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Energy performance of a dual air and ground-source heat pump coupled with a Flat-Panel ground heat exchanger

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Integrating air and ground source can be an effective solution to improve the performance of a heat pump by reducing the drawbacks of each individual technology. In fact, a dual source system not only greatly reduce the size of the ground heat exchanger, but also can achieve a higher efficiency by selecting the more thermally favourable source. Hence, the frosting/defrosting process, which regularly occurs in a common air source heat pump (ASHP) could be avoided. In the present contribution, the performance of a dual source heat pump (DSHP) has been numerically analysed. The energy demand for both heating and cooling of building has been estimated by means of the software EnergyPlus. Then, the resulting time series values are used as the boundary heat fluxes to model a ground heat exchanger. The commercial Finite Element Method (FEM) simulation package COMSOL Multiphysics is implemented to simulate the heat transfer in the ground which is produced by a horizontal Flat-Panel ground heat exchanger. A function has been properly implemented in COMSOL to control the switching between air and ground sources, according to their temperatures. Compared with an ASHP, the DSHP shows much higher efficiency because of the more favourable working conditions and the protection against frosting. Consequently, a DSHP should be a viable solution to combine the respective advantages of air source and ground source heat pumps.

Keywords: dual-source heat pumps, horizontal ground heat exchanger, finite element model (FEM)

INTRODUCTION

Nowadays, the reduction of greenhouse gas emissions and the rational use of energy have become a major issue. In view of this, the recent environmental policies have been promoting the renewable technologies expanded worldwide. Among them, air-source heat pumps (ASHPs) and ground-coupled heat pumps (GCHPs) are regarded as viable and efficient technologies for applications of heating and cooling in residential and commercial buildings [1]. These systems are gradually being applied with significant savings in terms of primary energy, due to their universal applicability and versatility. Due to their universal applicability and versatility, these systems have been gradually applied with significant saving of primary energy use in the recent years. The performance of a heat pump is significantly affected by the operating conditions, which depend on the heating/cooling demand and the heat source feature. In order to achieve higher efficiency than the widespread ASHPs, the GCHP systems use the ground as a heat source/sink, which often provides more favourable and stable temperature than outdoor air temperature. As the depth increases, the ground temperature fluctuations are reduced. The annual average temperature of the shallow ground depends on the location and it is approximately equal to the annual average air temperature [2]. In addition, the ground temperature can be significantly different between rural and urban areas, where the soil is usually warmer due to the urban heat island effect [3].

Besides the high efficiency, GCHPs have also higher purchase and installation cost than air-source systems due to the initial cost of the ground heat exchanger [4], which is recognized as the least efficient component of these systems. In addition, the performance of a GCHP is strongly affected by the ground heat exchanger, which can be installed in vertical boreholes or in shallow horizontal trenches (also referred as VGHE and HGHE, respectively). The HGHEs hold some advantages in terms of costs and installation but as well have drawbacks in terms of land area requirements and efficiency of soil heat transfer. In order to overcome the drawbacks of current available technology, recent studies have attempted to develop more efficient arrangements for the widespread HGHE configurations [5] or novel shapes such as the Flat-Panel, which has been developed at the University of Ferrara in 2012 [6].

In contrast, ASHPs have a low initial installation cost and are almost easily applied. However, during winter operations as well as under cold and humid weather condition, these systems are subjected to frosting on the evaporator. This phenomenon

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produces both reduction in the efficiency and the heating capacity of an ASHP [7], thus defrost cycles are required to remove the frost and improve the performance. If defrosting is obtained by inverting the refrigeration cycle, the coefficient of performance (COP) for the whole heating season can be reduced up to 12.6%, under certain conditions of relative humidity and outdoor air temperature [8]. Many techniques have been investigated to efficiently reduce defrosting cycles or completely prevent frosting on the outdoor unit of an ASHP [9].

In view of the disadvantages of a single source heat pump, the opportunity to couple the air-source with the ground-source in a dual air and ground source heat pump system can produce a significant efficiency improvement [10]. An optimised DSHP can achieve high efficiency by switching between air and ground sources/sinks according to the source temperature, thus preventing the frosting during winter. Moreover, the size of the ground heat exchanger can be considerably reduced with DSHPs, according the lower thermal energy exchanged with the ground in comparison with conventional GCHPs [11-12]. Therefore, the DSHP solution could offer a right balance between the individual ASHP and GCHP, thus enhancing the performance of heat pumps.

