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Title: "Heat transfer analysis of underground thermal energy storage in shallow trenches filled with encapsulated phase change materials",
Authors: Michele Bottarelli, Marco Bortoloni, Yuehong Su

Reference: Major Revisions to a previous version of the manuscript

Dear Editor,
We thank you and the Reviewer for your time and effort in evaluating and processing our manuscript.
We enclose a revised version incorporating all the changes suggested by the Reviewer and also our response to the Reviewer's comments.

Best regards

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31st March, 2015

Subject: Response to Reviewer
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Dear Sir/Madame,
We thank you for your effort in evaluating our manuscript.
The language has been revised according to the recommendation.
Some sentences have been modified as suggested.
Furthermore, all figures have been updated and Fig. 2 and Fig. 11 have been modified as recommended.
Best regards

Michele Bottarelli
Corresponding Author

Highlights

1. A drainage trench is studied as ground heat exchanger of a GCHP.
2. The trench is backfilled with encapsulated phase change materials (PCMs).
3. The heat transfer and fluid flow are solved in 2D via a numerical code.
4. More favourable working conditions are achievable for the heat pump using PCMs.
5. Adopting PCMs it is possible to make underground thermal energy storage for HGHE.

Heat transfer analysis of underground thermal energy storage in shallow trenches filled with encapsulated phase change materials

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ABSTRACT

The use of a horizontal ground heat exchanger may represent a reliable and cost effective option for ground-source thermal applications. This study presents the thermal performance analysis of a drainage trench used as ground heat exchanger (GHE) coupled with underground thermal energy storage (UTES). The trench is dug in shallow soil and filled with encapsulated phase change materials (PCMs) as granular filler. Two types of PCMs with different melting points are supposed to operate in summer and winter. Fluid flow and heat transfer in porous media are solved via a 2D finite element model to perform a yearly simulation under hourly-scale boundary conditions. The equivalent heat capacity approach is applied to consider the latent heat of the PCMs. The results show a significant capacity of the trench to smooth thermal waves produced by the heat pump. The effect of the PCMs is analysed by comparing with the corresponding case using coarse gravel as filling material instead of PCMs. The case without PCMs still shows good performance, but PCMs offers the advantages of a seasonal UTES and smoothing thermal wave as well. The proposed solution can be therefore considered as an advanced alternative to other widespread common GHEs.

KEYWORDS: *Phase change materials, Porous media, Numerical simulation, Ground heat exchanger, Underground thermal energy storage*

1 INTRODUCTION

The European policies for buildings energy saving and greenhouse gas emissions reduction widely supports the spread of renewable energy sources. Ground-source heat pumps (GSHPs) are regarded as a sustainable energy technology for space heating and cooling in commercial, industrial and residential buildings, as well as a profitable solution due to their high energy efficiency [1,2]. GSHPs exploit geothermal energy by means of ground heat exchangers, which can be installed vertically as boreholes (VGHEs) heat exchangers or horizontally (HGHEs) as a loop placed in shallow diggings a few meters deep in soil. VGHEs exploit a relatively steady and profitable geothermal source/sink, while HGHEs use unsteady heat source/sink, owing to seasonal shallow energy balance. The seasonal variation of the soil temperature can lead to unfavourable working conditions and, consequently, to an efficiency reduction. Nevertheless, the close dependence on environmental conditions avoids ground thermal drifts after long-term operation for shallow HGHEs [3]. As a consequence underground thermal energy storage using soil or gravel only is difficult to realise. Moreover, the ground thermal response is much slower than the heat pump requirement due to the low thermal diffusivity of the soil. This may cause a lower coefficient of performance of the GSHPs, because the heat pump has to decrease its operating temperature in time to deliver the same amount of heat. Employing PCMs is an effective measure to store thermal energy [4, 5] and it might be considered as an effective method to smooth the thermal wave generated from operation of a GSHP. Mixing of PCMs directly with backfill material, which is close to the GHEs or to install them in a surrounding shell, has been proposed in our previous studies [6, 7]. Use of the PCMs incorporated with GHEs may meet some instantaneous heating demand by a GSHP, thus reducing the sudden heating or cooling thermal wave upon the ground. Therefore, the peak temperature would be lower for the same length GHE, or the length of GHE could be shortened for the same peak temperature. In a cooling operation, the depletion of the latent heat due to the full solidification is regenerated during the summer season, which increases the underground thermal energy storage.
To improve the efficiency of a GHE, some new arrangements for the widespread slinky-coils installation and novel shapes of HGHEs have been proposed recently adopting plate exchangers [8, 9], due to their larger heat transfer surface. In order to enhance the above-mentioned features of HGHEs, a drainage trench is here proposed as an alternative to the flat-panel and in coupling with PCMs as evolution of a forthcoming work of Bottarelli, Di Federico and Fujii [10]. The trench is supposed to be dug in shallow soil and filled with encapsulated PCMs as granular filler with high hydraulic conductivity. Two horizontal pipes at the top and bottom of the trench act as inlet and outlet of the working fluid (water) that flows into the closed-loop of a system for heating/cooling of a residential building. The possible leakage of water in the surrounding ground may be reduced by means of waterproof geosynthetic membranes. Two different PCMs with different melting points are supposed mixed and filled in the trench, to operate in summer and winter. The fluid-flow and heat transfer in the porous media within the trench and in the surrounding soil are analysed via a 2D finite element model to perform a yearly simulation. Hourly time series are adopted as boundary conditions in order to consider the shallow energy balance at the ground surface and the energy requirement at the GHE. The approach of the equivalent heat capacity is employed to consider the latent heat of the PCMs.

