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Enhancement of shallow ground heat exchanger with phase change material

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ABSTRACT

Heat pumps perform better when coupled with ground as thermal source than with air. In literature, several studies and applications suggest and analyse the use of phase change materials (PCMs) coupled with single or double U-tube vertical borehole heat exchangers (BHEs). Usually, PCMs are mixed with the grouting material during the installation. An alternative solution to vertical BHEs is the use of horizontal ground heat exchangers (HGHEs). The present work investigates the possibility of coupling PCMs with a flat-panel HGHE installed inside a trench 2 m under the ground surface. The study analyses the case in which PCMs are adjacent to the HGHE, taking a cue from alternative coupling technologies which have PCMs added to the backfilling material of the trench where the HGHE is installed. The analysis has been conducted with COMSOL software tool. A simulation model of the system was developed to carry out a parametric analysis. The objective of the simulations is the investigation of the thermal behaviour of the HGHE patent pending coupled with PCMs under cycles of operation which represent how the heat pump could work in GSHP system. The results show the meaningful difference of using the PCM in direct contact with the HGHE.

1. Introduction

As widely known the building sector is responsible for about 40% of energy consumption [1]. Effective actions are necessary to ensure lowering energy use, increasing the exploitation of renewable energy sources, and consequently decarbonising the energy supply.

In the last years, heat pump (HP) systems have become the most promising and attractive sustainable solution to provide heating, ventilation, and air conditioning (HVAC) of buildings. In particular, ground source heat pump (GSHP) systems represent the most effective technology if compared to more common air source heat pumps (ASHP). The more stable and favourable ground temperatures, both during the heating and the cooling period, ensure better energy performance of the system [2,3]. Obviously, the geothermal field in GSHP systems must be adequately designed, and the thermal load (heating and cooling) of the building has to be balanced to ensure good performance over the years. A not dominant heating or cooling thermal load profile of the building could avoid the thermal drift of the ground storage due to the soil thermal imbalance [4]. In ASHP this distinctive feature has no effect, indeed the air source can be considered as an infinitive heat storage capacity. The sustainability of these plants and their impact on the environment significantly depends on the energy consumption of the plant during the operation. Aresti et al. [5] investigated the differences between ASHP and GSHP. The operating energy consumption represents at least the 83% of the total amount of the GWP (Global Warming Potential), which also includes the transportation, manufacturing, and installation of the plant. From this point of view the energy performance of the systems became a key factor to deem one solution better than the other.

In GSHP system the heat is extracted from or rejected to the ground via a closed loop. The heat exchange is obtained with ground heat exchangers (GHEs), through which pure water or a mixture of water-antifreeze fluid circulates as exchange medium between the HP and the ground. GHEs can be divided into two different typologies according to the depth and position of installation. Vertical single U, double U or coaxial borehole heat exchangers (BHEs) are installed at a depth usually ranging from 30m to 200m, depending on the ground conditions and composition [6]. The significant depth allows BHEs to exploit the highly stable temperatures which characterise this portion of soil, but it requires important and expensive drillings at the same time, thus resulting in a complex installation procedure [7,8]. Similarly to the vertical BHEs technology, foundation piles can be used as ground heat exchanger, therefore enjoying an economic benefit connected to the avoided

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Nomenclature

ASHP	Air Source Heat Pump
BHE	Borehole Heat Exchanger
COP	Coefficient Of Performance
EER	Energy Efficiency Ratio
GHE	Ground Heat Exchanger
GSHP	Ground Source Heat Pump
HGHE	Horizontal Ground Heat Exchanger
HP	Heat Pump
HVAC	Heating Ventilation Air Conditioning
MPCS	Microencapsulated Phase Change Slurry
PCM	Phase Change Material
Subscript	
Evap	Evaporator, Evaporating
Cond	Condenser, Condensing
HCF	Heat Carrier Fluid
Melt	melting
out	outlet
SL	solid-liquid
undist	undisturbed
Symbol	
c	Heat capacity, [kJ/(kg K)]
D	Distance, [cm]
Δ	Difference
h	latent heat, [kJ/kg]
L	Electric Energy, [Wh]
λ	Thermal Conductivity, [W/(m K)]
Q	Heat, [Wh]
ρ	Density, [kg/m^3]
T	Temperature, [°C]

installation costs [9]. This technology must be analysed differently from the previous one due to their less streamlined shape [10]. The diameter of the pile-holes ranges between 300 mm and 1200 mm and they reach depths usually between 10 m and 60 m [11]. For this reason, their thermal behaviour is more affected by the surface environmental conditions and their application is limited to specific cases. An alternative solution to vertical BHEs are shallow horizontal ground heat exchangers (HGHEs), which are located at a depth of a few meters. Therefore, their installation is easier and more cost effective than the one used for BHEs [12], and it can be controlled and monitored more in detail. Nevertheless, HGHEs need much more ground area than vertical systems and they are more affected by ambient air temperature fluctuations because of their proximity to the ground surface [13,14].

All the drawbacks mentioned above, as well as the high investment costs, have hindered the spread of the geothermal technology. For this reason, many studies have been focusing on the optimisation of the geothermal field, through the development of more efficient shapes of heat exchanger [15,16] and the improvement of the thermal conductivity of backfilling materials [17–23]. However, in order to increase the thermal performance of GHEs, vertical or horizontal ones, another possibility is the enhancement of the thermal storage capacity of backfilling materials used during their installation.

Within this background, the phase change material (PCM) has become a potential candidate to increase the heat storage capability of the soil. PCMs have a high specific heat storage capacity, although they present limits in terms of thermal conductivity [24]. In fact, PCMs have the capability of improving the heat storage because of their availability of latent heat at different temperatures but, on the other hand, the low thermal conductivity could negatively affect the heat exchange behaviour of the system. The application of PCMs in GHEs can compensate peak loads occurring during hard weather conditions, thus potentially allowing a reduction in the size and costs of the geothermal field.

The most common coupling technologies between PCMs and GHEs consist in the integration of PCMs directly mixed with the grout filling material of vertical BHEs or with the backfilling material of HGHEs [25]. The main objective of this solution is the increase of the underground thermal energy storage (UTES). Nevertheless, research has been almost exclusively conducted by numerical analysis, uncovering a lack of experimental investigations, and thus generating a critical knowledge gap about the realistic behaviour of the system [26].

Rabin and Korin [27] were the first to study the integration of PCMs mixed with sand as backfilling material for the GHX. Results of the numerical analysis, which considered organic PCMs and BHEs, demonstrated that PCM backfilling is able to increase the thermal performance of the system. Other works analysed the use of paraffin, salt hydrate, the adoption of acid mixtures, and the same mixtures with metal particles for thermal conductivity enhancement [28–32]. Eslami-nejad and Bernier [28] suggested a new approach for the borehole configuration to reduce the required length of GHEs in cooling-dominated climates. They surrounded the U-tube BHEs with a thermally enhanced PCM ring mixed with sand. They concluded that their configuration could reduce the total borehole length up to 9%. Wang et al. [29] used the PCM as grouting material and investigated their model by means of 3-D simulations. They found, similarly to the previous case, a reduction of the BHEs field size using PCM only with the thermal conductivity enhancement. Lei and Zhu [30] analytically examined the use of PCM as filling material for BHEs. Their results have been obtained using a quasi-steady approximation of the analytic solution. They found an increase of heat exchange of about 33% and 19% during the heating and cooling operation respectively. This result led to a possible reduction of BHEs total length. Li et al. [31] studied the use of shape-stabilised PCM as backfill in a U-tube BHE. The PCM was considered as a mixture of decanoic acid and lauric acid in a solid matrix of silica and graphite. They carried out simulations with Fluent software to compare the layout solution with PCM and crushed stone concrete backfill. They found an increase of heat exchange of about 37% using the PCM.