This study aims to evaluate the opportunity to realise a DSHP, and its potential benefits over conventional ASHP and GSHP. The analysis is carried out numerically, as the first step of future studies.

METHODS

This study has simulated the performance of a dual-source heat pump (DSHP) by using numerical analysis method. The ground coupling is intended to be used for supplemental heat extraction or rejection and as an alternative of a conventional outdoor air unit. The DSHP is assumed to be coupled with the ground by means of an innovative HGHE, named Flat-Panel (FP), which has been recently developed at the University of Ferrara.

The Flat-Panel is a rectangular module, 3m long and 1m high, consisting of two polypropylene (PP) sheets with the thickness of 4mm. They are welded by leaving 0.02m space between them in order to form a cavity to allow the working fluid flows. Within the cavity, a labyrinth has been designed as a series of rectangular channels with a high width-height ratio. The fluid flows for most of the length in a vertical direction, in order to avoid thermal stratification caused by buoyancy forces. The performance of Flat-Panel has been tested with an experimental setup at the Department of Architecture, the University of Ferrara (Italy) since 2011. The experimental setup covers a land area of about 320 m^2, and it is equipped with a 2 Flat-Panel which are installed 1.85 m deep in the soil to serve as the HGHE. Tests were conducted in different operating conditions (heating and cooling) and for different operating modes (continuous, discontinuous and pulsed). Tests were performed for different flow rates, in the range of 80l/h and 260l/h, thus the flow regime is always laminar. Overall, the HGHE showed very good performance in terms of heat transfer rate both in cooling and heating operations. A detailed description of the experimental setup and testing activity is reported in [13].

The TekneHub laboratory of the University of Ferrara, located in the northern Italy, has been taken as the reference case. The building has been simulated by means of the EnergyPlus (E+) software, in order to estimate the heating and cooling demand.

The resulting time series at hourly scale is used as the heat load in a 2D model of the HGHE, which is implemented in the commercial FEM numerical code COMSOL Multiphysics. The model is used to simulate the heat transfer in the ground with Flat-Panels, in order to evaluate the temperature trend of the ground source in comparison with that of the air. A user defined function has been used in the model to control the switching between air and ground sources, according to their temperatures. Finally, by analysing the system operation, the frosting prevention offered by the DSHP is calculated. Details are presented in the next paragraphs.

Building energy demand

In this study, the reference target for heating and cooling demand is the TekneHub laboratory of the University of Ferrara, shown in Fig.1, which belongs to the High Technology Network of Emilia-Romagna region of Italy. The Network is intended to promote the technology transfer between the university and industry sectors. In order to estimate the heating and cooling loads, the well-known building energy simulation software, EnergyPlus, is employed to simulate the TekneHub laboratory. EnergyPlus can predict the dynamic values of heating, cooling, lighting, ventilation, renewable energy generation as well as water use in buildings [14]. The accuracy of EnergyPlus simulation has been verified by many researchers, so it has been well accepted worldwide.

The TekneHub is in the city of Ferrara (N44.831, E11.599), which is located in the northern Italy, in the valley of the Po river. The local climate is usually referred to as a humid continental climate. The winter is harsh and humid, and the temperature often decreases below 0°C (2326 heating degree days). The summer is hot and muggy, with high temperature (higher than 35°C) during the day.

The building has only one floor with a gross floor area of 880m^2 and a gross volume of 3488m^3, subdivided in twenty rooms, laboratories and technical spaces. The building envelope is compliant with recent Italian regulations on the energy performance of building: the external walls are made of cavity brick walls with a polystyrene thermal insulation layer (calculated U-value of 0.21 W/m^{2}K); the roof is made of predalles precast roof slabs with 160mm of polystyrene thermal insulation layer (calculated U-value of 0.20W/m^{2}K); the floor consists of an insulated light concrete layer supported by a structural concrete aired slab and a concrete sub-foundation (calculated U-value of 0.24W/m^{2}K).