2 METHODS

The energy performance of a drainage trench heat exchanger vertically dug in the shallow ground and filled with encapsulated PCMs is analysed. For comparison, the GHE performance is also evaluated with coarse gravel instead of PCMs as filling material. The commercial numerical finite element code COMSOL Multiphysics V.4.4® is used for the calculations in unsteady-state. The Darcy's law and heat transfer in porous media modules are both applied jointly to simulate the groundwater flow through interstices in saturated conditions and to model heat transfer by conduction and convection within the porous media. The differential equations solved by the code are available in COMSOL. The Darcy's law COMSOL module combines Darcy's law with the continuity equation [11], so the resulting equation is solved in the trench part of the calculation domain.

The Darcy's law is suitable for this case study, since the pressure gradient is the major driving force for the fluid flow. The dependency of fluid density on the temperature is taken into account in the Darcy's law as shown in Eq.1 which states that the velocity field is determined by the pressure gradient and the structure of the porous medium:

$$\mathbf{u} = -\frac{K}{\rho g}\left(\nabla p + \rho g \nabla D\right) \tag{1}$$

Where K is the hydraulic conductivity (m/s), ρ the density (kg/m^3), p the pressure (Pa), g the acceleration of gravity (m/s^2), D the elevation head and ∇ is the partial derivative operator which defines the gradient of a quantity in space. Only conduction is solved for the remaining part of the domain, which is outside the trench and considered as a homogeneous and isotropic solid. The convection-diffusion equation solved for the porous media in the trench employs the thermo-physical properties averaging model to account for both solid matrix and fluid part within the trench, according to the following Eq.2 and Eq.3:

$$\left(\rho c_p\right)_{eq} = \theta_p \rho_s c_{p,s} + \left(1-\theta_p\right)\rho_l c_{p,l} \tag{2}$$

$$k_{eq} = \theta_p k_s + \left(1-\theta_p\right)k_l \tag{3}$$

where θ_p is the solid volume fraction, $(\rho c_p)_{eq}$ and k_{eq} are the equivalent heat capacity and heat conductivity of porous media, which are calculated respectively as the mass and volume weighted average between the solid (s subscript) and the water properties (l subscript), according to the temperature.

The coupling between the GHE and PCMs is here assumed to occur by using encapsulated paraffin as a backfill for the trench. The solid matter of the porous matrix is thus a mix of two different PCMs, in accordance with the respective mass ratio r_i supposed between each PCM. The first one, PCM_{WIN} (heating season in winter), is needed to prevent the energy exploitation at low temperature and the freezing of the working fluid, whereas the second one, PCM_{SUM} (cooling season in summer), is required for high temperature.

The equivalent overall density ρ_s, thermal conductivity k_s and specific heat capacity $c_{p,s}$ of the mixed backfill material are then obtained as a mass weighted average of the total liquid and solid mass related to the temperature. In addition, the latent heat of fusion is considered in $c_{p,s}$. In the following Eq.4, Eq.5 and Eq.6 the properties of solid are defined with evidence of the variables:

$$\rho_s = \sum_{i=1}^{n} r_i \cdot \left(1 - H_i(T)\right) \cdot \rho_i^S + \sum_{i=1}^{n} r_i \cdot \rho_i^L \cdot H_i(T) \tag{4}$$

$$\lambda_s = \sum_{i=1}^{n} r_i \cdot \left(1 - H_i\right) \cdot \lambda_i^S + \sum_{i=1}^{n} r_i \cdot H_i(T) \cdot \lambda_i^L \tag{5}$$

$$c_{p,s} = \sum_{i=1}^{n} r_i \cdot \left(1 - H_i(T)\right) \cdot \left(c_i^S + h_i^{SL} \cdot D_i(T)\right) + \sum_{i=1}^{n} r_i \cdot H_i(T) \cdot \left(c_1^L + h_i^{SL} \cdot D_i(T)\right) \tag{6}$$

where the functions $H_i(T)$ and $D_i(T)$ are introduced to control and drive the thermo-physical properties of each PCM during the phase change, as an evolution of what is reported in [12]. In the cited work, the PCM problem was numerically approached as simply porous media, which was composed by the two phases of the same material (solid, liquid). The specific heat capacity c_p 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}) were expressed in [10] 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 and changing around the melting point ($T_m \pm \Delta T$). These functions were introduced to moderate the switching between solid ($H(T_m-\Delta T)=0$) and liquid phase ($H(T_m+\Delta T)=1$).

