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Benefits in Coupling PCMs with Dual-Source Heat Pumps

Michele Bottarelli[1*], Gang Pei[2], Yuehong Su[3]

[1]University of Ferrara, Via Quartieri 9, 44121 Ferrara, Italy

[2]Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230027, China

[3]Department of Architecture and Built Environment, University of Nottingham, University Park, NG7 2RD, UK

[*]michele.bottarelli@unife.it

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ABSTRACT

Unlike high performance of ground-source heat pumps (GSHPs) as technology for space heating and cooling, installation costs of their ground heat exchangers (GHEs) make the technology less competitive in mild climates than air-source heat pumps. Recently, novel horizontal and shallow GHE solutions take advantage in heat transfer from advanced shapes, making similar solutions less expensive when compared with vertical boreholes. But, the payback remains too long to justify the initial investment. As a consequence, new strategies face the economic affordability by reducing the GHE length hybridizing with other thermal sources. A smart solution is the dual source heat pumps (DSHPs) which switch between air and ground, in order to reduce frosting issues and save the system against low/high temperatures affecting air-mode by using the ground as alternative source and thermal storage system. As the ground is not continuously exploited, GHEs can be sized shorter, and therefore their installation costs become lower than for a full geothermal system. To enhance further the energy performance, that kind of non-continues ground exploitation suggests the coupling of phase change materials (PCMs), as proposed in previous studies for full geothermic closed loop. Matching the former remarks, the present study faces numerically the GHEs coupling of a DSHP with PCMs, by analysing the performance for a whole year of thermal building loads with and without PCMs. As GHEs, the novel flat-panel solution is considered because its flat shape allows an optimal coupling with PCMs. The flat-panel is supposed installed edgeways into a very narrow trench, in which PCMs are mixed with the backfilling material. As PCMs, two different kinds of paraffin are considered to match winter and summer time with different melting points. A 2D model of the cross section of the installation is implemented in COMSOL Multiphysics to solve the heat transfer in porous media with unsteady boundary conditions. Cases with PCMs show better performance only if high thermal conductivity is numerically supposed, since their common low thermal conductivity affects the heat transfer and reduces all benefits.

1. INTRODUCTION

In order to improve the performance of a sole air-source or ground-source invertible heat pumps, dual source heat pumps (DSHPs) couple both air and ground as mutual and complementary thermal sources by switching between them to select more profitable temperatures and to reduce frosting issues, as reported in Corberán et al. (2018). As the ground thermal source is not continuously exploited, ground heat exchangers (GHEs) can be sized smaller, and therefore the installation costs of DSHPs are lower than a full ground source heat pump system (GSHP, DOE (2018). The intermittent ground thermal exploitation and the low thermal diffusivity of the soil suggest the potential of a further performance enhancement by coupling phase change materials (PCMs) directly into the backfilling material with GHEs, as proposed in previous researches for GSHP systems, Bottarelli et al. (2015) and Javadi et al. (2018).

The present study is hence aimed to investigate numerically coupling PCMs with GHE of a DSHP, by modelling and analysing the time-series and annual energy performance for a DSHP with and without coupling of PCMs for given time-series building thermal loads.

2. METHODOLOGY

The numerical analysis has been carried out by implementing the 2D cross section of a shallow GHE installation in COMSOL Multiphysics v5.5 for solving transient heat transfer in solid (Figure 1). The problem is numerically described by the following Eq.1 and solved via finite element method by considering the heat conduction in an equivalent solid to the supposed mixture of PCMs and soil, as better reported in COMSOL (2017) and Bottarelli et al. (2015):

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

where ρ_{eq}, c_{eq} and λ_{eq} are the equivalent density, specific heat and heat conductivity of the mixture, which can be calculated as the mass weighted average properties of the mixture at the given temperature.

The solid is composed by three materials (soil, PCM_1, PCM_2), which are only mixed into the GHE trench. The two different PCMs are supposed to support winter and summer time with different melting points, 7°C (PCM_1) and 26°C (PCM_2). Different densities, specific heats, conductivities are considered for the two PCMs to account the thermal properties of the backfill material according to their supposed volume ratios, 35% for PCM_1, 15% for PCM_2.

To control the phase change and all the previous thermal properties, the specific heat capacity is implemented in COMSOL by mean of the relationships reported in Bottarelli et al. (2015). The latent heat of fusion is accounted as an adjunct term to the specific equivalent specific heat by means of a normalized Dirac's pulse; the phase change between the liquid and solid phase is then expressed in as a function of a dimensionless variable to moderate the switching between solid and liquid phase, as reported in Bottarelli et al. (2015).