Yang et al. [32] investigated experimentally and by means of 3-D numerical simulations the effects of PCMs backfill in BHEs. They conducted experimental tests for winter and summer operating conditions finding positive results in terms of thermal interference radius reduction, delay of the variation of soil temperature and enhancement of the heat exchange rate.

Numerical findings showed that higher heat transfer performance can be obtained by using enhanced PCM [33]. The impact of PCM thermal conductivity on the GHE performance was numerically studied by Ref. [34]. Two types of PCM (paraffin and shape-stabilised PCM) integrated in the grout of a BHE were considered. Findings showed that – by adopting the enthalpy-porosity strategy – the low thermal conductivity of paraffin led to a lower thermal efficiency compared to regular grout. Whilst the studies mentioned above are based only on organic PCMs, Zhang et al. [35] numerically investigated the thermal performance of a BHE backfilled with hydrated salts. Results showed that the temperature differences of the working fluid at the inlet and outlet after 6 h of cooling operation increased if compared to the same BHE with a conventional backfill. Mousa et al. [36] investigated the energy performance of an energy pile of 1.5 m diameter and 25 m depth by means of numerical simulations. Their numerical model included the HP energy performance. The thermal behaviour of the energy pile was studied with and without PCM in different positions. They found an increase of up to 5.3% in the coefficient of performance (COP) of the HP during the change phase of the PCM and a decrease of up to 1.8%

The review of the literature uncovers that even less studies have considered the application of PCMs in HGHEs. The use of micro-encapsulated paraffin mixed with the backfilling soil of HGHEs was investigated by Dehdezi et al. [37]. Results of the numerical analysis demonstrated that PCM enhanced soil increased the COP of a HP system by 17% compared with ordinary backfilling material. Bottarelli et al. evaluated the impact of paraffin-based granules [38] and micro-encapsulated paraffin [39] mixed with sand as backfill of a novel HGHE [16]. Numerical results demonstrated that PCMs allow to mitigate seasonal ground temperature variations, also ensuring a higher COP of the HP. Differently from the previous study, Lingling et al. [40] used microencapsulated PCM for the enhancement of the heat carrier fluid of the ground loop. They use a microencapsulated phase change slurry (MPCS) by mixing the PCM with the water fluid in a serpentine shaped HGHE application at lab-scale. The results of the research show that the MPCS can improve the thermal behaviour of the HGHE during the phase change range of the PCM, but at the same time the pressure drops must not be underestimated. The pumping cost of the solution with MPCS can increase by 2–3 times the solutions with pure water.

To sum up, current literature does not only suffer from a lack of experimental data, validations and simulations about the integration of PCMs in HGHEs, but also from a comprehensive comparative analysis between different application methods and approaches. Indeed, the efficiency of PCMs can widely vary according to how and especially where they are installed or used in GSHP systems. For example, as described in Ref. [40], Lingling et al. have used the PCM in a non-conventional way exploring something different in comparison to the other studies present in literature. In HGHE application field, the large part of the works is focused on using PCM as backfill. There are not studies promoting a different approach i.e. use the PCM as a part of the HGHE. The present work suggests this new approach based on the results of an experimental facility. A small-scale experimental investigation about the coupling between HGHEs and PCMs was conducted in 2020 at the TekneHub Laboratory of the University of Ferrara (Italy). Three lines, composed of three novel HGHE each one, were installed with three different backfilling materials: sand, a mixture of sand with paraffin-based granules and macro-encapsulated hydrated salts. Results confirmed that PCMs can compensate peak loads occurring during hard weather conditions [41], but at the same time they revealed differences between the different backfilling solutions as described more in detail in the following of the paper.

In particular, the present study investigates the thermal performance of PCMs integrated in a patented HGHE under different coupling technologies. This type of HGHE is a flat-panel installed 1–1.5 m under the ground surface. The work analyses the case in which PCMs are adjacent to the HGHE, compared to alternative coupling technologies having PCMs added to the backfilling material of the trench where the HGHE is installed. The analysis was carried out by means of numerical simulations conducted with COMSOL simulation tool. A simulation model of the system was developed to carry out a parametric analysis. The objective of the simulations is the investigation of the thermal behaviour of the patented HGHE coupled with PCMs under the cycles of heat fluxes that simulate the operation of the HP.

2. Methodology

The present literature includes the results of studies about the use of PCMs in small and large energy devices, systems and plants to increase their heat capacity, especially in the field of renewable energy sources. Usually, the final aim is the improvement of their energy behaviour and management and obviously to increase the energy efficiency. Beyond these essential aspects, their use could be related to other reasons, that could be the reduction in volume of the heat storage devices for solving space issues or make available large amount of heat at defined temperature level during a process. These key points make the use of PCM the suitable solution as it allows to reduce the size of the devices and storage tanks that are involved in thermal process. On the other hand, these studies reveal the cons that generally affect the use of PCMs. Firstly, the low thermal conductivity that usually characterises these materials, and secondly the compatibility with other materials involved in the process. In energy systems in which the heat exchange is one of the fundamental characteristics of the process, high thermal conductivity values of materials are usually required and mandatory, except in the case of thermal insulation needs.

This work has been developed starting from a set of observations on experimental data obtained in a small-scale experimental facility. This output has pushed to the conceptualisation of a novel HGHE integrated with PCM about which a patent application has been submitted by the authors. The behaviour of the system has been investigated with COMSOL Simulation Tool [42].

2.1. The case study

As reported above in the text, the present study has been developed as furtherance of an ongoing research on an experimental plant installed at the TekneHub Laboratory in Ferrara (Italy). The small-scale experimental plant involves the activities of two projects focused on PCMs and GSHP system: the CLIWAX project [43] and the IDEAS H2020 project [44]. This experimental GSHP system was designed for using different renewable energy sources. The GHEs field represents the primary source for the HP, the sun and the air are used as secondary sources. In literature, these particular plants are named multi-source HP system [45]. The exploitation of different free sources allows to improve the overall energy efficiency and at the same time the ground could be thermally regenerated using the other free sources, e.g. with the air or the sun if available. The possibility to undersize the GHEs field can be obtained because the thermal loads involved in the HP system are not just provided by the ground loop. As widely known, this last aspect often represents the main issue in terms of initial investment costs in GSHP systems.