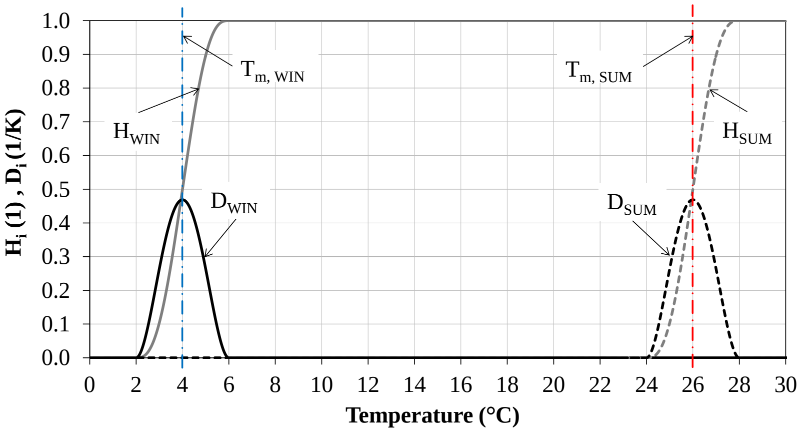

Fig. 1 D_i & H_i functions defining the phase change of the PCM_{WIN} (winter) and PCM_{SUM} (summer).

Here, two different PCMs are considered. As consequence, two different functions $H_i(T)$ are assumed as mass ratio of each specific PCMs, and similarly two different functions $D_i(T)$, in variation of [12] where the same functions were related to the volumetric fraction. The $H_i(T)$ and $D_i(T)$ functions for PCM_{WIN} and PCM_{SUM} are reported in Fig.1, with evidence of their melting points $T_{m,\,WIN}$ and $T_{m,SUM}$.

2.1 Model Domain

The numerical model is solved within a 2D domain consisting in a cross section which comprises the trench GHE and a wide surrounding soil part. The GHE is constituted by a drainage trench filled with spheres of encapsulated PCMs as granular filler through which the working fluid (water) of the closed-loop is flowing. The trench GHE is 1.2 m high and 0.3 m wide; it is installed from a 1.3 m to a 2.5 m depth. An impermeable layer surrounds the trench to prevent the discharge of working fluid. Two horizontal pipes at the top and bottom of the trench serve as fluid inlet and outlet. The drainage pipes have a diameter of 10 cm and are positioned 1.45 m and 2.35 m deep respectively. A symmetric approach is applied to the half of the domain in order to reduce the calculation time. The computational domain is sufficiently large to have an undisturbed boundary due to the system operation, and it is thus 10 m wide and 10 m deep, as shown in Fig.2.

Fig.2 also shows the full mesh and a mesh detail off the trench. It is composed by up to 18,500 triangular elements. To reduce the computational time and the numerical errors, the grid size is dense within the trench at the ground surface, coarse for the remaining surrounding soil. Almost 8,500 elements are reserved for the trench so the resulting triangular element size is between 0.039 cm^2 for fine grids and 0.027 m^2 for coarse grids.

The temperature of the working fluid is calculated at the inlet and outlet. Moreover, the ground temperatures for some specific points are calculated at the GHE average depth. The independency of results from grid size was checked by doubling the number of mesh elements; no significant differences were observed between the calculated temperatures at selected observation nodes.

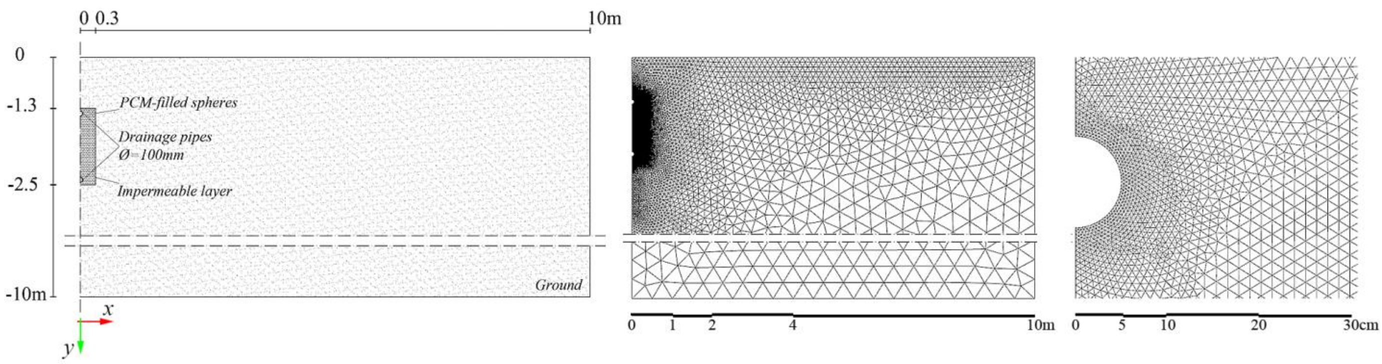

Fig. 2 Sketch of the symmetric model domain and of the mesh.

2.2 Initial condition

The initial condition of the unsteady state analysis is obtained by carrying out simulations in absence of the GHE activity and starting with an initial uniform domain temperature of 15°C. The initial average temperature value is equal to yearly average of the time series of outdoor air temperature, here conceptualized as a sinusoidal trend, representing the daily temperature variation during a whole year as detailed in [8, 9]. No evidence of thermal drift was highlighted after the 2nd year of simulation and thus this solution was assumed as initial condition.