Fig.1. TekneHub laboratory

Further details of the buildings components are not included in the present manuscript, for sake of brevity. An experimental analysis was carried to calculate the effective U-value of the external walls [15]. In view of this, the walls U-value in the model has been corrected to 0.38W/m^{2}K, according the experimental data we monitored. The building envelope has been modelled in 3D, as shown in Fig.2, by means of OpenStudio, which is a plug-in to the software Sketch-up, offering a graphic interface for EnergyPlus. The geometry model was first built up in OpenStudio with the default settings for EnergyPlus simulation, and some modifications were made through the IDF Editor of EnergyPlus.

Finally, the heating and cooling system of TekneHub is equipped with two air-to-air rooftop heat pumps with a capacity of 40kW each. In the EnergyPlus model, the air-conditioning plant is assumed to be a variable refrigerant flow (VRF) type, according to the two ASHPs installed. The details about the model of VRF and its settings can be found in the documentation of EnergyPlus [16]. The building is divided in two separate thermal zones, each one is assigned to a heat pump; the heating/cooling distribution system is modelled according to that installed and consists of several fan coil units which are set to operate continuously during the heating season whereas during cooling season from Monday to Friday, 12h a day; during public holidays the system is assumed to be turned off.

A comprehensive weather dataset (e.g. outdoor air temperature, solar radiation, humidity, soil temperature at different depths) were imported in EnergyPlus in order to run simulations. The dataset was collected in 2015 by means of a weather station (Davis Vantage Pro 2) installed in the garden of the TekneHub laboratory.

The EnergyPlus simulation has run for a whole year (2015), as shown in Fig.3, where the cooling peak load is obviously higher than the heating.

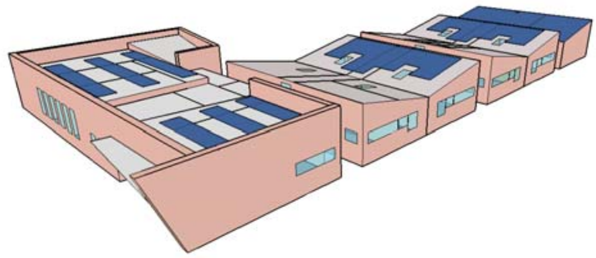

Fig.2. 3D model of the building envelope

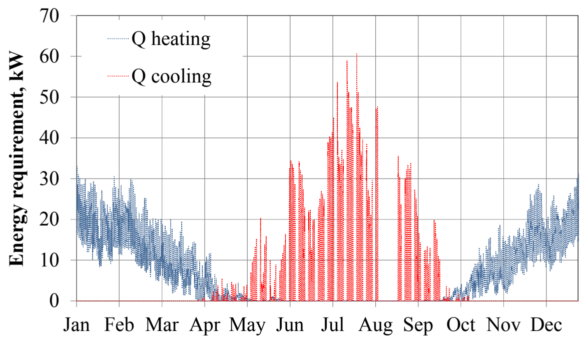

Fig.3. Building heating and cooling demand

The time series at hourly scale of the energy requirement for space heating and cooling were used to define the heat flux at the HGHE in the FEM model, as detailed in Section 2.2.

Numerical modelling

The numerical analysis is conducted by means of a commercial finite element numerical code COMSOL Multiphysics, solving the heat transfer problem in solids, thus, only conductive heat transport is considered. This study is focused on the evolution of the temperature distribution of the ground source, due to heat extraction/rejection by the ground coupling of the DSHP. The efficiency of the heat pump in fact depends on the temperature of the ground as a heat source or sink. Solving the 3D thermo-fluid dynamic problem within the HGHE is beyond the scope of this work. Therefore, the soil heat transfer has been simulated in a 2D domain. Here, the HGHE is assumed to be a Flat-panel (FP) [6, 13].

The 2D computational domain is modelled as a cross-section of an HGHE and a large surrounding soil part (6 m wide and 10 m deep), as shown in Fig.4 together with the full mesh and the boundary conditions.