The experimental results obtained from the real GSHP system with shallow flat-panel HGHEs have highlighted a particular behaviour of the ground loops. In particular, the investigated system has three ground loops. The first loop uses pure sand as filling material of the trench in which the flat-panel heat exchangers have been buried. In this study, this solution represents the standard application and the reference case in the following analysis. The second ground loop is filled with a mixture of sand and microencapsulated PCMs absorbed in granules for the enhancement of the ground source. The third loop was realised with sand and macroencapsulated PCMs in plastic containers. These three different configurations, without and with PCM, have allowed to obtain a direct comparison of their behaviours when they worked in parallel (with the same volume flow rate and supply heat carrier fluid temperature). The PCMs in the plant have been used in several parts of the system and not only in the ground heat exchangers loops. Nevertheless, the exploitation of the PCMs in the whole system does not affect what has been seen in the behaviour of the geothermal loops.

2.2. The experimental data of the GHEs loops

The positive effect due to the greater thermal capacity of the ground with PCMs has been verified through the monitoring data of the system installed in the plant. The behaviour of the trench filled with pure sand was used as reference in the comparison. In fact, the behaviours of the two solutions with PCMs have shown mean differences – up to 1 °C – in the heat carrier fluid temperature of the ground loop during the HP operation. In these applications the PCMs have been used in different ways with the aim of obtaining the same result in terms of enhancement. The PCMs were added to the trench filling material through a mix of PCM adsorbed in granules and containers filled with hydrated salt and installed in tidy positions in the trenches. More details about the installation are reported in Ref. [41].

These early analyses have shown different behaviours of the flat-panel HGHEs for the two proposed solutions just mentioned above, although the total amount of the latent heat and the melting temperatures of the added PCMs were the same for the two cases (PCMs adsorbed in granules and macroencapsulated in containers). The trends of the mean heat carrier fluid temperatures for the three cases – 2 with PCMs and 1 without – for the cooling period are reported in Fig. 1. These temperatures can be considered as the temperatures of the ground source during the cooling period. A similar result and trend have been obtained for the heating period as reported in Fig. 2. As it can be seen from the first chart the temperatures from the installation with macro-encapsulated PCMs in containers (named GHX3 in Fig. 1) are on average about 0.5–1 °C lower than the trench without PCMs and about 0.3–0.5 °C lower for the installation with PCMs in granules mixed with sand (GHX2). Similar differences in terms of behaviour can be seen for the heating period in Fig. 2. As expected, the temperature of the heat carrier fluid is lower in summer and higher in winter for the solutions with PCMs. However, the different behaviour among them was not expected, given that the total amount of heat storage due to the PCM is the same for the two enhanced solutions (GHX2 and GHX3). Each installation uses two PCMs with different melting point to make available the heat storage in heating and cooling periods at different temperature levels. The heat storages of the PCMs are equal to 33,3 MJ ($T_{Melt} = 8$ °C) and 22,2 MJ ($T_{Melt} = 27$ °C) for heating and cooling periods respectively. The properties of the PCMs are reported in Ref. [41].

This finding has pushed to analyse more in detail this phenomenon through the results of the study reported in this work. As mentioned above in the text, the analysis has been carried out by means of numerical simulations in COMSOL simulation tool [42].

2.3. The simulation model

The simulation model represents a slice of a small HGHE similar to the existing shallow flat-panel one, which was deeply described and discussed in a previous work [41]. This size of the model was used to easily reproduce the system in a real plant at laboratory scale keeping the computational resources limited. The HGHE used as reference for the definition of the main properties of the model is a flat-panel heat exchanger where the heat carrier fluid flows along its length. The small dimensions of the domain, the boundary conditions of heat flux and temperatures, and the exploratory aim of the research have allowed to neglect the effect due to the flow of the heat carrier fluid in the HGHE at this step of the study. The heat flux between the fluid and the ground takes place through the lateral surface of the exchanger vertically installed in the ground.

Considered the aim of the study, and given that the system is symmetric along the longitudinal horizontal axes of the HGHEs line, only one side of the HGHE and of its trench have been considered in the simulations. A reference scheme of the top view of the HGHE model with the boundary conditions is reported in Fig. 3. The red rectangle area in the figure represents the part of the heat exchanger and surrounding sand and soil used for the definition of the simulation model. The three sides in the figure indicated with Q = 0 together with the top and bottom sides of the parallelepiped are considered as adiabatic, while the last one has a constant temperature value equal to the undisturbed ground temperature. The effects of depth and temperature at the ground surface have been neglected because their impact on numerical solution is limited [46] in terms of temperature at the heat exchanger and in the soil.

A sketch of the simulation model with dimensions is shown in Fig. 4. The model is divided in two domains, which are simulated simultaneously by the program. The difference between the two volumes represented in the figure is the PCMs use. The model on the bottom right of the figure has the PCM while the one on the top left side works without PCM. The blue layers represent the water layer inside the HGHE while the yellow one is the PCM. The installation of the PCM has been considered as a thin sheet of material close to the flat-panel heat exchanger, this sheet can be in direct contact with the HGHE, or it can be moved far from heat exchange surface. The way of use the PCM in this study is different if compared to what has been seen in the experimental plant, where the PCM has been distributed in the filling material of the trenches without considering which could be the effects due to the distance between HGHE and PCM. As it will be described in the next section of the text, the manner in which PCM is used with the GHE heavily affected the behaviour of the ground loop in terms of heat carrier fluid temperature under fixed values of the heat flux.

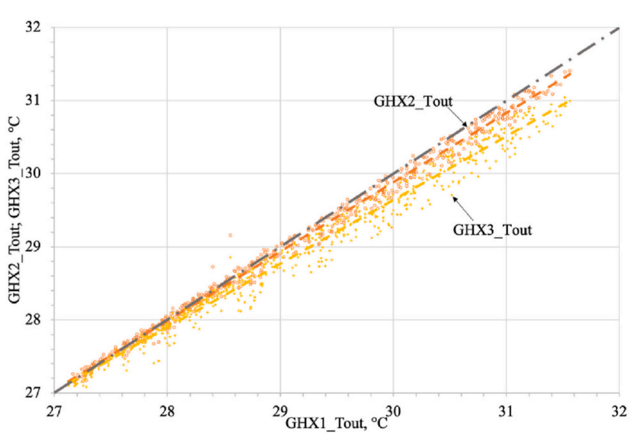

Fig. 1. Trends of the mean heat carrier fluid temperature in the ground loop of the GSHP system - COOLING [41].

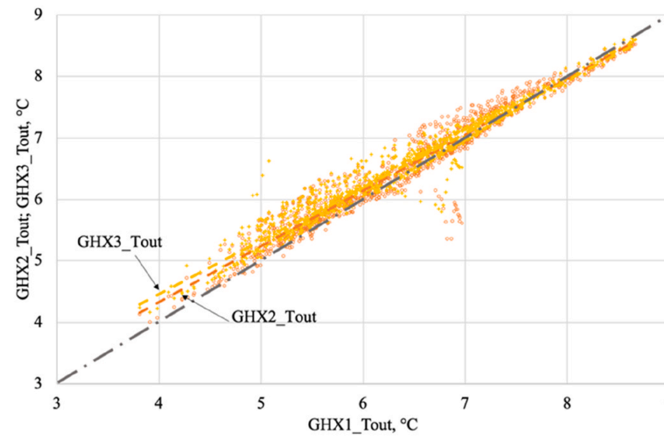

Fig. 2. Trends of the mean heat carrier fluid temperature in the ground loop of the GSHP system – HEATING [41].

