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Experimental study on a Dual-Source Heat Pump in ground mode to assess the soil thermal response by means of a Distributed Temperature Sensing system

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Abstract. In this paper, a Dual-Source Heat Pump (DSHP), able to exploit both aerothermal and geothermal energy sources, has been tested in ground mode to evaluate experimentally the soil thermal response in presence of an undersized Borehole Heat Exchanger (BHE) field. The field is instrumented with a Distributed Temperature Sensing (DTS) system, by which the geothermal fluid temperature can be measured over the entire length of the boreholes during the heat pump operation. The DSHP has been tested to reproduce the working profile of a heat generator coupled to a reference building, which has been numerically simulated by means of ALMABuild, a Matlab-Simulink tool. Three operating profiles have been identified within the simulation results to define three typical days of the heating season, characterized by different required loads. The results show that a DSHP operated in ground-mode and coupled to a borefield 50% undersized can meet completely the heating needs of a typical winter day, whilst higher building loads must be satisfied exploiting both air and ground sources. In this case, 80% of the undisturbed temperature of the soil can be recovered in an hour when aerothermal energy is extracted, thus the unit efficiency remains high and the investment cost is strongly reduced.

1. Introduction

In the recent decades, the increase of greenhouse gas emissions has encouraged the adoption of electric heat pumps to replace fossil fuel boilers in HVAC systems. Nonetheless, both Air-Source Heat Pumps (ASHPs) and Ground-Coupled Heat Pumps (GCHPs) present some limits: ASHPs operate with low performance when the outdoor temperature drops, due to thermodynamic reasons and the deposition of an ice layer on the external heat exchanger, while GCHPs need high investment cost to install the Borehole Heat Exchanger (BHE) field. In order to overcome these problems, Dual-Source Heat Pumps (DSHPs) able to exploit both aerothermal and geothermal energy sources and coupled to an undersized BHE field have been introduced [1-3]. In parallel, a correct design of the borefield is necessary to guarantee proper performance of the system and limit the investment cost linked to BHEs installation [4]. Although the traditional design procedures, such as the ASHRAE method, provide rapid and simple guidelines to calculate the total length of the boreholes, with these methodologies the borefield size is typically oversized and, consequently, the capital expenses increase. In order to limit this problem, a deeper knowledge of the ground properties and its thermal response can be achieved by means of Distributed Temperature Sensing (DTS) systems, typically based on laser measurements in optical fibres inserted within the BHEs or installed in the soil nearby [5-6].

With the aim to evaluate the benefits of the above-mentioned technologies, in this paper the prototype of an innovative DSHP has been tested in ground-source mode for different operating conditions. The prototype is coupled to a borefield made of 4 in-line vertical double-U tube BHEs having different lengths. The size of the field can be varied during each test with respect to its total length (i.e., 300 m) since each borehole can be intercepted individually. In order to evaluate dynamically the performance of the borefield for several operating conditions, the geothermal fluid temperature over the entire length of 2 BHEs has been measured experimentally by a DTS system during the heat pump operation, assessing the recovery time and the heat transfer rate.

2. Experimental test rig and Dual Source Heat Pump

The experimental test rig employed in this paper is shown in figure 1. The innovative DSHP prototype under test, able to exploit both aerothermal and geothermal energy sources, is placed within an underground climate chamber and is coupled to a hydronic loop, by means of which the building heating/cooling load can be emulated according to the Hardware-in-the-Loop (HiL) approach. A borefield made of 4 in-line vertical double-U tube BHEs having different lengths (i.e., two are 55 m long, namely BHE1 and BHE2, and two are 95 m long, namely BHE3 and BHE4) is adopted to reject/absorb heat to/from the ground when the DSHP operates in ground source mode. It is worth mentioning that the overall length of the borefield can be varied to check the influence of the BHE field size on the heat pump performance. In fact, each borehole can be intercepted independently by means of a shut-off valve. Additionally, as pointed out by figure 1, groundwater movement can be between 25-30 m and 36-50 m of depth.

