The 2nd International Energy Storage Conference

SUSTAINABLE ENERGY STORAGE IN BUILDINGS

19-21st June, Trinity College Dublin

Conference Programme

Final Conference of COST Action TU0802: Next generation cost effective phase change materials for increased energy efficiency in renewable energy systems in buildings (NeCoE-PCM)

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The 2nd International Energy Storage Conference

Sustainable Energy Storage in Buildings

Conference Programme

Organised by

Trinity College Dublin and the Solar Energy Society of Ireland

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COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Final Conference of COST Action TU0802: Next generation cost effective phase change materials for increased energy efficiency in renewable energy systems in buildings (NeCoE-PCM)

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Ground-source Heat Pumps: Benefits of using Phase Change Materials

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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 a 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 system is the GHX, 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 [1,2] 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 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 [3,4]. 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. Moreover, the depletion of the latent heat due to the full solidification is regenerated during the summer season, which increases the underground thermal energy storage.

We are currently analysing the performance of a novel GHX design with PCMs by means of an experimental setup and a numerical approach. The latter is presented here.

2. METHODOLOGY

The coupling between a ground heat exchanger (GHX) and PCMs is assumed to occur by mixing the encapsulated PCMs with the soil, and use the mix as a backfill for the trench around the GHX panel. The analysis was carried out by means of a numerical model (COMSOL Multiphysics), implemented in a 2D domain with time-varying boundary conditions to study the temperature distribution in the ground and at the GHX.

2.1 Model domain

The model domain considers a cross section which comprises of a GHX panel, a PCM layer and a wide surrounding soil part. The PCM layer has been described above as a mix of encapsulated PCM and soil in a specified volumetric ratio.

A symmetric approach is applied to the half of the domain in order to reduce the finite elements calculations. The ground heat exchanger was assumed to be a flat-panel that shows high heat transfer capacity, as reported in [5], and it is easy to reproduce it in a 2D approach.

As presented in Fig. 1, the size of the domain is 6 m wide and 6 m deep. The GHX is 1 m high and laid between 1 and 2 m deep. The PCM layer is placed between the surface of the GHX (side *d*) and the soil on the right side (sides *a,b,c*). The thickness of the PCM was assumed to be equal to 0.20 m and the resulting volume for each metre of flat-panel length is 0.20 m^3/m. The dimensions were taken to be similar to those in the field trial, which is under testing at the Dept of Architecture at the University of Ferrara, Italy to compare modelling to experimental results in the near future.

To minimize the numerical errors and to expedite the computation, 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 full mesh is shown in Fig. 1 and it is limited to 15,000 elements to reduce the computational time. Almost 10,000 elements are reserved for the PCM layer, so the resulting grid size is between 0.02 cm^2 for fine grids and 72 cm^2 for coarse grids.

Fig. 1 also shows three measurement points (1, 2, 3), which are placed at 0.1, 0.5 and 1.0 m away from the flat-panel. The first point is inside the PCM layer, while the other points show the temperature of the ground at different distances. In the results, the temperature are presented as single-point values for these points and as average values for the GHX surface (side *d*) and at the PCM-soil interface (sides *b, c & d*).

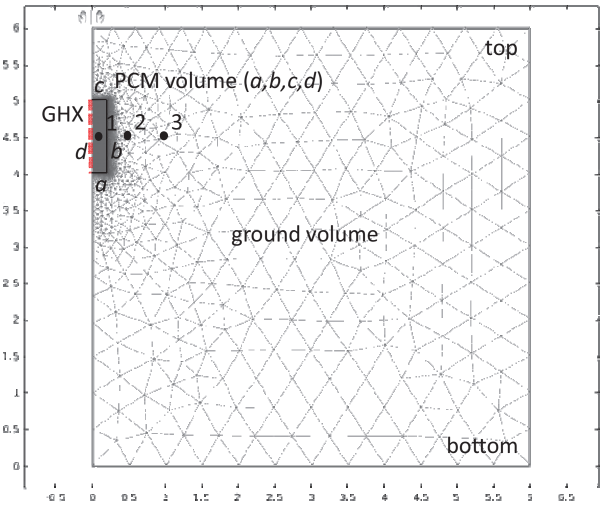

Figure 1: Domain of the one-half symmetric model

2.2 Initial and boundary conditions

Boundary conditions of the 1st and 3rd kind are fixed at the outer domain boundaries as thermal conditions.