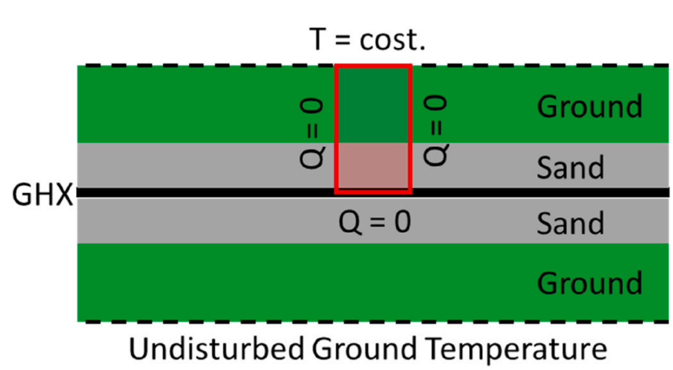

Fig. 3. Top view of the scheme of the GHE (Top side Q = 0, Bottom Side Q = 0).

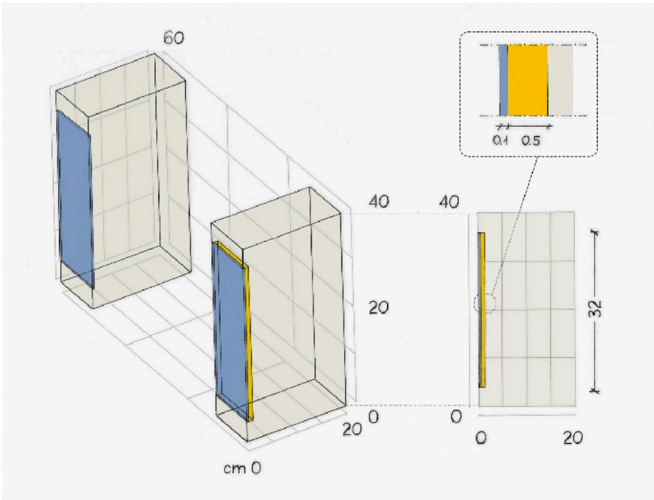

Fig. 4. Sketch of the simulation model (measures in cm).

The results of this work summarise the first part of an ongoing extended study. The dimensions and the size of the simulation model are compatible with a real flat-panel heat exchanger at laboratory scale.

For the definition of the model the following assumptions have been considered.

- the thickness of the plastic layer between the heat carrier fluid and sand or PCM has been neglected, therefore the fluid layer in the model is in direct thermal contact with the sand or PCM, depending on the case under consideration. The plastic layer would have represented the HGHE envelope.
- the thermal conductivity of PCM and sand have the same value in the simulations. This choice was oriented by the study objective. This assumption is not so far from the reality if the sand is dry, and it represents the worst working condition of the geothermal loop. The simulations want to investigate the change in thermal behaviour due to the position of the PCM respect to the HGHE.

The thermal properties and behaviour of the PCM over its phase change have been simulated using the approach and the equations reported in Ref. [38]. Specific equations have been defined to numerically analyse the PCM as a porous media of two components, the solid part and liquid part of the same PCM. In detail, the specific heat capacity, which is affected by the latent heat due to the solid-liquid transition and vice-versa, was defined by means of a normalised Dirac's pulse f(T), expressed in K^{-1}. Furthermore, a dimensionless variable has been used to describe the phase change as it similarly happens in Ref. [41], this datum represents the volume fraction of the liquid phase in the PCM, with a value between 0 (solid) and 1 (liquid) around the melting point range. More details can be found in Ref. [38]. The complementary value of the liquid fraction is the solid fraction that has been used in results of the present study.

The main thermophysical properties of sand and PCM are summarised in Table 1, while for the water the properties have been gathered directly from COMSOL database. The properties of the PCM reported in the table were used as input data in the equations described above, which evaluate the effects of the temperature and solid fraction of the PCM.

Table 1
Thermophysical properties used in the simulations.

	λ	ρ	c	h_{SL}	T_{melt}	ΔT_{melt}
	W/(m K)	kg/m^3	kJ/(kg K)	kJ/kg	°C	°C
Sand	0.4	1400	0.9	–	–	–
PCM	0.4	1400	0.9	150	29	4

3. Simulations

3.1. Preliminary remarks

The aim of the study is to investigate how much and in what way the use of PCMs combined with flat-panel HGHEs affects the behaviour of the ground loop in GSHP systems. In particular, a proper use of the PCMs could lead to positive effects on the GSHP in the short-time operation with an increase of the performance in terms of COP value.

As expected, the PCM added to the ground or to the trench filling material increases the heat capacity of the space volume close to the HGHEs improving its heat capacity potential. For the objective of the simulations, this latter phenomenon is not the key point of the work since this topic is widely discussed and described in the present literature.

The study wants to highlight that the operating conditions of the HGHEs field, and therefore the trends of the heat carrier fluid temperatures, are heavily affected from how the PCM is used in addition to the HGHEs. The findings summarised in following represent an exploratory investigation for the future experimental activities.

3.2. The approach used in the simulations

The simulations have been set up in such a way that the role of the PCM could be evaluated. This objective has been pursued by assuming some characteristics of the model purposely equal, thus highlighting the effect of the latent heat of the PCM as the system layout changes. A set of simulations have been carried out by modifying the thermal load applied to the model and the distance between the heat exchange surface and the volume of PCM. As it can be seen in the simulation model in Fig. 3, the PCM is represented as a thin layer of 0.5 cm. The PCM in that sketch is close to the HGHE, but in the study the distance has been increased in order to make a comparison between two different layouts.

As described in the previous section, the impact due to the PCMs use in GSHP has been investigated. An operation compatible with that of a HP has been considered as a sequence of ON-OFF heat flux cycles on the ground loop. This approach is similar to what happens in GSHP systems with ON/OFF driven compressor. During the ON operating period the heat flux was applied on the ground heat exchanger. The fluid follows the trend of the heat flux required by the HP. The temperature changes as function of the thermal load and of the heat exchange on the ground loop. In our model, the heat exchanger is represented through the external surface of the fluid layer as shown in Fig. 3 and the operating conditions could be compared to what happens during the cooling season. The time unit is equal to 5 min, as shown in Fig. 5 the ON period is equal to one time unit while the OFF period is three times the ON period. In all the cases the cycles are repeated for 12 h, and the comparisons were made over this period of time. The time-step used in COMSOL simulation tool for the solution of the equations which describe the conductive problem is equal to 15 s.

In a full-size system, these sequences are affected from many external variables like the thermal load profile of the building, the size of the storage tank on the user and source side respectively, etc. In our case, the sequence in Fig. 5 has been defined and used in order to have a reference for the analysis that could be traced back to the typical operation of a HVAC system during the cooling period. The case studies analysed in the present work, with and without the PCM, use the same load profiles, intended as a sequence of heat fluxes, as boundary condition in the simulations.