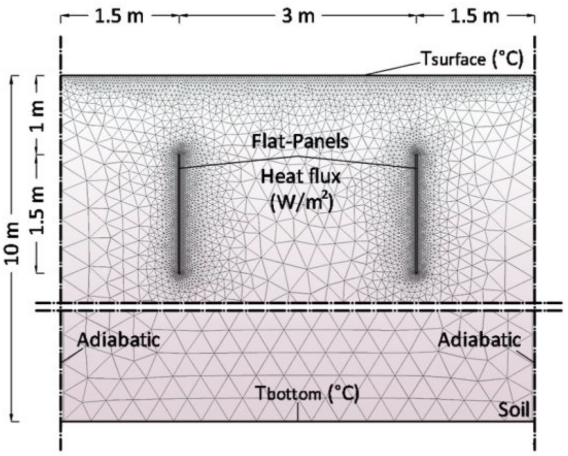

Fig.4. Sketch of the 2D model domain, boundary conditions and mesh

Two parallel lines equipped with Flat-Panels (1.5m high) are assumed to be placed at an average depth of 1.75m with a distance of 3m, in order to take into account of the thermal interference between each line. In the model domain, the FPs were simplified as boundary condition. According to a 2D approach, the Flat-Panel shape may be simplified as a cold/hot plate, to and from which heat flows from the surrounding soil mainly by heat conduction. From this point of view, a 2D model can be considered as representative of a three-dimensional geometry in the hypothesis that the temperature variations are small along the exchanger (between inlet and outlet sections) and that no thermal stratification occurs within the working fluid (for FPs this is not expected due to the labyrinth). In view of this, the results are compared in terms of the average temperature at the interface between HGHE and the ground, which is representative of the average temperature of the working fluid.

The soil is considered to be homogeneous with constant thermal properties (thermal conductivity, density, heat capacity), as reported in Table.1.

Table 1. Physical properties of soil

Thermal conductivity	Density	Specific heat
(W/mK)	(kg/m^3)	(J/kgK)
0.8	1600	1500

In the model, the hourly scale time series of the measured temperature at the soil surface in 2015 is set as the boundary condition at the top, whereas a constant temperature at the bottom, is equal to the yearly average ground temperature at shallow depth (16.7°C). An adiabatic condition is assigned to the side boundaries of the domain.

In the model, the Flat-Panels were treated as boundary heat sources at the interface between the ground and the Flat-Panels, thus the heat flux q_g (W/m^2) is calculated at hourly scale by means of Eq. 1:

$$q_g(t) = \frac{r \cdot q_t}{S_{FP}} \tag{1}$$

Where: q_t (W/m^3) is the building heating/cooling demand, as calculated at hourly scale by means of the EnergyPlus model according to the building gross volume (3488m^3); S_{FP} (3 m^2/m) is the heat transfer surface of a single Flat-Panel for unit length of the HGHE (1m) and r (m^3/m) is a parameter which is used to assign a portion of the building gross volume to the unit length of HGHE (1m). Therefore, the product of r and q_t is the rate of heat transfer for unit length of HGHE, expressed in W/m, which commonly used to identify the performance of HGHEs and VGHEs.

In the model, the resulting q_g time series was assigned as a 2nd kind boundary condition at each line composing the flat-panel HGHE.

In setting the heating/cooling load at the HGHE we assumed a simplification by neglecting the electricity share as defined by the heat pumps coefficient of performance, since the analysis is focused on the ground heat transfer due to HGHEs.

To control the switching between air and ground sources thus simulating the operation of a DSHP, a user-defined function has been programmed in COMSOL. On one hand, the temperature of the air source is defined by means of the outdoor air temperature time series (year 2015) implemented in the model. On the other hand, the temperature of the ground source is the calculated average temperature at the Flat-Panel boundary condition at each time step (1h).

The function is set to activate the boundary heat source at the Flat-Panel, according to the ground heating/cooling load, when the ground source temperature is more favourable than that of the air source, and meantime the outdoor air temperature is lower than 5°C (thus avoiding most of frosting conditions). The ground allows better working conditions when its temperature is higher than that of the outdoor air in winter, or lower in summer. Otherwise, in all other conditions, the boundary heat source term is set to zero, thus simulating the operation of the ASHP using the air source only.