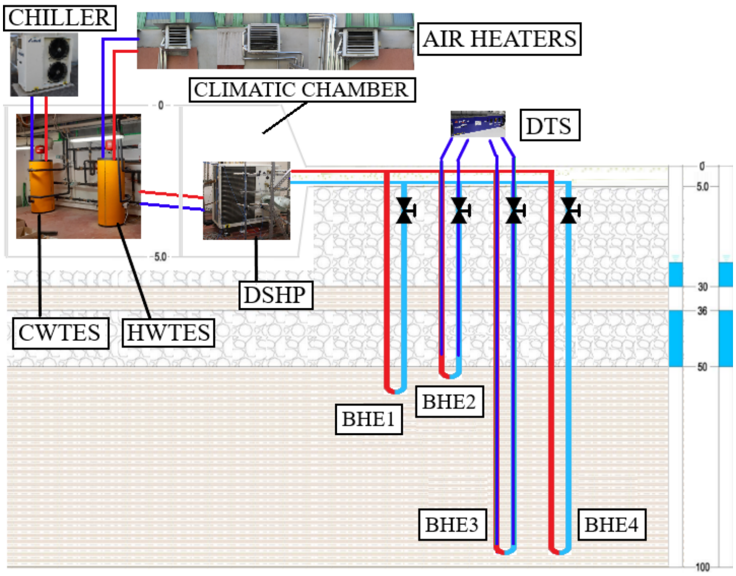
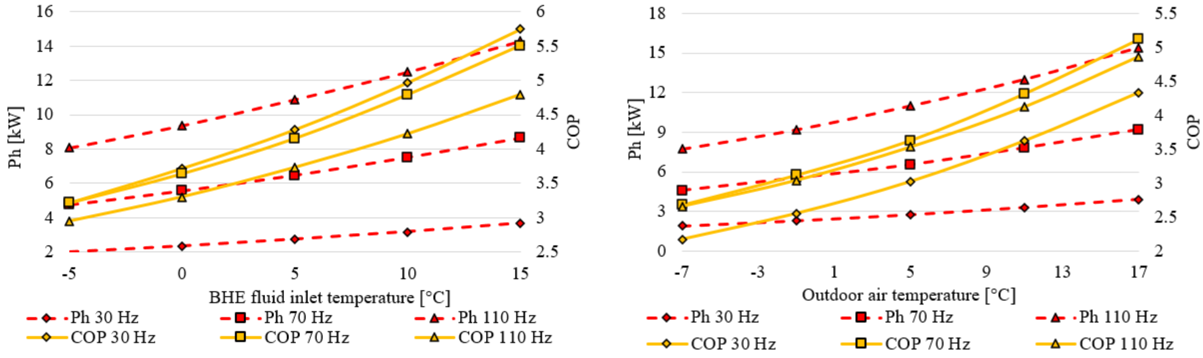


Figure 1. Experimental test rig.

A Distributed Temperature Sensing (DTS) system is installed in the BHE field to measure dynamically the fluid temperature distribution along different boreholes when the DSHP is tested in ground-source mode. More in detail, fibre optical cables are placed within supply and return pipes of a single U-tube of BHE2 and BHE3, having a length of 55 m and 95 m, respectively. The installed DTS system (SMARTEC, DiTemp Light Reading Unit) has a minimum spatial resolution of 2 m, a measurement time higher than 10 s and a resolution of ±0.1 K.

The heat pump tested in this work is a variable-speed dual-source prototype using R-410A as refrigerant. The rated heating capacity of the unit operating in ground source mode is 12.5 kW, evaluated in the following conditions: borehole fluid temperature at the inlet of the heat pump evaporator equal to 10 °C, load water inlet and outlet temperature equal to 35 °C and 40 °C, respectively. In figure 2a and 2b, values of thermal capacity (P_h) and Coefficient of Performance (COP) given by the manufacturer are reported for both operating modes (i.e., air source and ground source) as functions of the external source temperature at the heat pump inlet, for different inverter frequencies.



(a) (b)

Figure 2. Heating capacity (P_h) and *COP* of the DSHP as functions of the BHE fluid inlet temperature (a) and outdoor air temperature (b) for different inverter frequencies (water temperature at the inlet/outlet of the heat pump condenser of 35/40 °C).

In order to guarantee proper operations of the DSHP, a hot water thermal energy storage (HWTES in figure 1) tank is placed in the hydronic loop (load side). The tank has a volume of 0.5 m^3 and the hot water produced by the heat pump flows in a coiled heat exchanger, immersed within the tank. The HWTES is connected to a second thermal energy storage tank of cold water (CWTES, see figure 1), having a volume of 0.5 m^3. An external chiller coupled to the CWTES, and three external air heaters linked to the HWTES (see figure 1) allow to dissipate heat to the ambient air (when needed). Further details on the experimental test rig, the sizing of its components and the typical operating conditions can be found in [7] and are not reported here for sake of brevity.