At the top and at the bottom of the domain, constant temperatures of 3°C and 14°C, representing undisturbed conditions, are assumed, and the right side of the domain is assumed adiabatic. In order to simulate the thermal behaviour caused by the GSHP, a time varying heat flux was added to the GHX wall (side *d*, Fig.1). The time-series sets the operating mode of the system with a time interval 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^{2}K, as obtained from the experimental test carried out in our laboratory. The fluid temperature is fixed constant by 1.5°C lower than that on the GHX wall. Thus, the resulting power may vary from 0.0 W/m^2 (OFF-mode) to 37.5 W/m^2 (ON-mode). Due to the model symmetry, the GSHP overall power is 75W/m^2, which represents a high value for a horizontal shallow system. The daily ON/OFF-mode time program of the GSHP is shown in Fig.2. The time-dependent model reproduces an energy demand profile that is higher during the night and at noon.

The initial condition of the unsteady state thermal analysis was obtained as a solution of the steady state problem, executed in absence of the GHX activity and starting with an initial overall domain temperature of 14°C.

2.3 Material properties

The 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 layer reserved for the GHX backfill material. For this layer, two cases are considered either by mixing PCM and soil in a volumetric ratio of 25%, or by saturating the supposed soil porosity (40%) with water. In the first case, a microencapsulated organic PCM is considered as model which does no harm to environment by chemical and physical means. In the second case, the water is assumed as PCM with regards to the temperature of the GHX working fluid, which operates close to 0°C. The generalized thermal properties of the studied model organic PCM are defined according to the presented thermal data of fatty acid ester based PCMs in [2,6] and for water and ice, they are taken from [7] in literature. The values of latent heat (h_{sl}), melting point (T_m), density (ρ), specific heat (Cp) and heat conductivity (λ) for the materials are summarised in Tab. 1.

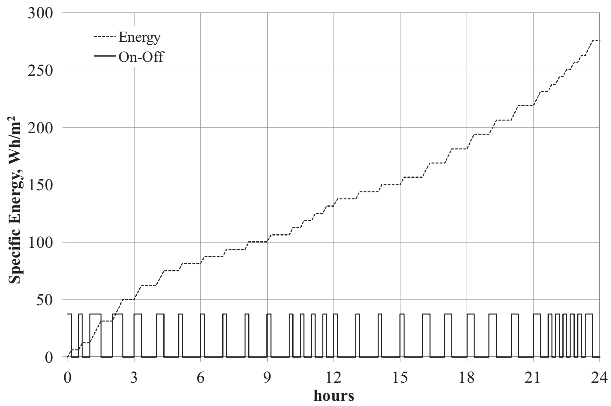

Figure 2: Daily ON/OFF time program of the GSHP

Table 1 Materials properties.

	h_{SL} (kJ/kg)	T_m (K)	ρ (kg/m^3)	Cp (kJ/kgK)	λ (W/mK)
Soil	-	-	1600	1400	1.60
PCM^S	214	273±1.5	1105	1400	0.17
PCM^L	214	273±1.5	1013	1780	0.17
Water^L	334	273±1.0	997	4230	0.57
Ice^S	334	273±1.0	920	2040	1.88

^{S} solid phase, ^{L} liquid phase

To control the phase change, a relationship between the latent heat and the temperature is introduced in the model as an evolution of the method reported in [8].

In the original method, the specific heat capacity Cp is defined to consider the latent heat of fusion by means of a normalized pulse *D(T)*, shown in Fig.3, expressed in K^{-1}. Moreover, the phase change between liquid and solid is expressed as function of a dimensionless variable *H(T)*, ranging between 0 and 1 with respect to the temperature ($T_m \pm \Delta T$), to moderate the switching between solid and liquid. Especially, *H(T)* is ratio of the PCM liquid phase.