3.3. Results and discussion

The outputs of the simulations have shown the key role of the PCM

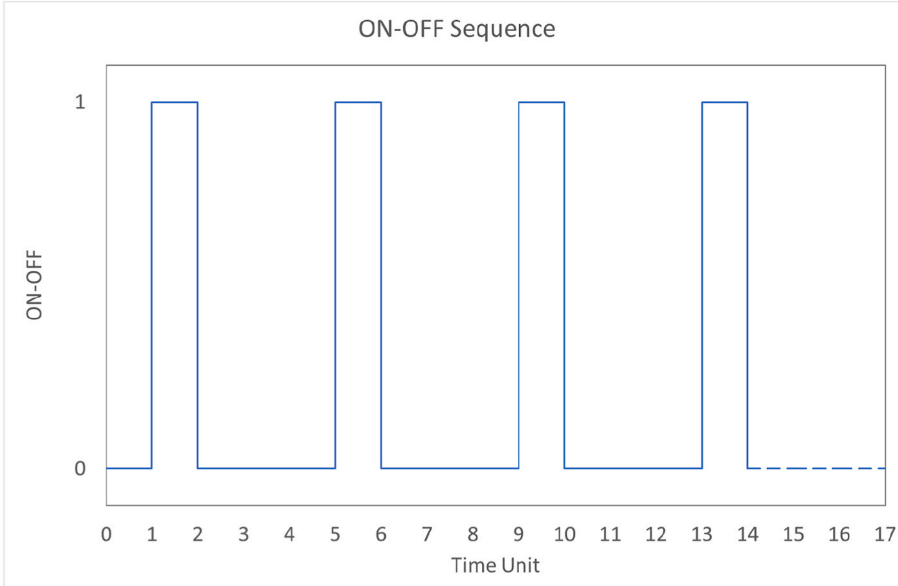

Fig. 5. ON-OFF cycles (Time Unit = 5 min).

when applied to the flat-panel HGHE, highlighting more in detail what had been seen in experimental data that have led to this work. The role of PCM becomes relevant especially when it works close or even in direct contact with the HGHE. In the real experimental plant data, the fluid temperatures in Figs. 1 and 2 have suggested this phenomenon. In the first case, the PCM close to the heat exchanger could be considered as an extra component or device installed in the shallow HGHEs field with the final aim of increasing the UTES, while in the second case the system could be considered as a novel HGHE which includes the PCM, as it will show in the description of the results.

The outputs of the simulations are the heat carrier fluid temperatures that should characterise the heat exchanger to get the same heat flux used as input to the model. The results show meaningful differences of these temperatures as the HGHEs layout changes. A set of 5 simulations have been summarised in the present work to support this insight; the details of the boundary conditions are reported in Table 2.

Different values of heat fluxes at the GHEs have been considered from 100 W/m^2 to 500 W/m^2 in order to investigate the effects of the thermal load on the GHE behaviour. Obviously, the PCM quantity could be an added variable of the system, but in our case the objective of the work is not the optimisation of this parameter and for this reason the amount of the PCM is always the same in the simulations. In particular, the amount of the latent heat due to the PCM layer is equal to 33.6 kJ. As it can be seen from the table, one of the simulations has been carried out for the PCM close to the exchange surface to highlight the change of the behaviour of the GHE. Each simulation has been defined with a code as reported in the table.

The results are summarised in Fig. 6. The charts show the trend of the temperatures described for the heat fluxes reported in Table 2 and the solid fraction of the PCM. This last represents the ratio between the solid mass and the liquid mass of the PCM volume present in the simulation model. The shape and the timing of the heat fluxes profile is shown in Fig. 5. This load profile was used as input in the model for each simulation. The heat fluxes are equal to 3.2 W, 6.4 W, 9.6 W and 15 W for the case A, B, C and D respectively, considering the heat exchange area of the model.

As it can be seen from the charts, for long operating periods of the system the difference in terms of fluid temperature gradually becomes less evident as the effect of latent heat wears off. Once the latent heat storage has been almost totally exploited, the behaviour of the model is almost similar, while still maintaining a difference between the temperature levels of the solution with and without PCM. Although the thermal recovery (temperature at the heat exchange surface) is much more evident in the case of the solution without PCM, the temperatures with the phase change effect contribution are always lower than the other case.

A further analysis regards the study of the system with the PCM at 3 cm far from HGHE (case C3). This comparison was carried out considering as reference the case C of the simulations. The direct comparison between the case C0 and C3 is shown in Fig. 7. As it can be seen in the chart, the change of the layout led to a meaningful change in the resulting temperatures. The temperatures reduction during the 12 h of operation, from the case C3 to the case C0, could reach a maximum of 4 °C only by changing the position of the PCM. This difference increases to 5.5 °C if the comparison is done with the solution without PCM.

The simulations have highlighted how much the previous change in the layout of the system affects the thermal behaviour of the HGHEs. This latter phenomenon is particularly emphasised by decreasing the distance between the HGHEs and PCM installed in trench. Obviously, these differences in working temperatures influence the HP performance.

For this reason, the results of the simulations have been used to evaluate which would be the benefits in terms of energy saving potential using this novel layout of the HGHE coupled with a water-to-water HP.

For this aim, the energy performances of a HP were considered in the next analysis. The properties of the HP are summarised in Table 3. This table represents the energy performance map of a HP that works with R410a as refrigerant. The data includes the energy demand of the compressor and was calculated with the following boundary conditions: pinch point at evaporator and condenser equal to 5 °C, no subcooling at the outlet of the condenser and superheating equal to 5 °C at the outlet of the evaporator. The comparison has been done for the reference case

Table 2
Main boundary conditions used in the simulation.

Sim. Code	Heat Flux	Time-step of the sim.	T_{undist}	$D_{HGHE\text{-}PCM}$
	W/m^2	s	°C	m
A0	100			0
B0	200			0
C0	300	15	20	0
C3	300			3
D0	500			0