Additionally, temperature sensors (RTD Pt100, range from −5 °C to 50 °C, accuracy class 1/10 DIN, uncertainty ±0.15 K), electromagnetic flow meters (Siemens, SITRANS F M MAG 1100 as sensor and MAG 6000 as transmitter, range 0–5000 l h^{-1}, overall accuracy 0.2% ± 1.77 l h^{-1}) are installed in the hydronic loop to check the operation of the system and evaluate the energy performance of the heat pump under test. A power meter is also used during experimental tests (Fluke 1735 three-phase power quality logger, accuracy ± 1%) to measure the electric power input of the tested heat pump and assess its *COP* experimentally.

3. Methods

In the first phase of the research, the DSHP has been operated continuously up to 8 hours in heating mode exploiting the ground as external heat source. Different configurations of the BHE field (i.e., total BHE length ranging between 55 m and 300 m) were considered to assess the temperature distribution along the boreholes when heat is extracted from the soil (i.e., during the heat pump operation) and during the recharging process (i.e., the recovery of the undisturbed ground temperature when the DSHP is switched off). The heat transfer rate between BHE fluid and soil, as well as the Recharging Time (RT, namely the time interval needed by the BHE fluid to achieve 95% of its initial temperature) have been evaluated at different depths. Since water is used as BHE fluid to improve heat transfer coefficient, a threshold temperature value has been defined to avoid freezing. For borefield configurations characterized by a reduced length, the heat pump operation is stopped when the BHE fluid temperature at the heat pump outlet drops below 5 °C.

A second series of experimental tests has been carried out to evaluate the thermal response of the soil when the heat pump is operated with an intermittent working profile, typical of heat generators dedicated to the climatization of buildings. The detached residential building described in [3], located in Bologna and coupled to a GCHP having the same size of the tested DSHP, has been considered. Building heating and cooling loads and the heat pump behavior have been simulated by means of ALMABuild [8], a freely-available Matlab-Simulink tool for the dynamic modelling of buildings and HVAC systems. In figure 3 the monthly energy demand of the building is reported. It is evident how the heating demand during the cold season is 85% higher than the cooling energy need, making the building loads strongly unbalanced. To size the length of the BHE field coupled to the GCHP of the reference building, and to evaluate the linear thermal resistance of the boreholes, the methodology reported by ASHRAE [9] and by [10] have been followed, respectively, by considering the main characteristics of the borefield (diameter D, conductivity k, volume flow rate per tube $\dot{V}_{tube}$, shank spacing s, specific thermal capacity c_p, density ρ, thermal diffusivity α, undisturbed ground temperature T), reported in table 1. Also, no groundwater movement has been considered in the numerical model of the BHE field [4].

Table 1. Borefield main characteristics; subscript: internal *i*, external *e*, grout *gt*.

Pipe: PE100-RC			Borehole: double U-tube			
k [W m^{-1} K^{-1}]	D_i [m]	D_e [m]	D [m]	$\dot{V}_{tube}$ [l min^{-1}]	k_{gt} [W m^{-1} K^{-1}]	s [m]
0.36	0.0262	0.032	0.152	17.6	1.6	0.083
Fluid: water			**Ground: clay and gravel**			
c_p^{1} [J kg^{-1} K^{-1}]	ρ^{1} [kg m^{-3}]	k^{1} [W m^{-1} K^{-1}]	α [m^2 s^{-1}]	k [W m^{-1} K^{-1}]	T [°C]	
4203	999.8	0.56	7.99E-07	1.53	14.2	

According to the standard [9], the nominal length of the borefield is 198 m. To perform experimental tests with a well-sized borefield coupled to the DSHP, BHE 1, 2 and 3 have been selected for a total length of 205 m. This BHE length has been also adopted for the numerical simulation considering 2 boreholes (2×102.5). Within the numerical results, three typical days of the heating season, characterized by severe (S), average (A) and mild (M) outdoor air conditions and, thus, heating loads, have been identified to characterize the entire season. For each day, the heat pump operating profile has been evaluated with ALMABuild and has been reproduced in the test rig. The selection of different building loads allows to understand if an undersized borefield can be exploited in some periods of the heating season. In figure 4 the heat pump operating profiles and the outdoor air temperature for the selected days are illustrated. For each selected day, experimental tests have been performed by varying the overall length of the BHE field between 55 m and 300 m to evaluate the thermal response of the soil and assess the heat pump performance with undersized or oversized BHE fields.