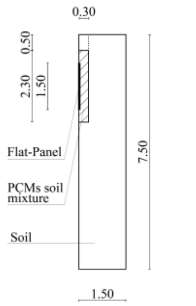

Figure 1: Domain

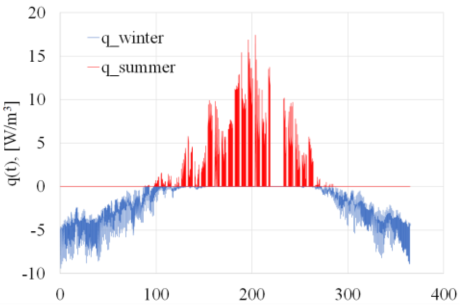

Figure 2: Heat load (reference case)

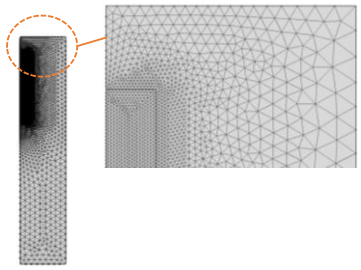

Figure 3: Mesh

As a GHE, the Flat-Panel solution (FP) is considered because of its flat shape which allows a better coupling with PCMs. The FP is 1.5 m high and supposed installed edgeways into a trench 2.8m deep and 0.6m wide, in which PCMs are mixed together with the soil. A 3.0 metres FP span is considered, so that the full domain in COMSOL is set 1.5 m wide (half span) and 7.5 m deep, having a symmetry condition at the FP section and an adiabatic one on the opposite side. On top, the soil temperature time series is set as monitored by means of a comprehensive local weather dataset collected for year 2015 with the weather station operating at the TekneHub Laboratories of the University of Ferrara (Italy), and the yearly average air temperature is fixed at the bottom.

Time series of air temperature and wind have been used to implement and solve in EnergyPlus the energy requirements for space heating and cooling of the whole lab ($3300 m^3$), as widely reported in Bottarelli et al. (2015) and depicted in Figure 2.

For simplicity, the resulting heat load has been used for the boundary condition at the FP (q_{FP}) , as follows:

$$q_{FP} = r \cdot q(t) \cdot \frac{1}{S_{FP}} \tag{2}$$

where r is the volume-to-length ratio between the building volume (m^3) and the trench length (m), $q(t)$ is the specific energy requirement calculated for unit building volume (W/m^3), and S_{FP} is the FP heat transfer surface (m^2) for unit length of trench (m).

To differentiate the DSHP from the GSHP case, a control function has been implemented in COMSOL. For the DSHP, when the FP temperature is lower than the air temperature in winter (higher in summer), q_{FP} is supposed to be exchanged with the air rather than the ground, and therefore the FP heat flux is temporary set to zero. In wintertime, this control is carried out when the air temperature is below the cut-off value of 5°C, to preserve the thermal energy stored during the summer time in the ground.

3. RESULTS

A preliminary analysis has been carried out to warrant the mesh independence of the results, which has been achieved with 9574 elements (Figure 3), mainly concentrated around the GHE trench.

In Figure 4 the average temperatures at the FP surface for the two conditions of DSHP and GSHP are reported, both with and without the PCMs, together with the air temperature. Due to the too low values achieved by the initial GSHP case, the FP heat flux was halved by setting a halved value for the volume-to-length ratio r. As a consequence, a double FP length should be needed to satisfy the same energy requirement. The DSHP case shows always higher temperatures than the GSHP case, since able to switch to the air, when the ground temperature is lower in winter. However, this strategy leaves a warmer ground at the beginning of summer and therefore less advantageous in summer time. On the contrary, the lower ground temperature of GSHP case makes the condition disadvantageous in winter time, but profitable in summer. Similarly, the usage of PCMs shows the same behavior between winter and summer time, but the performance of both cases are clearly improved.

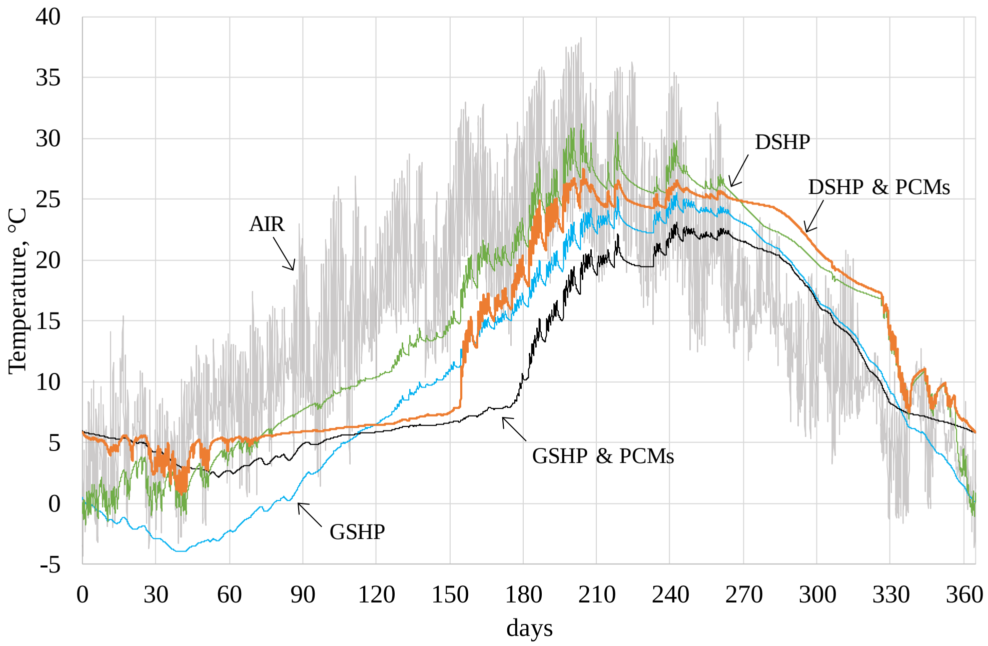

Figure 4: Resulting ground temperatures at the Flat-Panel section

In Table 1, the overall energy exchanged in winter and in summer are summarized together with the energy weighted temperature at which the heat transfer has occurred with the ground and fully with the thermal source selected (air/ground). The two cases (GSHP, DSHP) are summarized both with and without PCMs, but with a volume-to-length-ratio of 10 for the GSHP case and 20 for DSHP, since a higher value for GSHP leaded to temperatures several degrees below zero, and therefore not complaint with common operating values.

For the GSHP case, PCMs provide more profitable ground average temperatures at the FP, since increase from 2.8 to 6.6 °C in wintertime, and decrease from 19.5 to 15.3 °C in summertime. For the case DSHP, the improvement in ground mode is from 3.9 to 6.0 °C in wintertime, and from 23.5 to 20.2 °C in summertime. The DSHP values would seem worse than those of the GSHP, but it has to be noted that the GHE length is halved for the DSHP case, since the volume-to-length factor is twice that of the GSHP case. Moreover, if the air/ground average temperature is taken into account for the DSHP case, the improvement is from 7.0 to 7.9 °C in wintertime, and from 16.2 to 15.7 °C in summertime. The previous remarks show that PCMs improve always the performance of both system, and that the DSHP case shows mainly better temperatures than GSHP, even if a few degrees.

In terms of heat exchanged with the ground in wintertime, the DSHP shows to be able to exchange 37.3 kWh per square meter of Flat-Panel with PCMs against the 48.9 kWh/m^2 of the GSHP, but with half the length, which means halved installation cost, and with a more profitable average temperature (7.9 against 6.0°C). In summertime, the DSHP case with PCMs is able to exchange 33.0 kWh/m^2 at 15.7 °C, on average, and the GSHP case 21.2 kWh/m^2 at 15.3 °C. Therefore, with the same GHE length the DSHP case would be able to exchange with the ground 74.6 and 66.0 kWh/m^2 in winter and summer season, while the GSHP case has 48.9 and 21.2 kWh/m^2, which remain invariant due to the sole ground source is used.

Table 1: Winter and summer heat transferred, and average temperatures in heat transfer

PARAMETERS	DSHP	GSHP	DSHP & PCMs	GSHP & PCMs	UNIT
Volume-to-length factor	20	10	20	10	m^3/m
Winter heat from ground	-27.3	-48.9	-30.5	-48.9	kWh/m^2
Summer heat to ground	29.3	21.2	30.6	21.2	kWh/m^2
Winter ground average temperature	3.9	2.8	4.4	3.6	°C
Summer ground average temperature	23.5	19.5	22.0	17.3	°C
Winter air/ground average temperature	7.0	*(2.8)*	7.2	*(3.6)*	°C
Summer air/ground average temperature	16.2	*(19.5)*	15.9	*(17.3)*	°C
Average heat flux at FP in wintertime	-28.9	-8.6	-29.2	-8.6	W/m^2
Average heat flux at FP in summertime	31.9	16.7	32.1	16.7	W/m^2
Operating time in winter	943.8	5666.0	1041.8	5666.0	h
Operating time in summer	916.2	1273.0	954.6	1273.0	h

4. CONCLUSIONS

Dual source heat pump (DSHP) is a strategy to improve the energy performance of heat pump systems devoted to air conditioning needs in mild climate, since it makes possible to explore a more advantageous thermal source between air and ground, if compared with a sole ground source heat pump (GSHP).

In addition, use of a DSHP can allow to roughly halve the length of GHE, which means halved installation costs. Furthermore, the usage of PCMs can improve the energy performance of both cases by smoothing thermal wave, particularly for the DSHP case, making the topic worthy of further analysis.

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