The finite element grid resolution is higher at the FP boundary where higher temperature gradients are expected and coarse in the outer domain. The full mesh consists of 11,200 elements. In order to check the grid independence, a preliminary analysis has been carried out by increasing the number of the elements.

The initial temperature profile of the soil for simulations is obtained from the measured temperature of the ground at different depth.

A parametric study of the heat load at the flat-panel HGHE has been performed, thus simulating different sizing of HGHE. In a DSHP in fact, the HGHE is intended to be used as an alternative of a conventional outdoor air unit for heat extraction or rejection, thus the size of the HGHE can be significantly reduced with DSHPs, because the ground source is not always operating. In view of this, five different values of the parameter *r* have been assumed (5, 7.5, 10, 15, 20), i.e., for example, when *r* = 5, 5m^3 of building volume is supplied for each meter of FP.

RESULTS AND DISCUSSION

The numerical simulations were run for the different values of the parameter *r* under the same boundary conditions. Each simulation was carried out for two consecutive years. The present paper is focused on the temperature variation in the ground source occurring due to the heat extraction/rejection by the HGHE.

The daily average temperature of the ground source is shown in Fig.5 for each test case, throughout a whole year.

The temperature is calculated as the average temperature at the FP boundaries, where the heat flux was applied as shown in the previous Fig.4. The ground source temperature is compared with the outdoor air temperature T_{air}, which represents the air temperature at the outdoor unit of an ASHP.

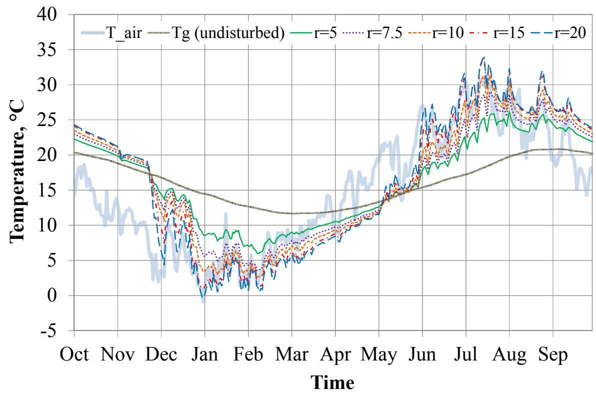

Fig.5. Daily average temperature of the ground

The undisturbed ground temperature at the average depth of the HGHE (-1.75m) is also included in Fig.5. Up to the middle of November, the outdoor air temperature allows more favourable working condition (>5°C) therefore the air source is selected by the DSHP instead of ground source. After the 20th of November the ground temperature is profitable during the night-time and when T_{air} decreases below 5°C, the DSHP switches to the HGHE. On the contrary, the ground is used as a heat sink for the whole summer period, when its temperature is more favourable than that of the air. Summertime, the discontinuous operating mode of the air-conditioning system produces a quick temperature increase at each start-up, due to the higher ground load. Overall, the higher the value of *r*, the higher the ground load is for heating and cooling at the HGHE. Therefore a significant variation is observed in the ground temperature. As a consequence, for *r* equal to 15 and 20m^3/m, the ground source is no longer convenient in late heating and cooling season.

The maximum and minimum temperatures of the ground source (in the heating and cooling season, respectively) are summarized in Table.2 for each case, together with maximum value of the heat transfer rate at the Flat-Panel. In addition, we calculated the overall length of the HGHE which is required to cover the peak energy demand of the building (60.57kW), according to the values of parameter *r*. The size of the HGHE can be reduced

Table 2. Temperature of the ground source, HGHE size

r	$HGHE_L$	q_{max}	T_{max}	T_{min}
(m^3/m)	(m)	(W/m)	(°C)	(°C)
5	698	86.8	27.4	5.5
7.5	465	130.2	31.1	2.7
10	349	173.7	34.4	1.4
15	233	260.5	37.7	-1
20	174	347.3	38.4	-3.2

significantly with a DSHP: for r=10m^3/m the overall length of the HGHE can be almost halved, while maintaining acceptable operating conditions. Although a further reduction can be achievable for r=15m^3/m and r=20m^3/m, the temperatures of the ground source are not favourable and would require the use of a mixture water/glycol as working fluid, in order to prevent freezing wintertime.