The modification of the original method is carried out by introducing the COMSOL routine named Heat Transfer in Porous Media, which performs the heat conduction in a porous media, taking into account the soil porosity and the presence of a liquid. Here, the solid matter of the porous media is considered as a mix between soil and PCM, in accordance with the volumetric ratio *r*. Thus, for the solid and liquid phases, the specific heat may be defined as follows:

$$C_S(T) = (1-r)\cdot C_S^t + r\cdot(1-H(T))\cdot\left(C_S^{psm} + h_{SL}D(T)\right) \quad (1)$$

$$C_L(T) = C_L^{pcm} + h_{SL}D(T) \quad (2)$$

where C_S and C_L are the specific heat of the solid and liquid matter composing the porous media, in relation with the specific heat of soil (C_S^t) and the PCM (C_S^{pcm}, C_L^{pcm}).

Finally, the overall specific heat of the mixed backfill material is obtained by the model as a weighted average of the total liquid and solid mass. Unlike the specific heat, a weighted average of the volumetric ratio between liquid and solid is carried out to calculate the thermal conductivity.

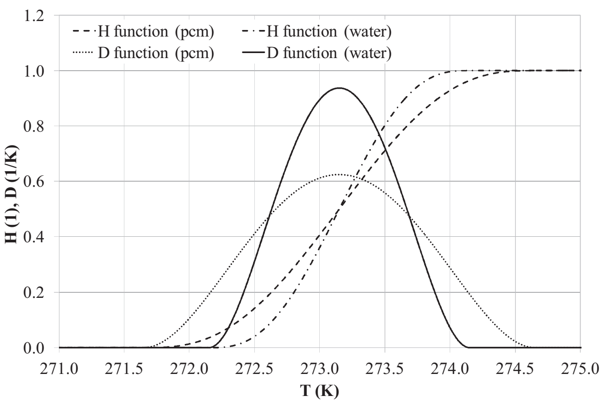

Figure 3: D(T) & H(T) functions for PCM and water

3. RESULTS

The simulation period for the two considered cases was extended to 60 days in unsteady state conditions, which almost represents a permanent dynamic equilibrium for the case without PCM.

The results are here presented mainly by means of two different kinds of graphs, in which the PCM cases are compared with the case of pure soil only, for each scenario. The graph of first kind shows the time series of the temperature at the observation points. For the graph of second kind, the time series of the flux at the boundaries of the PCM layer (sides *a, b,* c) are compared in presence of the difference of the temperature at the GHX wall (side *d*).

Fig. 4 displays the first kind of graphs for the case with and without PCM. Here, the condition with PCM shows temperatures at the GHX surface that are moderately higher than the case without PCM, but clearly with a more smoothed oscillation. It happens due to the effect of latent heat, which is available at the working temperatures, at least for the first month. Also the ground temperatures at the points 1, 2, 3 are higher in the situation with the PCM, because the energy requirement is partially covered by the latent heat and the ground is less involved in the heat transfer as thermal source.

The previous remarks are even clearer in Fig. 5, which reports the second kind graph, which is the trend of heat fluxes together with the difference of temperature at the GHX wall (side *d*). After 10 days, the heat flux at sides *a, b,* c of the model without PCM reaches an equilibrium average value of 20 W/m. In the case with the adopted PCM, the heat flux from the ground reaches similar values only after 60 days, when the PCM is fully solidified. At this time, the integration of the difference between the heat flux at the GHX (side *d*) and at the boundaries of the PCM layer (sides *a, b, c*) is equal to 11 MJ, which represents the overall latent heat of the amount of PCM mixed with the soil. The average temperature difference between the two models (with and without PCM) is 0.7°C during the first 30 days, then drops down due to the diffuse solidification of the PCM close to the GHX. Moreover, because the PCM has a lower thermal conductivity in comparison with the soil, the solidification induces a lower temperature at the GHX wall in comparison with the model without PCM. Thus, the temperature difference becomes negative after the 40th day.

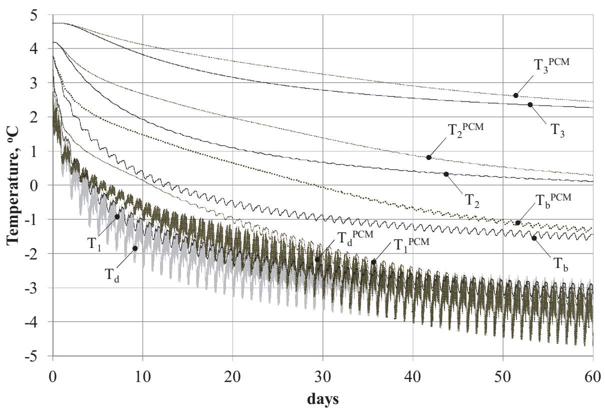

Figure 4: Ground vs. PCM: comparison of temperatures

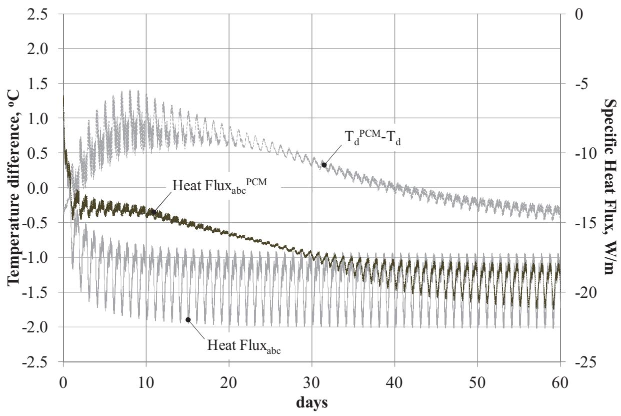

Figure 5: Ground vs. PCM: comparison of heat fluxes

In Fig. 6, the temperatures of the second scenario show the remarkable effect of the supposed PCM, which in this case is water. The thermal properties of water are better than those of the previous PCM, and also the amount is larger (40% vs. 25%). Especially, the latent heat is almost twice (334 vs. 214 kJ/kgK) and the thermal conductivity is higher both for the solid (1.88 W/mK) and liquid phases (0.57 W/mK) when compared to the former PCM (0.17 W/mK). As a result, it improves the thermal behaviour of the system and does not deplete its functionality during the simulation time.

In Fig. 7, the heat fluxes of the two models are clearly different; in the first month, the soil heat flux is almost halved in the saturated soil in comparison with the natural soil. As a consequence, the temperature difference of 1.5°C persists for 60 days on average. Even if this difference doesn't seem remarkable, the cumulative effect on the coefficient of performance of a GSHP would be useful, since the system operates for two months. But still more interesting is the remark that the system works for long around -1°C, protected by the thermal behaviour of the saturated soil.

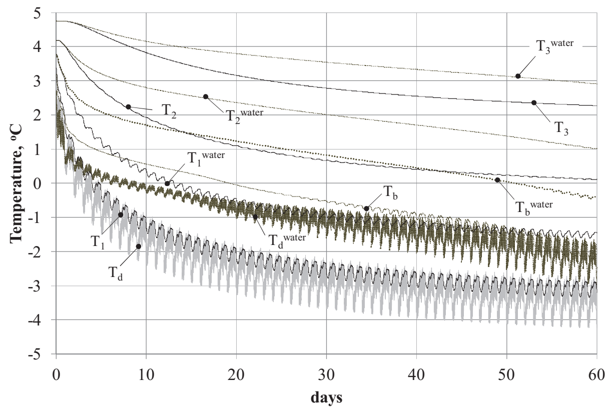

Figure 6: Ground vs. Water: comparison of temperatures

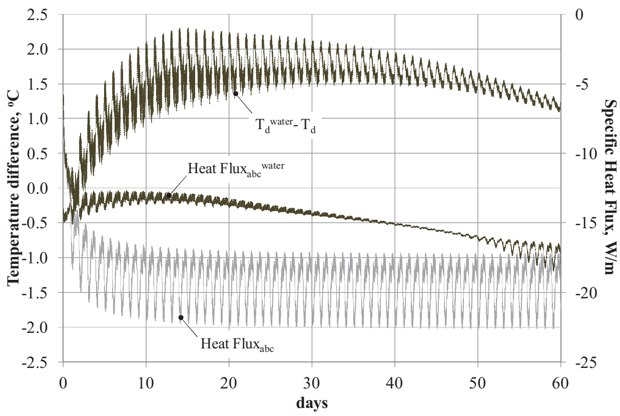

Figure 7: Ground vs. Water: comparison of heat fluxes

Fig.8 shows a comparison between the evolution of the solid-liquid interface in the PCM layer for the two considered cases, in five time steps. Since the phase change has been assumed as controlled by the function H, the interface is not a single boundary, but multiple zones located between the H values of 0 and 1. So, on the right side of the value 0, only the liquid phase is present in the layer, and on the left of the value 1, only the solid phase. The shape of the interface is justified by the major impact of the GHX at its middle, moderately deformed toward the top, in accordance with the overall temperature distribution in the model, given that it is cooler at the top and warmer at the bottom of the domain.

Finally, in Fig.9 the cumulative energy extracted by the GHX at the side *d* of the PCM layer is shown, together with its equivalent specific heat that takes into account the latent heat. For the energy evaluation, the average temperature on the GHX wall (side *d*) is considered. The comparison of the performances between the PCM and water is self-evident. The better thermal properties of water in comparison with the supposed PCM, allows an energy exchange only related to the heat latent that is almost three times higher, as expressed also from the equivalent specific heat.

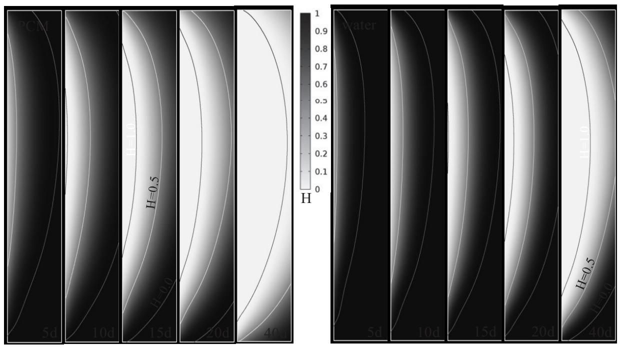

Figure 8: Solid-liquid interface at the PCM-water layer

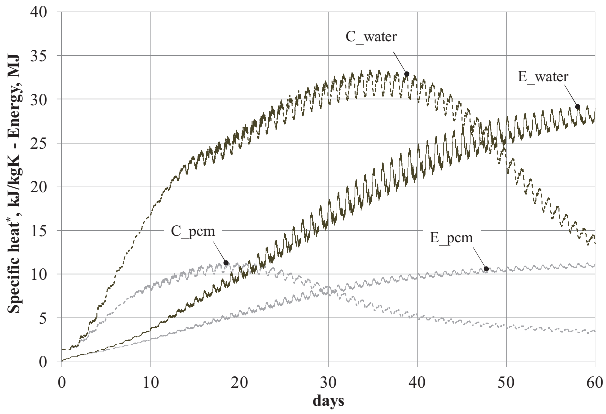

Figure 9: Equivalent specific heat and heat latent (PCM vs. water)

4. 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 encapsulated 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 porous media 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 trial field.

Unlike the evaluated condition, the ground temperature changes continuously with time due to the overall energy balance (deep ground, solar energy, and 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. When the melting point is around 0°C, water is certainly the better solution, because of its high thermal properties, in terms of specific heat and thermal conductivity, also in its solid state. Moreover, water is cheap, does not represent an environmental risk and the soil saturation is achievable with an ordinary drainage system disposal in the trench and linked to a downpipe, if the groundwater table was too deep.

Also 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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