2.3 Boundary conditions for ground surface and soil

Boundary conditions of the 1st and 2nd kind are fixed at the outer domain boundaries as thermal and hydraulic conditions for solving the numerical problem. A temperature of 15°C, equal to the average air temperature of the whole year, is considered at the boundary at the bottom. The right-hand side of the domain is assumed adiabatic while a condition of symmetry is applied on the left-hand side.
An hourly time varying heat flux is imposed as thermal conditions at the soil surface to reproduce the shallow energy balance. The time series represents the net amount of solar heat transferred to soil. The ground surface heat flux is obtained as an indirect solution from a preliminary simulation of the model without any GHE activity, since not enough data were available to provide a more detailed estimate of the surface energy balance. In this simulation, a soil temperature hourly time series is imposed at the soil surface. This is obtained from the sinusoidal time series of the air temperature adopted for the previous analysis by means of a reduction factor set equal to 0.6. The factor value is chosen in accordance to the temperatures monitored at the soil surface in a trial field operating at the Department of Architecture of Ferrara University. The daily averaged temperature at the ground surface and the corresponding hourly heat flux are shown in Fig.3. For the considered temperature time series, the resulting values of heat flux vary from +60 W/m^2 and -48W/m^2.

2.4 Boundary conditions on the GHE

To define an hourly energy requirement in heating and cooling mode the methodology reported in [8, 9] is applied, where the energy requirement of a hypothetical building is linked to the previous air temperature time series. The building is simplified in a lumped system, and its energy variation occurs owing to the heat transfer through its envelope. The system is set in heating mode from October 15th to May 15th, and in cooling mode from May 15th to October 15th. Within these time intervals and according to a fixed time schedule, the system can be turned on if necessary to reach the target indoor temperature, set at 20 °C in winter and 25 °C in summer. The GSHP operation scheduling is created to represent typical working conditions for a residential building in a mild climate: 5 – 9 am and 4 – 11 pm during working days, and 7 am – 12 pm on the weekends. Moreover, it is defined the overall energy requirements for heating and cooling.
To relate the building energy requirements to the GHE, a water mass flow rate ($\dot{m}$) is calculated with Eq.7, assuming a difference of 1°C (ΔT) between the inflow and outflow water temperature, the specific heat capacity of water reported in Tab.1 (c_w) and a power of 40 W/m for each meter trench when the system is turned on.

$$\dot{m}_w(t) = \frac{\dot{Q}(t)}{c_w \Delta T} \tag{7}$$

The resulting flow rate is 0.095 kg/s, chosen in accordance to the mass flow rate measured in the abovementioned trial field in Ferrara. This is halved owing to the symmetry of the domain and applied at the outlet according to the previous switching on/off time series. The target difference ΔT between inflow and outflow temperatures becomes the thermal boundary condition at the GHE when the working fluid is flowing within the trench. The hourly scale time series for the power switching on/off at the GHE is thus obtained as shown in Fig.4 in a weekly detail. Generally, the total amount of thermal energy extracted during the heating season is 54.5 kWh for one meter long trench, that rejected to the soil in summer 27.7 kWh/m. The number of hours in heating operation is 2750, while 1474 hours in cooling. Finally, a pressure head is applied as hydraulic condition at the inlet to consider the saturation of the trench. No mass flow is allowed through the boundary of the trench.

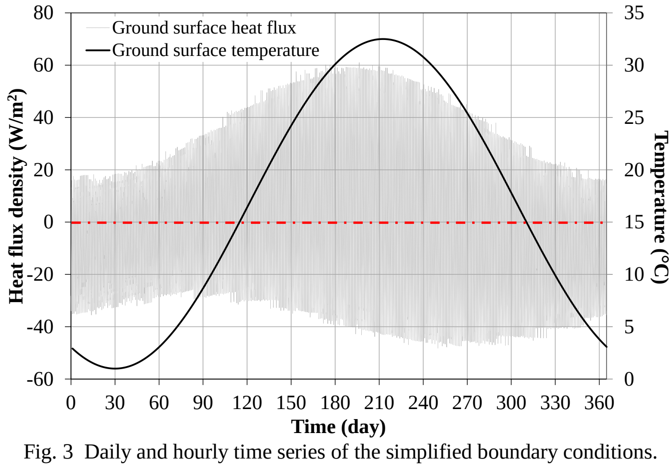

Fig. 3 Daily and hourly time series of the simplified boundary conditions.

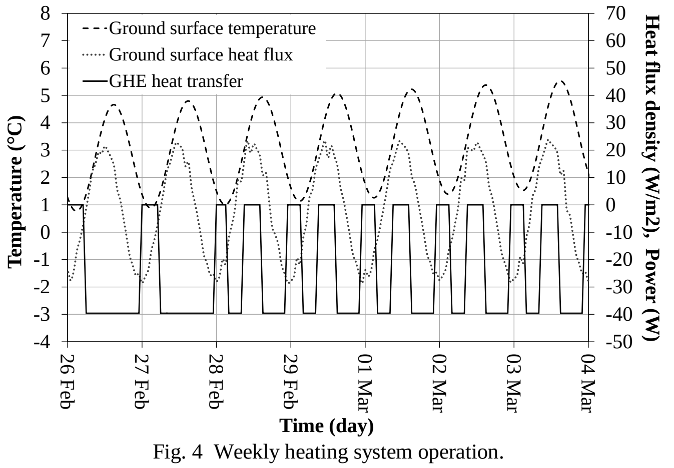

Fig. 4 Weekly heating system operation.