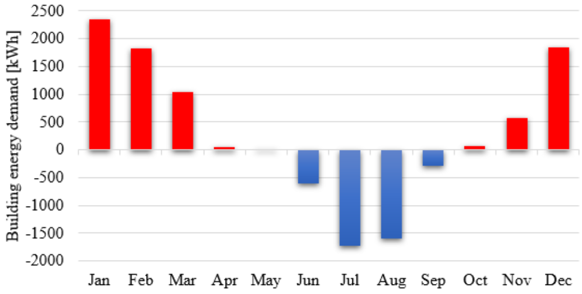


Figure 3. Monthly energy demand of the building for space heating and cooling.

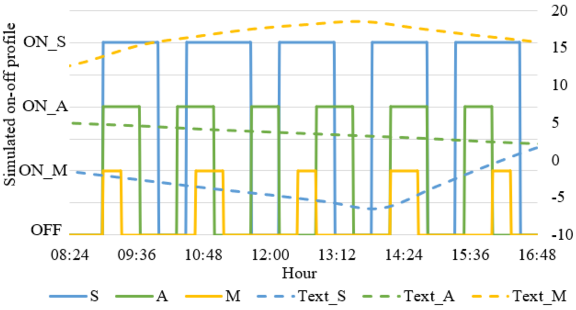


Figure 4. Simulated profiles and corresponding outdoor air temperature.

Each experimental run can be divided in three phases: i) in the first phase the undisturbed ground temperature is measured; ii) in the second step the DSHP is operated in ground mode following the operating profile obtained from dynamic simulations; iii) in the third phase the heat pump is completely switched off to evaluate the ground RT. In addition, when the heat pump must be turned off for safety reasons and cannot guarantee the building thermal load, the unit is re-started in ground source mode only at the next start-up indicated by the selected operating profile. During this time interval, the DSHP can be operated in air source mode even for low values of the outdoor air temperature to exploit the capability of the ground to recover its initial thermal level. It is important to highlight that in this circumstance, the BHE field configuration coupled to the DSHP operating in ground mode only is not proper and a longer field would be needed to match the load. Five configurations of the borefield have been considered and are reported in table 2 as a function of the selected typical days. As evidenced in table 2, all configurations have been tested in the severe day (S1, S2, S3, S4, S5), three configurations in the average day (A1, A2, A3) and one in the mild day (M1). During the operation of the DSHP, in all the described experimental tests, the water temperature at the inlet/outlet of the heat pump condenser has been maintained equal to 35 °C and 40 °C, respectively, whilst the inverter frequency of the compressor has been set to the maximum value (110 Hz).

Table 2. Configurations of the BHE field considered in the second series of tests with corresponding percentage of under- and over-sizing.

Configuration	Mild day (M)		Average day (A)		Severe day (S)	
1 (-73%)	M1)	1×55 m	A1)	1×55 m	S1)	1×55 m
2 (-54%)			A2)	1×95 m	S2)	1×95 m
3 (-27%)			A3)	1×55 m + 1×95 m	S3)	1×55 m + 1×95 m
4 (0%)					S4)	2×55 m + 1×95 m
5 (+46%)					S5)	2×55 m + 2×95 m