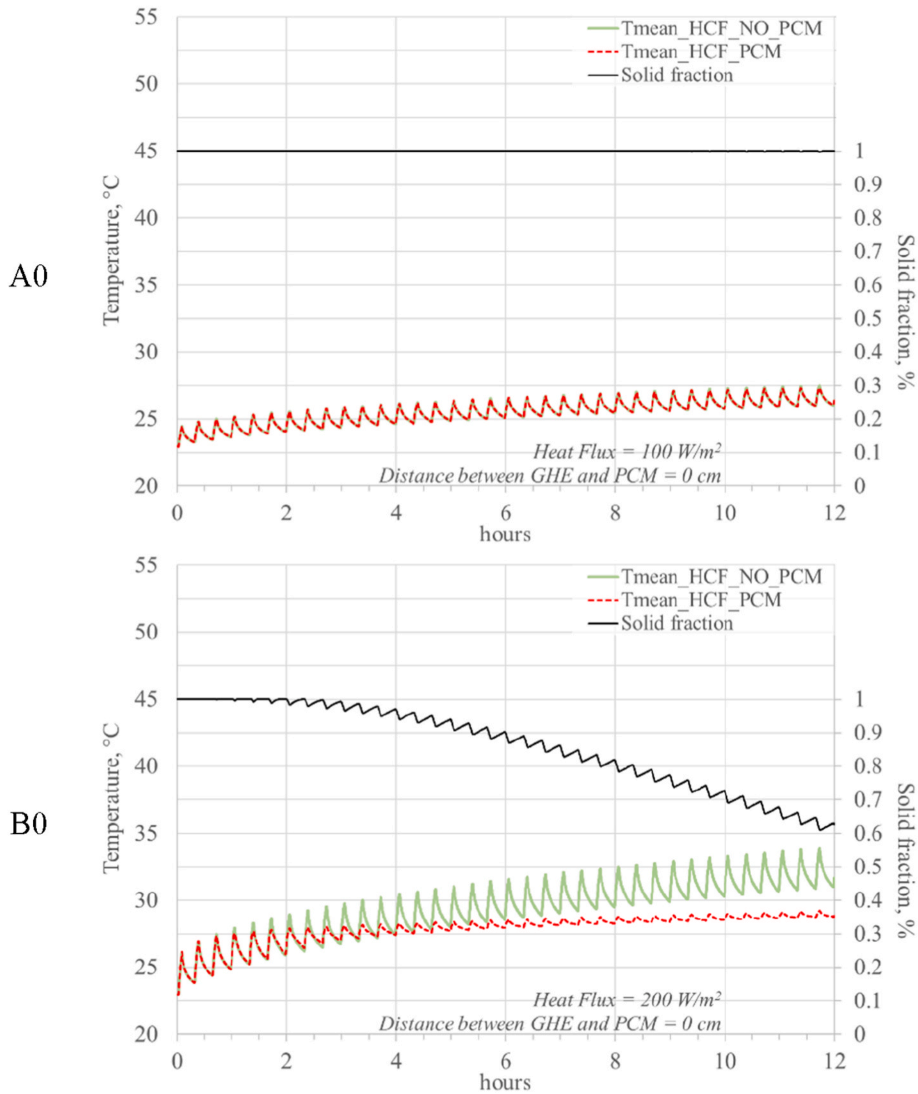

Fig. 6. Results of the simulations.

without PCM and the cases C0 and C3.

The results of this analysis are summarised in Table 4. As it can be expected the solutions with PCM are better than the one without (Case C). What was not expected is the difference in energy saving between the cases C3 and C0, which all include the PCM but in different positions. The mass of PCM is the same in both cases, but the case C0 has an energy saving potential that is three times the case C3. This result confirms and quantifies what has been already anticipated by describing the temperature trends of the simulations.

From the practical and operational point of view, once the latent heat of the PCM has been exploited, the working conditions of the heat exchanger are similar and the behaviour for the two solutions is almost the same except for an obvious heat wave delay transfer to the ground. The possibility of using this device in the emerging multi source HP systems allow the possibility of easily regenerate the PCM using other free renewable sources available in the plant. In particular, in the heating period the solar loop can be used to liquify the PCM during the sunny days when the HP is switched off, while in the cooling period the air loop or the solar loop during the night time can be used to extract heat from the PCM and ground and therefore solidify and regenerate the latent heat of the PCM for the next day.

4. Conclusions

The continuous search for innovative and improving solutions for ground heat exchangers in HP applications has led the authors to study the PCM effect in addition to shallow type of HGHEs, a so called flat-panel. The use of HGHEs in GSHP systems is limited if compared to vertical BHEs, especially for the large space required for the installation. Also, the research field is more oriented towards the study of vertical system, especially in PCM application. The present study has highlighted, using numerical simulations, how the operating conditions of GSHP systems may have significant deviations if the PCM is installed in one position rather than in another. In this preliminary analysis the following conclusions and observations can be summarised.

- the study of novel layout solutions in HGHEs applications need to be further investigated to overcome the issues and making this technology competitive in GSHP field
- the use of PCM in proximity or coupled directly with the HGHEs seems to work better than solutions with greater distances or with PCM added to the backfill material
- The use of PCM in addition to the flat-panel HGHE allows to obtain an improvement in HP performance with a consequent energy saving

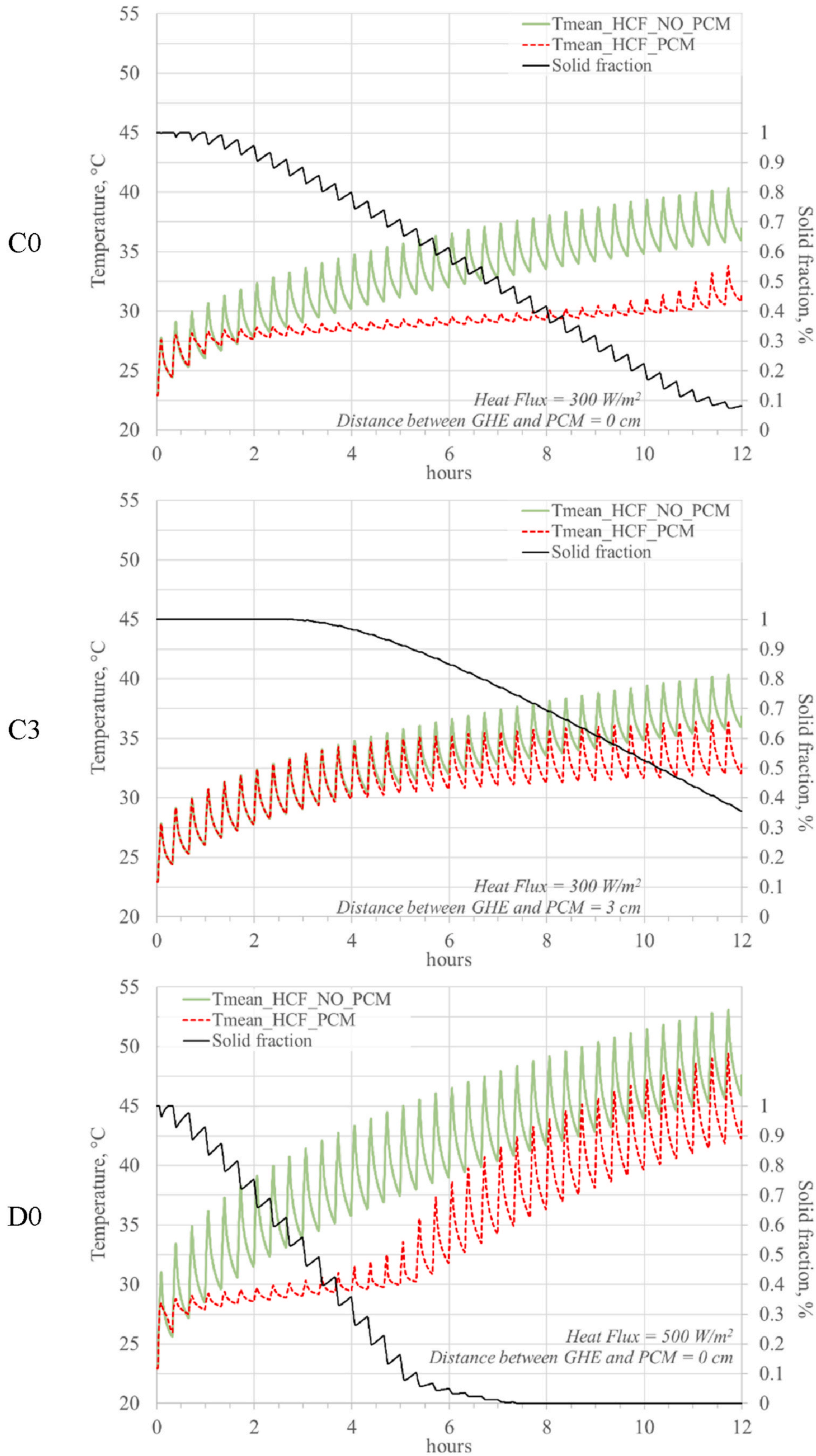

Fig. 6. (*continued*).

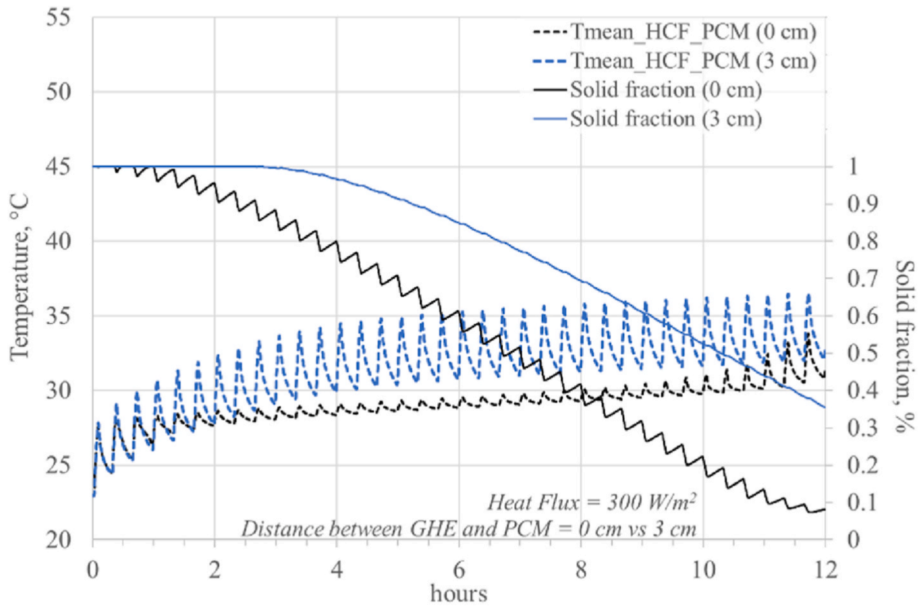

Fig. 7. Comparison between case C0 and case C3.

Table 3
Properties of the HP.

T_{evap}	T_{cond}	T_{HFC}	EER
°C	°C	°C	–
2	42	37	3.81
	40	35	4.07
	38	33	4.33
	36	31	4.61
	34	29	4.90
	32	27	5.20
	30	25	5.50

Table 4
Results of the energy saving potential.

Sim. Code	Q_{cond}	Q_{evap}	L_{comp}	EER	ΔL_{comp} [a]
	Wh	Wh	Wh	–	%
C (no PCM)		5323	1282	4.15	-
C3	6605	5374	1230	4.37	−5
C0		5471	1134	4.82	−14

[a] Value normalised with useful thermal effect at the evaporator side.

of about 10%. Consequently, a reduction of the HGHE field size can be obtained for the same energy consumption.

A future development of the proposed application will be the energy analysis of case studies extended to long operating period over seasons and years. This approach will allow to evaluate how much the boundary conditions, like weather and thermal load profiles of the building, affect the final results. Furthermore, this type of novel HGHEs are good candidates in multi-source HP systems where the free renewable sources, different from the ground, i.e. air and sun, can be exploited for PCM thermal regeneration when available.

CRediT authorship contribution statement

Giuseppe Emmi: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing. **Michele Bottarelli:** Conceptualization, Methodology, Software, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] European Commission – Department, Energy. Energy efficiency in buildings. https://ec.europa.eu/info/news/focus-energy-efficiency-buildings-2020-lut-17_en. (Accessed 21 May 2022).
[2] I. Al-Hinti, A. Al-Muhtady, W. Al-Kouz, Measurement and modelling of the ground temperature profile in Zarqa, Jordan for geothermal heat pump applications, Appl. Therm. Eng. 123 (2017) 131–137.
[3] P.D. Pouloupatis, G. Florides, S. Tassou, Measurements of ground temperatures in Cyprus for ground thermal applications, Renew. Energy 36 (2011) 804–814.
[4] E. Bisengimana, J. Zhou, M. Binama, K. Zhao, S. Abbasa, Y. Yuan, The frosting and soil imbalance performance issues of building heat pumps: an overview, Energy Build. 273 (2022), 112387.
[5] L. Aresti, P. Christodoulides, G.A. Florides, An investigation on the environmental impact of various Ground Heat Exchangers configurations, Renew. Energy 171 (2021) 592–605.
[6] C.A. Cruickshank, C. Baldwin, Sensible thermal energy storage: diurnal and seasonal, in: T.M. Letcher (Ed.), Storing Energy, second ed., Elsevier, Amsterdam, 2022, pp. 419–441.
[7] G.A. Florides, P. Pouloupatis, S. Kalogirou, V. Messaritis, I. Panayides, Z. Zomeni, G. Partasides, A. Lizides, E. Sophocleous, K. Koutsoumpas, The geothermal characteristics of the ground and the potential of using ground coupled heat pumps in Cyprus, Energy 36 (2011) 5027–5036.
[8] M.C. de Freitas Muraria, C. de Hollanda Cavalcanti Tsuhaa, F. Loveridge, Investigation on the thermal response of steel pipe energy piles with different backfill materials, Renew. Energy 199 (2022) 44–61.