2.5 Material Properties

The model domain consists of different materials: a porous medium as backfill material within the trench, water as working fluid and the soil outside the trench. For simplicity the soil is taken as homogeneous and solid, so mean thermal properties are considered. This assumption is commonly used in literature for the purpose of modelling HGHEs. Even though heterogeneity of shallow soil affects the results, the impact can be considered negligible, as reported in [13]. The thermo-physical properties of the water are assumed variable with temperature, so natural convection are expected within the porous medium due to density variations of the working fluid. The trench granular filler material is a mix of encapsulated phase change materials with a porosity of 40%, in accordance with the respective mass ratio r_i. Thus, the 65% of solid matter is made up of PCM_{WIN} (melting point 4°C), the remaining 35% by PCM_{SUM} (melting point 26°C).
The micro-encapsulated solution is here considered as a material that causes no chemical or physical harm to the environment. The generalized thermal properties of PCMs are defined according to the thermal data of fatty acid ester based PCMs in [14, 15].
For simplicity, the two PCMs have the same thermo-physical properties, which are assumed constant at the phase change. In particular, assuming that the density of each PCM does not change between the solid and liquid phase allows avoid the moving mesh method which should be introduced to ensure the mass conservation when density variations occur in phase change. This inaccuracy should not affect much, because the thermal problem is focused on the high latent heat. In the case without PCM, the paraffin microspheres are replaced by coarse gravel having the same porosity and hydraulic conductivity. Finally, the soil outside the trench is taken to be sandy loam. All hydraulic and thermo-physical properties of materials are taken from the UNI-11466, the recent Italian standard regulation about geothermal heat pump systems (2012).
The values of density (ρ), specific heat capacity (c_p), heat conductivity (k), latent heat (h_{sl}), temperature of melting (T_m) and hydraulic conductivity (K) adopted for the materials are summarised in Table 1 and Table 2.

Tab. 1 Thermophysical properties of materials.

	h^{sl} (kJ/kg)	T_m (K)	ρ (kg/m^3)	c (J/kgK)	k (W/mK)	r_i (%)	*Note*
$Soil^{domain}$	-	-	1800	1200	1.00	-	soil outside the trench
PCM_W	150	278±2.0	790	2200	0.21	(60)	PCM for winter
PCM_S	150	298±2.0	790	2200	0.21	(40)	PCM for summer
Gravel	-	-	2200	840	2.3	-	
Water	-	-	1000	4230	0.57	-	

Tab. 2 Hydraulic properties of materials.

Material	Hydraulic conductivity, K (m s^{-1})	Porosity, n (%)
Backfill material[1]	*1.0 x 10^{-2}*	*0.40*
$Soil^{domain}$	-	-

[1] *Mixture of gravel, PCM_{SUM} and PCM_{WIN}*

3 RESULTS

The purpose of the analysis is to evaluate the performance of a drainage trench as ground heat exchanger in coupling with phase change materials. In order to assess the effect of PCMs on the working fluid temperature and on the thermal field of the ground around the heat exchanger, the results are compared with those of an equivalent GHE filled with coarse gravel. Numerical simulations are conducted for 2 years for both cases to check the stability of the solution. In fact, since the heat flux applied as a boundary condition at the ground surface is obtained from a previous simulation with a temperature time series and in the absence of GHE, a condition of thermal imbalance can occur when the GHE is considered. As a consequence, it should be expected a final thermal field different from the case without a trench GHE. Here, even a minor temperature drift is detected, but this is almost constant between the two consecutive simulations, so a stationary trend is achieved.
According to the simplifications and assumptions considered, the results are presented in terms of temperature and energy for the boundary conditions considered. The temperatures of the working fluid at the inlet and outlet of the GHE are evaluated. Moreover, the temperatures within the drainage trench and the surrounding soil were analysed by means of probes, placed at the average depth of the heat exchanger (-1.75 m) and at various distances from the axis of symmetry. In relation to the temperature of the trench, is thus described the phase change for the two PCMs. The energy saving allowed by the use of the PCMs is estimated in comparison to the case of the trench filled with gravel, in relation to the respective temperature of the working fluid leaving the GHE. Finally, the Darcy's velocity field and the temperature field are evaluated in the model domains.
The resulting hourly time series of temperature for the two cases simulated, with (PCM) and without (G), are shown in the following Fig.5 and Fig.6. The evaluation is done for a whole year, from the beginning of the heating season set at 15th October. The inlet temperature curves in the PCM and G cases are the temperature of the water flowing into the trench, measured at the upper pipe boundary; the other three curves show the temperature at the trench average depth, 0.3, 1.0 and 10.0 meters far from the GHE centre.

In the first three months of heating period, the resulting inlet temperature is lower by 0.45 K on average in the case PCM in comparison with the case with coarse gravel, due to the lower thermal diffusivity of PCMs. After this time interval the inlet temperature drops below 7°C, activating the phase change and reversing the trend. In the following two months the GHE with the PCM operates always at a higher temperature, with a maximum difference of 1.7 K. For over a month the difference is higher than 1 K, so the heat pump operates in more favourable working conditions and a better efficiency is achieved. At the end of the heating season, the availability of energy in the form of latent heat is nearly exhausted, and the inlet temperature is equivalent between the two cases. Furthermore, the natural rising of the soil temperature due to the external environmental conditions is delayed by the subsequent PCM re-liquefaction. Regarding the temperature at the point (0.3;-1.75 m), placed at the outer limit of the trench, it is observed that it is higher in the case PCM than the case G. In the latter case the temperature at that point is close to that of the working fluid, on the contrary an average difference of 0.9 K is detectable in the PCM case with lower oscillations within the phase change interval. Indeed, the encapsulated PCM has a lower thermal conductivity than the gravel, so the working fluid has a minor effect on the temperature in the remote areas of the trench, where the heat transfer is mainly conductive. However, when the phase change is in progress, the thermal wave generated from operation of the GHE is dampened as highlighted by the temperature time series at the point 1 meter away from the trench. For more than 90 days the temperature is higher than in the case G. Finally, there are no differences of temperature between the two cases 10 meters away from the GHE, because the energy exploitation made by the heat exchanger isn't detectable at this distance.
The behaviour is similar in summer, when the GSHP system operates in cooling mode. However, in the first 25 days of operation the PCM case benefits from the lower initial temperature due to the energy exploitation made in winter. Afterwards, the effect of PCM is clearly visible for 45 days in which the inlet temperature is 0.5 K lower than the case G on average, with a maximum difference of 1.1 K. Moreover, a maximum temperature of about 27.7°C is reached in the case G, unlike that of the case with PCM which does not go over 26.7°C and about 10 days delay. For both cases, a reduced thermal drift of 0.4 K is identified at the end of the period as specified previously in the text.
Fig.7 and Fig.8 show the resulting weekly time series of the inlet and outlet temperature for both cases. The week is chosen in the second half of February, when the temperature of the working fluid is around values in which the phase change occurs and therefore the difference is the maximum between the two cases. The case PCM shows that the inlet temperature is higher by up to 1.5 K than the case G with gravel, and the heat pump can consequently work in more favourable conditions in the first case. Moreover, when the system is working and the water is circulating through the trench, its temperature is relatively stable in the first case. On the contrary, the temperature of working fluid decreases during operation intervals without PCMs, so the heat pump is forced to follow the negative trend, although there is a recovery when the system is turned off.

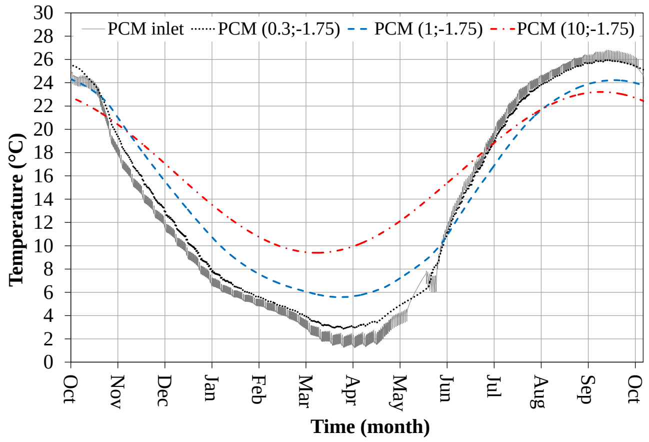

Fig. 5 Time series of temperature for a whole year with phase change materials (PCM)

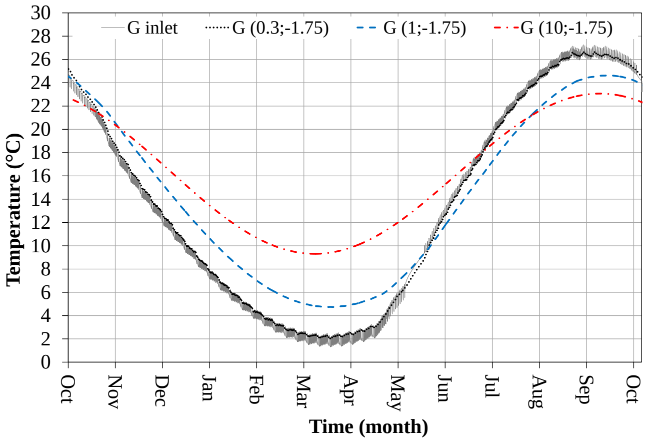

Fig. 6 Time series of temperature for a whole year with gravel (G)

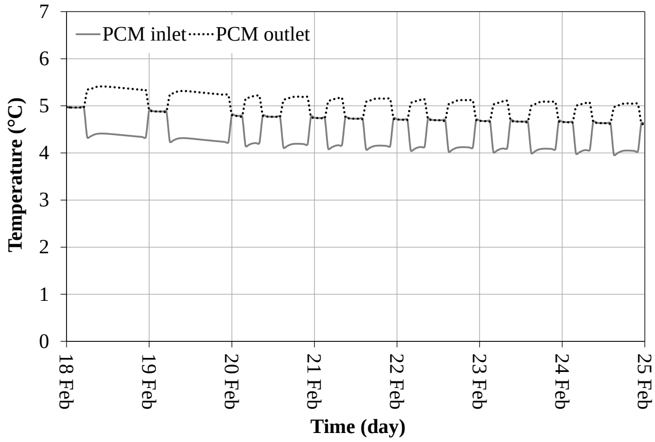

Fig. 7 Time series of temperature at inlet and outlet temperature for a week (PCM)

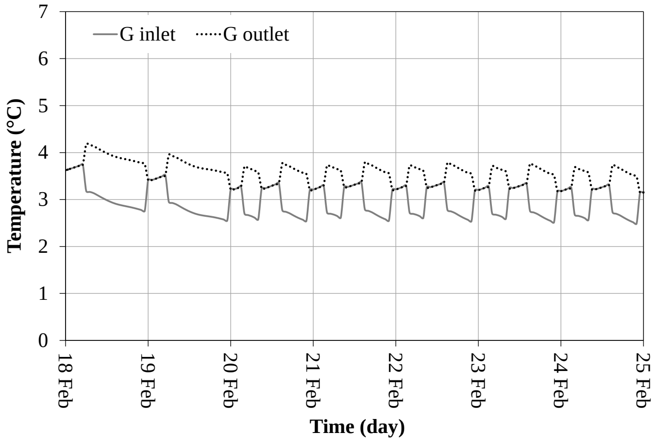

Fig. 8 Time series of temperature at inlet and outlet temperature for a week (G)

The solid phase for PCM_{WIN} and PCM_{SUM} are reported in Fig. 9, together with the daily averaged temperature of the trench. For completeness, also the outlet temperature in the case with gravel as filling material is included. At the beginning of the heating season, fixed at 15th October, PCM_{WIN} is in the liquid phase while PCM_{SUM} is completely solidified. The solidification process of PCM_{WIN} starts at 10th January and ends at 4th May according to the temperature. The effects on the temperature within the trench are clear, but most of PCM_{WIN} solidifies by mid-March. From that instant, the temperature begins to decrease and it equals the temperature of the case G in about fifteen days. This implies that the amount of PCM_{WIN} provided, equal to the 65% of the total solid mass that constitutes the porous matrix, is not enough to cover the energy demand of the whole heating season. Probably, a larger amount would have been more suitable for the present application. In addition, at the end of heating season, the melting of PCM_{WIN} stabilizes at low values the soil temperature that otherwise would tend to rise naturally.
When the GHE starts working in cooling mode, albeit at daily partial load, approximately 25% of PCM_{WIN} is still in the solid phase. As a result, part of the energy injected into the soil by the GHE is absorbed in the phase change of PCM_{WIN}, and benefits continue for a further month. In summer, the melting of PCM_{SUM} starts around 25th of July; the maximum melting reaches 93% of the total PCM_{SUM} mass within the trench. Although PCM_{SUM} constitutes only 35% of the porous matrix which corresponds to 21% of the trench total mass, it maintains its effectiveness for the entire period, resulting properly sized in relation to the lower heat load in cooling mode.
Finally, the benefits or disadvantages obtained from the use of PCMs in coupling with a shallow ground heat exchanger are investigated in terms of energy, according to Eq.7 where the difference of temperature (ΔT) is considered between the outlet temperature in the case with and without PCMs. For the simplification adopted, the trend of energy is shown in Fig.10, together with the daily-averaged outlet temperature for the two cases. According to the previous comments on Fig.5 and Fig.6, in the initial part of winter the negative curve trend shows the disadvantage related to the low thermal diffusivity of the PCMs. Similarly, the phase change at the end of heating season is disadvantageous because it slows down the thermal recovery of the soil. However, the overall benefits provided in the whole heating season by using PCMs amounts to 5.3 kWh/m, compared to a seasonal requirements of 54.4 kWh/m. The disadvantages are less evident in summer, and the energy saving reaches 13.4 kWh/m compared to a cooling load of 27.7 kWh/m. The yearly total energy saving is thus 18.7 kWh/m.
Fig.11 shows the Darcy's velocity field within the trench, when the system is working (a) or turned off (b), respectively, at two different simulation time on 25th of February. Fig.11.a shows low flow regions at the two corners on the rightside of the trench, where the heat transfer should be considered mainly conductive. Fig.11.b depicts the velocity field when the circulator is switched off, and how the variations in water density incurs natural convection in the trench. Fig.11.c shows the temperature contours and for a zoom of the domain at the same time step of Fig.11.a and how the GHE heat transfer affects this part.

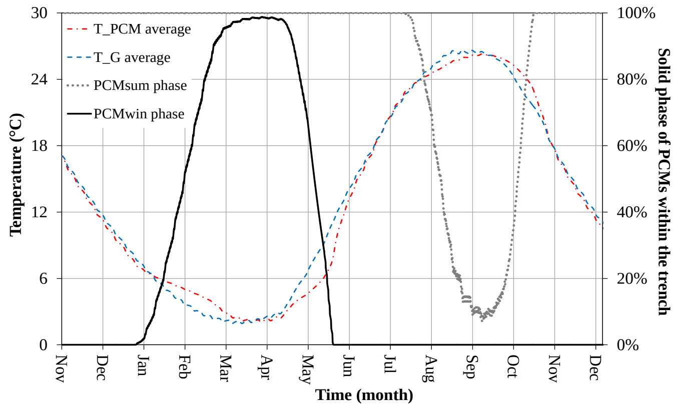

Fig. 9 PCM_{WIN} and PCM_{SUM} solid phase fraction.

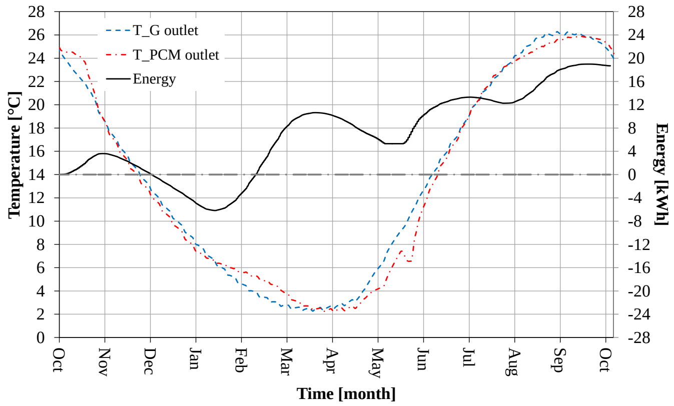

Fig. 10 GHE heat transfer.

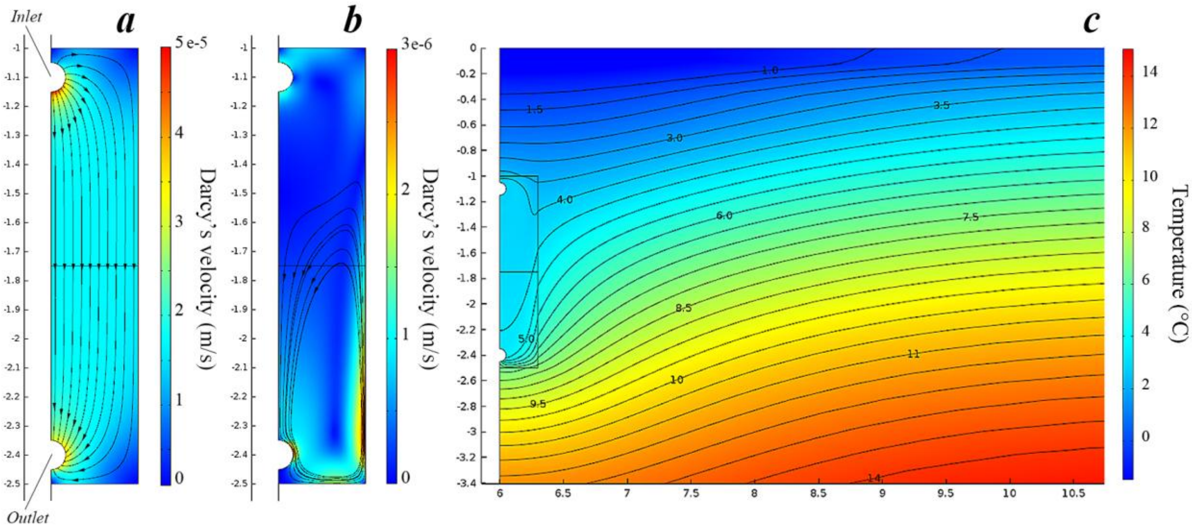

Fig. 11 Darcy's velocity field within the trench and thermal field in the domain on the 25th February.

4 CONCLUSIONS

The coupling between phase change materials (PCMs) and ground heat exchanger (GHE) based on a drainage trench has been presented and the potential benefit numerically analysed. The trench dug in the shallow ground and filled with encapsulated PCMs acts as a GHE with water flowing among granules. The purpose is evaluated through numerical modelling in a 2D symmetrical domain, in which the fluid flow and the heat transfer in porous media are solved in unsteady state and saturated conditions, under hourly-scale boundary conditions. The approach of the equivalent heat capacity is employed to consider the latent heat of the PCMs. In order to assess the effect of PCMs on the working fluid temperature and on the thermal field of the ground around the heat exchanger, the results are compared with those of an equivalent GHE filled with coarse gravel.

The proposed use of the PCMs is effective, if properly sized. Compared to the use of gravel as filling material, the case with PCMs generally shows more favourable and stable values of working fluid temperature. As a consequence, better working conditions for the heat pump are achievable. Furthermore, due to the larger latent heat in the phase change, PCMs dampen the thermal wave generated by the heat pump transferred to the ground by the GHE. Additionally, the use of PCMs in coupling with this type of GHE can be sized as a protective device to prevent the freezing of the supposed working fluid (water) and thus to avoid the system arrest. However, it must be highlighted that the low thermal conductivity of the PCMs causes a lower efficiency of GHE in spring and autumn when the temperature is different from the melting point. Anyway, in the case with PCMs, the effect of energy exploitation on the ground thermal field away from the GHE is lower than in the case without PCMs. This means that the trench can be placed with a shorter span for assigned energy demand, or vice versa, according to the higher energy availability as latent heat close to the GHE.

Finally, it should be also taken into account the opportunity for horizontal and shallow GHEs to attempt the underground thermal energy storage by adopting PCMs, as consequence of the seasonal energy reloading of the latent heat eventually exploited.

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