4. Results

In the first part of this work, the DSHP has been tested in geothermal mode with different configurations of the borefield (i.e., configurations 1, 2 and 5) to analyze the heat transfer rate between fluid and soil and the RT at different depths. It is worth mentioning that when the BHE field is significantly undersized, the heat pump operation had to be interrupted before the estimated timeline (i.e., 8 hours) due to the overcoming of the threshold temperature value linked to the freezing risk. Figure 5 shows the Charge Percentage (CP) of the BHE fluid (namely the ratio between the mean water temperature within the BHE and its undisturbed value) during the recharging period as a function of the borefield configuration. For sake of clarity, it must be declared that the described configurations have been tested in different days. As pointed out by figure 5, the geothermal fluid recovers 95% of its initial undisturbed temperature in less than 7 hours (around 400 min) after the heat pump shut down in every BHE configuration. Results point out also that, in the complete BHE field configuration (configuration 5), the longer borehole (black curve in figure 5) presents a larger CP (82% at the initial time) with respect to the shorter one (75% at the initial time, red curve). Indeed, although the water temperature at the borefield inlet is the same throughout the period of operation, the temperature distribution along the boreholes changes according to their length: the longer borehole shows a mean BHE fluid temperature higher due to a larger heat transfer area. When configurations 1 and 2 are considered (single borehole active, green and blue curves in figure 5), it is interesting to note that in the first 60 minutes of the recharging period the heat transfer rate between ground and BHE2 and BHE3 employed singularly is significantly higher (0.08 K min^{-1}) compared to that of the same boreholes (red and black curves) tested in the complete borefield configuration 5 (0.03 K min^{-1}). In fact, when the boreholes are utilized alone in an undersized field, the fluid temperature decreases faster along the test and a bigger temperature gradient between fluid and soil is present at the heat pump shut down. Furthermore, in a single borehole configuration, the fluid within the shortest BHE takes slightly less time, on average, than that in the longer one to recover its initial temperature, equal to the undisturbed soil temperature. This phenomenon can be better explained analyzing the data reported in figure 6, in which the fluid temperature distribution along the boreholes, measured by the DTS system, is illustrated as a function of time and depth. When the recharging period begins (time 0 min) the fluid temperature distribution along both boreholes overlaps. In the first stage of the process, up to 40 min, the water stored in the shorter BHE2 absorbs more heat from the surrounding soil compared to that within the longer BHE3 (about +1 K in the first 50 meters). It is interesting to highlight that the water temperature difference between BHE2 and BHE3 in deeper layers of the ground (20-50 m) remains almost constant between 40 and 220 min after the beginning of the recharging phase and vanishes completely after 24 h.

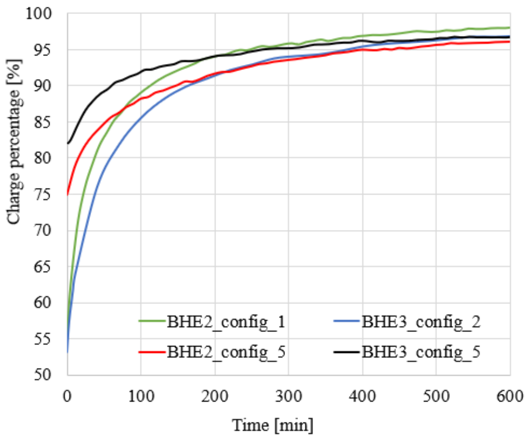


Figure 5. Charge percentage of the BHE fluid during the recharging period.

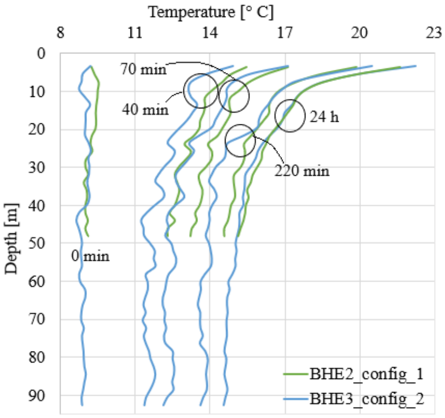


Figure 6. Vertical temperature profile within BHE2 and BHE3 as function of time during the recharging period.

As can be seen in figure 5, for a single borehole configuration the recharging process is fast: the ground recovers 80% of its undisturbed temperature in about one hour. For this reason, the analysis of the ground thermal response under an intermittent operation of the DSHP coupled to an undersized borefield has been performed. In this way, the capability of the ground to restore rapidly its thermal level between two consecutive start-ups of the heat pump can be investigated to figure out if the building energy demand during the winter season can be met by adopting an undersized BHE field. This second series of experimental tests has been carried out considering the three operating profiles of the heat pump reported in figure 4, reproduced by the DSHP operated in geothermal mode and coupled to the borefield configurations of table 2. Figure 7 shows the water temperature distribution within the inlet pipe of BHE3 during case study A2 (i.e., operating profile of the average day with borefield 54% undersized) as a function of time and depth. Results point out that sharp variations of the fluid temperature within the BHE can be observed in correspondence of the heat pump start-ups and shut-downs.