[9] A. Zarrealla, G. Emmi, R. Zecchin, M. De Carli, An appropriate use of the thermal response test for the design of energy foundation piles with U-tube circuits, Energy Build. 134 (2017) 259–270.
[10] Q. Zhao, B. Chen, M. Tian, F. Liu, Investigation on the thermal behavior of energy piles and borehole heat exchangers: a case study, Energy 162 (2018) 787–797.
[11] C. Han, X. Yu, Sensitivity analysis of a vertical geothermal heat pump system, Appl. Energy 170 (2016) 148–160.
[12] S. Karytsas, I. Choropanitis, Barriers against and actions towards renewable energy technologies diffusion: a Principal Component Analysis for residential ground source heat pump (GSHP) systems, Renew. Sustain. Energy Rev. 78 (2017) 252–271.
[13] Y. Shi, F. Xu, X. Li, Z. Lei, Q. Cui, Y. Zhang, Comparison of influence factors on horizontal ground heat exchanger performance through numerical simulation and gray correlation analysis, Appl. Therm. Eng. 213 (2022), 118756.
[14] I. Sarbu, C. Sebarchievici, Ground-Source Heat Pump Systems, Academic Press, Cambridge, 2016, pp. 71–128.
[15] M. Bortoloni, M. Bottarelli, Y. Su, A study on the effect of ground surface boundary conditions in modelling shallow ground heat exchangers, Appl. Therm. Eng. 111 (2017) 1371–1377.
[16] M. Bottarelli, M. Bortoloni, Y. Su, On the sizing of a novel Flat-Panel ground heat exchanger in coupling with a dual-source heat pump, Renew. Energy 142 (2019) 552–560.
[17] L. Mascarin, E. Garbin, E. Di Sipio, G. Dalla Santa, D. Bertermann, G. Artioli, A. Bernardi, A. Galgaro, Selection of backfill grout for shallow geothermal systems: materials investigation and thermo-physical analysis, Construct. Build. Mater. 318 (2022), 125832.
[18] H. Yu, T. Xu, Y. Yuan, F. Gherardi, B. Feng, Z. Jiang, Z. Hu, Enhanced heat extraction for deep borehole heat exchanger through the jet grouting method using high thermal conductivity material, Renew. Energy 177 (2021) 1102–1115.
[19] C.S. Blázquez, A.F. Martín, I.M. Nieto, P.C. García, L.S. Sánchez Pérez, D. González-Aguilera, Analysis and study of different grouting materials in vertical geothermal closed-loop systems, Renew. Energy 114 (2017) 1189–1200.
[20] R. Borinaga-Treviño, P. Pascual-Muñoz, D. Castro-Fresno, J.J. Del Coz-Díaz, Study of different grouting materials used in vertical geothermal closed-loop heat exchangers, Appl. Therm. Eng. 50 (2013) 159–167.
[21] F. Delaleux, X. Py, R. Olives, A. Dominguez, Enhancement of geothermal borehole heat exchangers performances by improvement of bentonite grouts conductivity, Appl. Therm. Eng. 33–34 (2012) 92–99.
[22] C. Lee, K. Lee, H.S. Choi, H.P. Choi, Characteristics of thermally-enhanced bentonite grouts for geothermal heat exchanger in South Korea, Sci. China E 53 (2010) 123–128.
[23] M.L. Allan, S.P. Kavanaugh, Thermal conductivity of cementitious grouts and impact on heat exchanger length design for ground source heat pumps, HVAC R Res. 5 (1999) 85–96.
[24] R. Stropnik, R. Kozelj, E. Zavrl, U. Stritih, Improved thermal energy storage for nearly zero energy buildings with PCM integration, Sol. Energy 190 (2019) 420–426.
[25] S. Barbi, F. Barbieri, S. Marinelli, B. Rimini, S. Merchiori, B. Larwa, M. Bottarelli, M. Montorsi, Phase change material-sand mixtures for distributed latent heat thermal energy storage: interaction and performance analysis, Renew. Energy 169 (2021) 1066–1076.
[26] W. Zhao, Z. Hu, W. He, S. Zhang, H. Yu, G. Xu, H. Chen, Intermittent mode analysis of a borehole ground heat exchanger with novel phase change backfill materials, Appl. Therm. Eng. 189 (2021), 116716.
[27] Y. Rabin, E. Korin, Incorporation of phase-change materials into a ground thermal energy storage system: theoretical study, J. Energy Resour. Technol. 118 (1996) 237–241.
[28] P. Eslami Nejad, M. Bernier, A preliminary assessment on the use of phase change materials around geothermal boreholes, Build. Eng. 119 (2013) 312–321.
[29] J.L. Wang, J. De Zhao, N. Liu, Numerical simulation of borehole heat transfer with phase change material as grout, Appl. Mech. Mater. 577 (2014) 44–47.
[30] W. Yang, R. Xu, B. Yang, J. Yang, Experimental and numerical investigations on the thermal performance of a borehole ground heat exchanger with PCM backfill, Energy 174 (2019) 216–235.
[31] H. Lei, N. Zhu, Analysis of phase change materials (PCMs) used for borehole fill materials, Trans. Geothermal. Resour. Council 33 (2009) 93–98.
[32] X. Li, C. Tong, L. Duanmu, L. Liu, Research on U-tube heat exchanger with shape-stabilized phase change backfill material, Procedia Eng. 146 (2016) 640–647.
[33] D. Qi, L. Pu, F. Sun, Y. Li, Numerical investigation on thermal performance of ground heat exchangers using phase change materials as grout for ground source heat pump system, Appl. Therm. Eng. 106 (2016) 1023–1032.
[34] J. Chen, S. Mao, C. Chen, P. Li, L. Hou, Liao, Efficiency analysis of utilizing phase change materials as grout for a vertical U-tube heat exchanger coupled ground source heat pump system, Appl. Therm. Eng. 130 (2018) 698–709.
[35] M. Zhang, X. Liu, K. Biswas, J. Warner, A three-dimensional numerical investigation of a novel shallow bore ground heat exchanger integrated with phase change material, Appl. Therm. Eng. 162 (2019), 114297.
[36] M.M. Mousa, A.M. Bayomy, M.Z. Saghir, Long-term performance investigation of a GSHP with actual size energy pile with PCM, Appl. Therm. Eng. 210 (2022), 118381.
[37] P.K. Dehdezi, M.R. Hall, A.R. Dawson, Enhancement of soil thermo-physical properties using microencapsulated Phase Change Materials for ground source heat pump applications, Appl. Mech. Mater. 110–116 (2011) 1191–1198.
[38] M. Bottarelli, M. Bortoloni, Y. Su, Heat transfer analysis of underground thermal energy storage in shallow trenches filled with encapsulated phase change materials, Appl. Therm. Eng. 90 (2015) 1044–1051.
[39] M. Bottarelli, M. Bortoloni, Y. Su, C. Yousif, A.A. Aydin, A. Georgiev, Numerical analysis of a novel ground heat exchanger coupled with phase change materials, Appl. Therm. Eng. 88 (2015) 369–375.
[40] X. Lingling, P. Liang, A. Zarrella, Z. Derun, D. Minghao, Z. Shengqi, An experimental investigation on performance of microencapsulated phase change material slurry in ground heat exchanger, Renew. Energy 198 (2022) 296–305.
[41] M. Bottarelli, E. Baccega, S. Cesari, G. Emmi, Role of phase change materials in backfilling of flat-panels ground heat exchanger, Renew. Energy 189 (2022) 1324–1336.
[42] COMSOL Multiphysics, Reference manual [online]. Available at: http://www.comsol.com. (Accessed 21 May 2022).
[43] CLIWAX, Materiali a cambio di fase per l'harvesting energetico in climatizzazione [online]. Available at: http://cliwax.it. (Accessed 21 May 2022).
[44] IDEAS, Novel building integration designs for increased efficiencies in advanced climatically tunable Renew. Energy Syst. [online]. Available at: https://www.horizon2020ideas.eu [Accessed 21 May 2022].
[45] G. Emmi, A. Zarrella, M. De Carli, A heat pump coupled with photovoltaic thermal hybrid solar collectors: a case study of a multi-source energy system, Energy Convers. Manag. 151 (2017) 386–399.
[46] M. Bortoloni, M. Bottarelli, Y. Su, A study on the effect of ground surface boundary conditions in modelling shallow ground heat exchangers, Appl. Therm. Eng. 111 (2017) 1371–1377.