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Ground-Source Heat Pumps using Phase Change Materials

Michele Bottarelli[1*], Aleksandar Georgiev[2], Ahmet Alper Aydin[3], Yuehong Su[4], Charles Yousif[5]

[1] University of Ferrara, Department of Architecture, Via Quartieri 8 – 44121 Ferrara, Italy

[2] Technical University of Sofia, branch Plovdiv, Department of Mechanics,
25 Tsanko Diustabanov St., Plovdiv 4000, Bulgaria

[3] Technische Universität München, Chair of Urban Water Systems Engineering,
Am Coulombwall 85748 Garching, Germany

[4] University of Nottingham, Department of Architecture and Built Environment,
University Park, NG7 2RD, United Kingdom

[5] University of Malta, Institute for Sustainable Energy, Barrakki Street, Marsaxlokk, MXK 1531, Malta

michele.bottarelli@unife.it

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ABSTRACT

Employing Phase Change Materials (PCMs) is normally considered as an effective measure to store thermal energy, by means of their latent heat during phase changing. But, it could also represent a method to smooth the thermal wave generated from operations of thermal machines, such as ground-source heat pumps (GSHPs). This paper evaluates the application of PCMs through numerical modelling to solve the heat transfer in ground carried out by a horizontal and shallow ground heat exchangers (GHXs), when coupled to a GSHPs. The PCMs are assumed to be mixed directly with backfill material close to the GHXs or placed in a surrounding shell that is in direct contact with the heat exchangers. Results showed that the use of the PCMs incorporated with GHXs meets the instantaneous heating demand by the GSHPs, and reduces the sudden cooling wave on the ground interface. By calibrating the amount and the properties of the PCM in accordance with the energy requirements of the GSHP, it is possible to balance the heat extraction of the operating time to the heat recovered during the off time of the GSHP. As a consequence, the peak temperature results could be smoothed by up to 0.7 K in comparison to the case without PCMs. Thus, higher coefficients of performance (COP) are expected for GSHPs. Moreover, the underground thermal energy storage is recovered for shallow GHXs, getting over the seasonal variations due to weather change.

1. INTRODUCTION

Ground-source heat pumps (GSHPs) 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 (GHXs), which can be installed vertically or horizontally. In the horizontal installation, the heat exchangers are placed in shallow diggings few meters deep in soil, as opposed to the vertical solution where the heat exchangers are installed in boreholes drilled down up to a hundred meters deep. Owing to their different depths of installation, the vertical solution exploits a real geothermal source, while for the horizontal one, the ground source may mainly serve as a solar energy buffer. However, the weakest link in a GSHP systems are the GHXs, because the heat transfer in the ground is mainly conductive and its thermal diffusivity is also low. This means that the ground thermal response is much slower than the heat pump behaviour, resulting in transfer of thermal waves to the ground through the GHXs by means of the closed loop. This may cause lower COP at the GSHPs.

Employing Phase Change Materials (PCMs) is an effective measure to store thermal energy (Aydin, 2013) and it may also be considered as an effective method to smooth the thermal wave generated from operation of a GSHP. The approach is known when the PCMs are introduced directly in a tank within a closed loop, especially for vertical closed loop. However, use of a tank containing PCMs could be an expensive solution for the horizontal closed loop GHXs system, due to their low energy performance. Moreover, the heat transfer may not be effective for the bulky PCM tank. So, we have proposed to mix the micro-encapsulated PCMs directly with backfill material, which is close to the GHXs or install them in a surrounding shell. There is little research reported in literature about this idea, and the performance is not yet well investigated (Haiyan and Neng, 2009; Rabin and Korin, 1996). Use of the PCMs incorporated with GHXs may meet some instantaneous heating demand by a GSHP, thus reducing the sudden heating or cooling wave upon the ground. Therefore, the peak temperature would be lower with an equal GHX length, or the GHX length could be shorter with an equal peak temperature. We are currently analysing the performance of a novel GHX design with PCMs by means of an experimental setup and a numerical approach. This latter is presented here.

2. METHODOLOGY

In order to assess the PCM effect on the thermal behaviour of GHXs, a finite element model was implemented to simulate the heat transfer performed by a GHX *with* and *without* a PCM layer attached to its surface. The numerical tool used here is a commercial software (COMSOL V4.3a), in which the heat transfer problem is solved for a soil section where the GHX is buried. To analyze the suppression of heat wave by the PCM, the GHX was assumed to be operating according to a daily schedule, in which ON/OFF periods are alternated. All major details are presented below.

2.1 Model Domain

For simplicity, the domain considers a transversal section which comprises of a ground heat exchanger, a PCM layer as the backfill material all surrounded by soil. A symmetric approach is applied to one-half of the domain in order to reduce the finite elements. The GHX was assumed to be a flat-panel that shows high heat transfer capacity, as reported in (Bottarelli and Di Federico, 2012), and it is easy to reproduce it in a 2D approach. As presented in Fig. 1, the size of the domain is 25 cm wide and 20 cm deep. The heat exchanger is 10 cm high and laid between 7.5 and 17.5 cm deep. The PCM layer is placed between the surface of the GHX and the soil on the right side. The thickness of the PCM was assumed to be equal to 4 mm and the resulting volume for each metre of flat-panel length is 4.0E-04 m^3/m. These sizes were taken to be similar to those of the physical model, which is under testing in the laboratory at the Department of Architecture at the University of Ferrara, to be able to compare modelling to experimental results in the near future. Fig. 1 also shows the measurement points, which are placed at 0, 50 and 100 mm away from the flat panel. The first point is for the temperature measurement at the interface between the GHX and the PCM layer, while the other two points show the temperature of the ground at different distances.

To minimize the numerical errors and to expedite the computational time, the size of the finite elements was chosen to be fine for the area close to the GHX and coarse for the area far from it. The resulting sizes are between 0.0035 cm^2 for fine grids and 0.45 cm^2 for coarse grids. The full mesh is shown in Fig. 2 and it is limited to 4800 elements to make a shorter computational time.

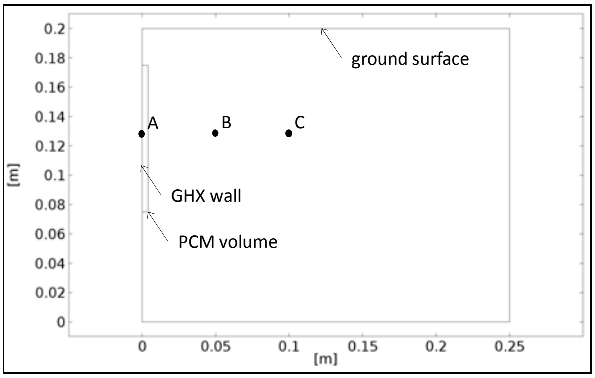

Figure 1: The domain for the symmetric model

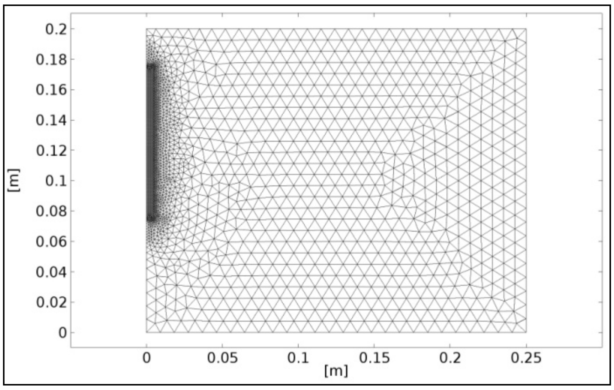

Figure 2: Meshed domain of the model

2.2 Initial and boundary conditions

The thermal analysis was performed starting from an initial temperature of 15°C. Boundary conditions of the 1st and 3rd kind are fixed at the outer domain boundaries as thermal conditions. At the bottom of the domain, a constant temperature of 15°C, representing an undisturbed condition, is assumed. This condition allows the thermal equilibrium of the domain and helps to supply latent heat of fusion to the PCM. All other boundaries are assumed adiabatic. In order to simulate the thermal behaviour caused by the GSHP, a time varying heat flux was added to the GHX wall. The time-series sets the operating mode of the system with a time pitch of ten minutes. The heat flux is obtained through the combination of a set temperature of the working fluid with a convective heat transfer coefficient h, fixed at 25W/m^2K, as obtained from the experimental test. Depending on the considered case,, the fluid temperature is fixed at 4°C or 8°C lower than that on the GHX wall. Thus, the resulting power may vary from 0 W/m^2 to 200 W/m^2, when the GSHP is in operation.

2.4 Material data

The two materials making up the domain are the soil and the PCM. The soil is considered unchangeable and fills all around the domain with exception of the volume reserved to the PCM. For the case *without* PCMs, the former volume is assumed to be filled with PCM having a latent heat set to zero (PCM^0). For the cases *with* PCMs, the study considers three different simulations using three kinds of PCMs ($PCM^{1,2,3}$). The values of latent heat (h_{sl}), melting point (T_{sl}), density

(ρ), specific heat (C_p) and heat conductivity (λ) for the soil and the PCMs are summarised in Tab. 1.

Table 1: Soil and PCM properties

	h_{sl} *(kJ/kg)*	T_{sl} *(±0.5 K)*	ρ *(kg/m^3)*	C_p *(kJ/kg K)*	λ *(W/m K)*
Soil	-	-	1600	1400	1.6
PCM^0	-	-	1200	1400	1.2
PCM^1	150	10.5	1200	1400	1.2
PCM^2	150	12.5	1200	1400	1.2
PCM^3	50	10.5	1200	1400	1.2

The first condition (PCM^1) aims to represent a reference case. With the exception of its melting point, the properties are taken from literature, typically for paraffin as reported in (Lock, 1996). By means of preliminary simulations, the PCM melting point was chosen to be the average of the temperature fluctuation caused by the GSHP operation in the similar case but *without* PCM. The second case (PCM^2) is an outcome of the previous one, because the heat power is halved. Similarly, the new melting point is defined by the average of the new temperature fluctuation for a similar case *without* PCM. Finally, the third case (PCM^3) aims to assess the minimum amount of PCM strictly needed to cover the energy requirement of the first case. With the assumed latent heat, the first case showed to have more energy storage than that required. So, we reduced the latent heat to consider a new backfill material with different ratio of PCM and soil, until the minimum resulting temperature didn't reach 10°C at the observation point "A". This condition represents the depletion of the PCM latent heat. Beyond that, the system starts to behave like the case *without* PCM.

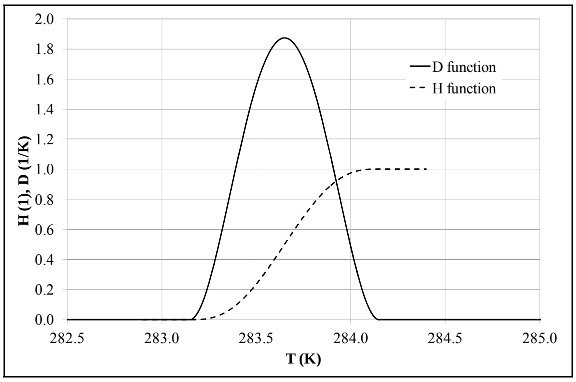

Figure 3: *D and H* functions

To approximate better the PCM behaviour, a relationship between the latent heat and the temperature is introduced in the model as reported in (COMSOL, 2012). For simplicity, we assume that the thermal properties do not differ between solid and liquid, due to the employment of micro-encapsulated PCM. The specific heat capacity C_p has been defined to consider the latent heat of fusion by means of a normalized pulse *D* shown in Fig. 3, expressed in K^{-1}. This correlation represents how the heat transfer rate is related to the temperature. Moreover, *D* is expressed as function of a new dimensionless variable *H*, ranging between 0 and 1 with respect to the temperature, to moderate the switching between solid and liquid (Fig. 3).

3. RESULTS

The simulation period for each case was extended to four days to reach a permanent dynamic equilibrium. The results are presented here by means of two different kinds of graphs, in which the cases are compared in pairs. The first kind of graph shows the time series of the temperature at the observation points. The graph zooms on the time series to appreciate the pulsed operating mode of the GHX (ON/OFF) and its daily cycle. In the second kind of graphs, the difference between the two instantaneous temperatures (IST) of the conditions *with* and *without* PCM, the progressive mean (MED) and the cumulative sum (SUM) of the temperature difference are plotted. The IST value expresses the thermal smoothing obtained by applying the PCM. The MED value has to be considered as average thermal behaviour of the case *with* PCM in comparison with the case *without* PCM. Finally, the SUM value is related to the global energy savings, because it adds all temperature differences, that affect the COP of the GSHP. All data included here are for the system while in operation mode ON.

Three comparisons are presented in the following graphs, as summarized in Tab. 2. In the first comparison, the conditions *with* and *without* PCM are shown adopting a fixed temperature difference of -8°C between the temperature at the point "A" and the working fluid in the GHX. This temperature difference defines the heat flux according to the empirically acquired heat transfer coefficient (25 W/m^{2}K). In the second one, the behaviour of two different combinations between PCMs and heat flux is analysed, by varying the working difference of temperature and the melting point. Finally, the same initial power condition is applied to two PCMs with similar melting points, but different latent heat. In this case, the latent heat is reduced to achieve the depletion of the energy storage for the supposed PCM mass.

Table 2: Identification of the cases

	Temperatures		*Boundary Condition*
Case	*T1*	*T2*	*ΔT*
1	PCM^0	PCM^1	-8K
2	PCM^0	PCM^2	-4K
3	PCM^1	PCM^3	-8K

Fig. 4 displays the first kind of graphs for Case 1. Here, the condition *with* PCM shows temperatures at the GHX surface always higher than the case *without* PCM. It happens due to the effect of latent heat, which is available at the working temperatures. Also the ground temperatures are higher in the situation *with* the PCM. It could be related to the strong recharge effect of the fixed temperature at the bottom, whose impact is more significant on the system owing to the thermal energy storage potential of the PCM. The behaviour is summarized in Fig. 5; the maximum instantaneous difference of temperature between the two situations (IST value) achieves 1.5°C and its average value (MED value) reaches a steady condition of 0.7°C. It means that for the condition *with* PCM, the outlet temperature from the GHX is 0.7°C higher than that *without* PCM.

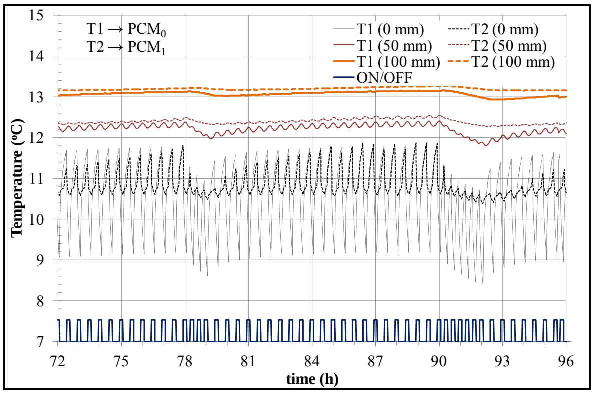

Figure 4: Comparison of instantaneous temperatures for Case 1

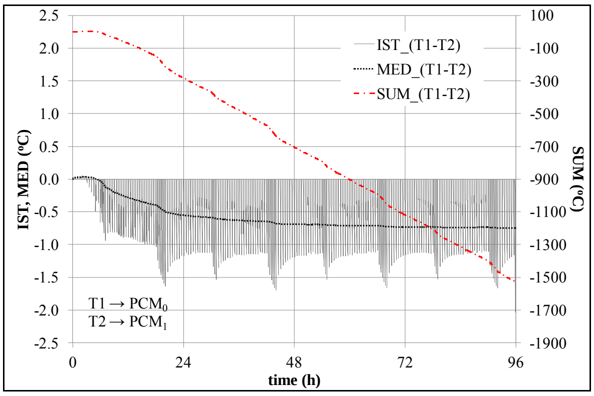

Figure 5: Comparison of temperature differences for Case 1

In Fig. 6, the temperatures of the second case still show that the melting point of the new type of PCM has been selected correctly, according to the different average working temperature of the case *without* PCM (12.5°C). The spread is smaller than in the previous case, while the ground temperatures are higher. It happens due to the lower energy requirement, which is related to the lower difference in temperature required at the GHX. As a consequence, the effect of the PCM is lower and the MED value is halved, in accordance with the new halved power (Fig. 7). Even if this difference doesn't seem remarkable, the cumulative effect on the coefficient of performance of a GSHP would be felt, since the system operates for long periods of time.

Finally, the condition with a lower latent heat is compared with the initial standard condition. As reported in Fig. 8, the value of 50 kJ/kg represents the limit of the latent heat for the present heat transfer case. The temperature at the observation point "A" gets over the melting point only in some instances, when the energy storage is depleted by the specific energy requirement. Thus, the latent heat and/or amount of utilised PCM, which also affects the total latent heat sink volume, are not enough to sustain a continuous IST difference during 96 hours. The material cannot undergo its phase change cycle completely due to improper soil temperature profile, as PCM cannot keep the temperature profile in a fixed interval. The temperature differences summarised in Fig. 9 are very small and should be attributed to few and short working periods when the PCM^3 is depleted.