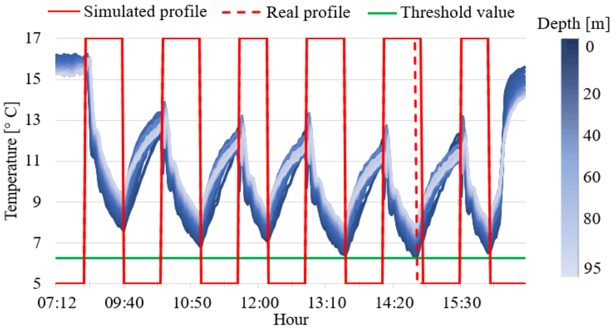


Figure 7. Water temperature distribution within the inlet pipe of BHE3 (case study A2).

For example, in the first start-up in figure 7 the mean water temperature drops of 4 °C in 6 minutes. Moreover, data shown in figure 7 indicate that the required building thermal load with average outdoor conditions can be satisfied by BHE3 only, thus employing a borefield of reduced length (54% undersizing). Indeed, the effective heat pump operating profile (dashed red line in figure 7) overlaps the simulated profile (continuous red line) for almost the whole day. The heat pump must be switched off to prevent freezing only for a limited period during the fifth start-up, for about 5 minutes. Coherently, during the heat pump operation the highest fluid temperature is obtained in the inlet pipe at the borehole bottom, as pointed out by the light blue colour of the chromatic scale. Additionally, it can be noticed that the minimum value of the fluid temperature achieved at the borehole head (dark blue colour) does not vary from the fourth start-up. It is possible to conclude that steady-state conditions were achieved:

heat extracted from the fluid at the heat pump evaporator and thermal energy gained from the soil have the same value. Therefore, the analysed configuration of the BHE field, characterized by an undersizing of about 50%, can be adopted to meet the building heating load for most part of the season. It is important to stress that, adopting a glycol solution instead of water as geothermal fluid, the minimum achievable temperature would be much lower and, consequently, no heat pump stops due to freezing risk would have been necessary in this case.

In order to fully characterize the heat pump performance along the experimental tests carried out in this work, table 3 reports for each test the average values of the Coefficient of Performance (namely, the ratio between heating power supplied and electric power absorbed by the heat pump) in ground-mode (COP_g), air-mode (COP_a) and in dual-source mode (COP_d). Regarding COP_d, both sources must be exploited (due to freezing risk). According to table 3, the thermal energy demand of the building in the severe day test can be satisfied in ground-mode only by configurations S3 (27% undersizing), S4 (nominal length of borefield) and S5 (46% oversizing) in which the operation time matches the scheduled time. On the contrary, with configurations S1 and S2 (undersizing of 73% and 54%, respectively) the heat pump cannot guarantee the whole building load during the most severe part of the season due to the rapid drop of water temperature and the consequent shut-down of the heat pump for freezing risk. However, the adoption of a DSHP permits to install a borefield strongly undersized, such as that in S1 and S2 configurations, even for the most critical outdoor conditions thanks to the capability to exploit also the aerothermal energy source. As pointed out in the previous part of the paper, the temperature of the soil around the boreholes can increase sharply when the heat pump works in air-source mode, and so, the ground thermal level can be restored.

Table 3. Main experimental results.

Case study	Under/over- sizing [%]	COP_g	COP_d	COP_a	Operation time [min]	Scheduled time [min]
M1	-73	4.29	4.31	4.89	115	120
A1	-73	4.23	3.87	3.39	150	220
A2	-54	4.29	4.25	3.39	215	220
A3	-27	4.25	4.25	3.39	220	220
S1	-73	4.32	3.40	2.85	153	320
S2	-54	4.32	3.69	2.85	221	320
S3	-27	4.17	4.17	2.85	320	320
S4	0	4.40	4.40	2.85	320	320
S5	+46	4.39	4.39	2.85	320	320

Furthermore, it can be observed that the heat pump experimental performance in ground-mode (COP_g) is only slightly influenced by the borefield configuration. This mainly depends on the temperature of the water at the inlet of the heat pump evaporator, which does not change significantly over the tests. On the other hand, for a fixed reference day, the time operated by the DSHP in ground-mode varies strongly as a function of the borefield size. As an example, the minimum period operated by the heat pump in ground-mode in the most severe day test ranges between 153 min (case S1) to 320 min (cases S3, S4 and S5, building load completed satisfied). This implicates that the less the ground is exploited, the more the DSHP works in air-mode with a consequent reduction of the overall heat pump efficiency (COP_d in table 3), especially in the most severe part of the season when the average performance of the unit mainly depends on the external air temperature and on the BHE field size. