall density, thermal conductivity and specific heat of the mixed backfill material were obtained as a mass weighted average of the total liquid and solid mass at a given temperature, as reported in the following equations with evidence of the variables:

$$\rho_{eq} = \left(1 - \sum_{i=1}^{n} r_i\right) \cdot \rho_G + \sum_{i=1}^{n} r_i \cdot (1 - H_i(T)) \cdot \rho_i^S + \sum_{i=1}^{n} r_i \cdot \rho_i^L \cdot H_i(T) \tag{2}$$

$$\lambda_{eq} = \left(1 - \sum_{i=1}^{n} r_i\right) \cdot \lambda_G + \sum_{i=1}^{n} r_i \cdot (1 - H_i(T)) \cdot \lambda_i^S + \sum_{i=1}^{n} r_i \cdot H_i(T) \cdot \lambda_i^L \tag{3}$$

$$c_{eq} = \left(1 - \sum_{i=1}^{n} r_i\right) \cdot c_G + \sum_{i=1}^{n} r_i \cdot (1 - H_i(T)) \cdot \left(c_i^S + h_i^{SL} \cdot D_i(T)\right) + \sum_{i=1}^{n} r_i \cdot H_i(T) \cdot \left(c_i^L + h_i^{SL} \cdot D_i(T)\right) \tag{4}$$

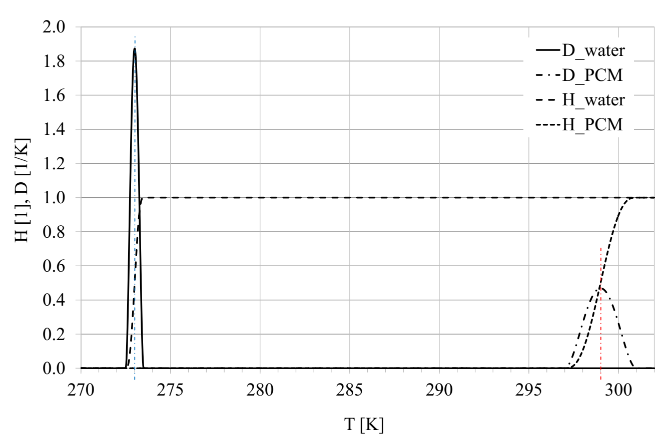

Fig. 1. D & H functions indicating the phase change of water and paraffin.