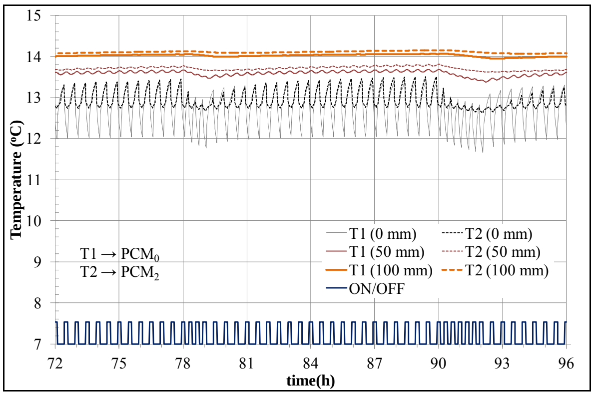

Figure 6: Comparison of instantaneous temperatures for Case 2

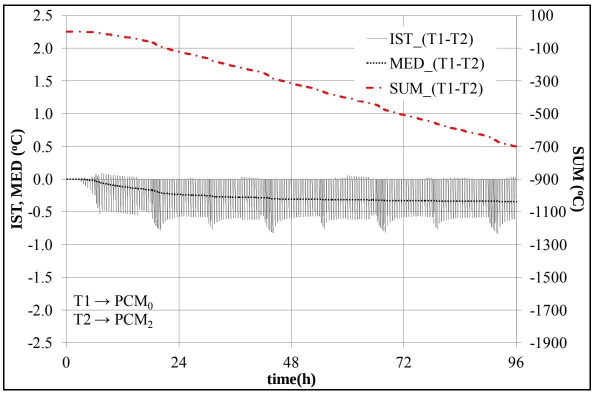

Figure 7: Comparison of temperature differences for Case 2

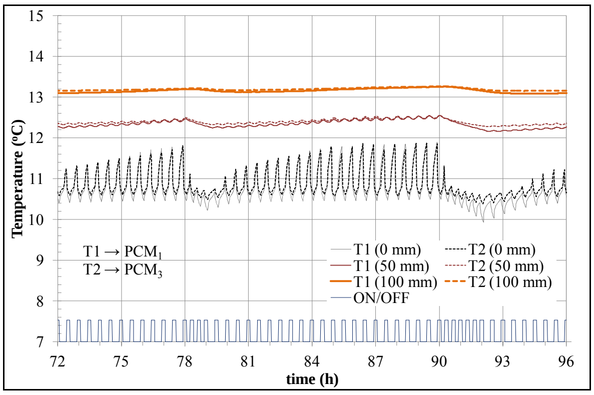

Figure 8: Comparison of instantaneous temperatures for Case 3

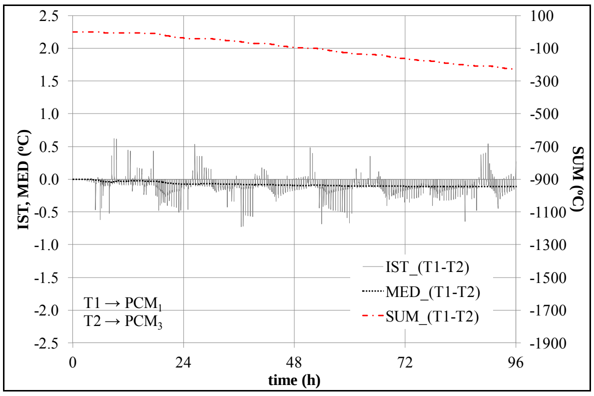

Figure 9: Comparison of temperature differences for Case 3

5. CONCLUSIONS

The coupling between phase change materials (PCMs) and ground heat exchangers (GHXs) has been proposed to analyze the potential energy saving benefits in an unsteady heat transfer problem. The PCMs are assumed to be mixed directly with backfill material close to the GHXs or installed in a proximate surrounding shell. The application is evaluated through numerical modelling to solve the heat transfer in ground carried out by a GHX. The numerical approach is planned to be followed up with an experimental test and thus the domain used in this paper physically represents the actual design of the physical model.

By calibrating the amount and the properties of the PCMs according to the energy requirements assumed at the GHX for the case *without* PCMs, it was possible to balance the energy consumption of the operating time to the heat recovery during the off-time of the GSHP. It was done in thermal steady-state soil conditions. The use of PCMs coupled with GHXs meets the instantaneous heating demand by a ground-source heat pump (GSHP), reducing the sudden cooling wave upon the ground loop coil. As a consequence, the peak temperature was smoothed up by 0.7 K, when compared to the case *without* PCMs. Thus, higher coefficients of performance are expected for GSHPs.

Unlike the evaluated condition, the ground temperature changes continuously in time due to the overall energy balance (deep ground, solar energy, surface convection). Anyway, the potential of PCM would still be significant especially to support the system for late wintertime, when the ground temperature reaches its lowest value and remain so for a long time. The PCM with the appropriate melting point and most economical cost may then be used for the specific purpose.

Moreover, it should be taken into account the new opportunity for horizontal and shallow GHXs. Unlike the vertical and deep borehole, it is normally unsuitable to attempt the underground thermal energy storage (UTES) for shallow GHXs, due to the thermal balancing that occurs seasonally by the weather and sunshine. By adopting PCMs, it is possible to restore the depleted latent heat moving from the wintertime to the summertime, and then to recover the UTES opportunity for shallow GHXs.

Thus, the PCM employment shows two benefits:

- It is able to absorb the thermal shock due to a sudden increase in demand;
- It represents an energy storage that could be sized to preserve the soil thermal depletion (late in wintertime) and whose recharge is carried out naturally in summertime.

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