A DSHP use the ground as the heat source/sink only partially, according to the adopted criteria and the environmental conditions. Fig.6 shows the ratio between the operating time (h) of the flat-panel HGHE and the overall operating time of the DSHP for heating and cooling. Similarly, we calculated the ratio of the energy exchanged with the ground (Wh/m) and the overall energy requirements. According to the adopted operating criteria and for r=5 m^3/m, the geothermal heat exchanger is operating the 23.4% and 88.5% of the time in winter and summer, respectively; the energy exchanged is the 41.7% and 95%. As the value of r increases (therefore the HGHE size decreases) a negative trend was observed. The reduction is significant for r=15 m^3/m and 20 m^3/m, due to the progressive thermal degradation of the ground source.

In addition, a DSHP can prevent the frosting at the outdoor unit by switching between air and ground sources that is always occurring when the average air temperature at the evaporator is below the frosting point temperature, In view of this, we calculated the amount of days in 2015 during which the frosting can be avoided. The frosting is assumed to occur when the leaving air temperature at the outdoor unit is below 0°C and below the dew-point. Moreover, we assumed that the air-source exchanger cools the air flowing across the fins by 4K.

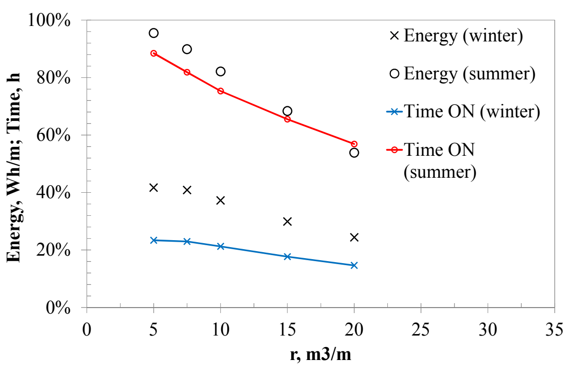

Fig.6. Annual percentage operation time of the flat-panel HGHE

The frosting prevention occurs only when the HGHE is operating. The resulting days of frosting prevention are reported in Fig.7, for each test case, together with the outdoor air and the dew point temperature.

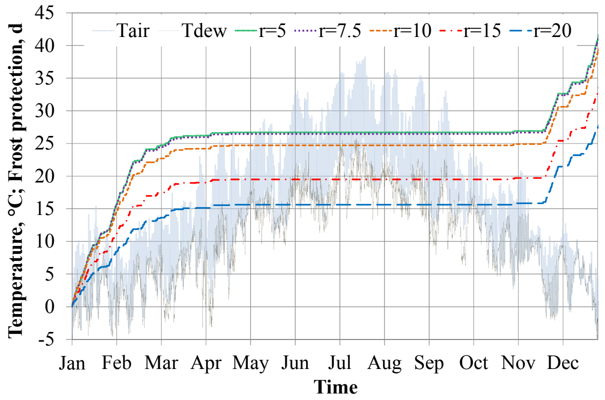

Fig.7. Frosting prevention as indicated by the accumulative days, owing to use of the DSHP

CONCLUSIONS

This study has evaluated a dual source heat pump (DSHP), in order to demonstrate its potential benefits over conventional individual air-source heat pump (ASHP) or ground-source heat pump (GSHP). A combined use of two software, COMSOL and EnergyPlus, has been used to evaluate a dual air and ground source heat pump. The model has been put forward as a modification to an existing air source air conditioning plant, in order to find out the potential benefit of coupling a novel flat-panel horizontal ground heat exchanger (HGHE).

The simulation results show that an HGHE can be suitable for supplemental heat extraction or rejection and as an alternative of a conventional outdoor air unit, allowing more favourable working conditions. The installation of the innovative Flat-Panel HGHE offers an efficient and cost effective solution to the generally expensive ground heat exchanger. Use of a DSHP can reduce the required size of a ground heat exchanger, so the presented dual source heat pump may be fairly profitable. In addition, the switch between the air source and ground source can effectively alleviate the frosting issue which is a common issue for operation of a heat pump in the cold winter. The preliminary results by this study have provided a valuable information for further investigation.

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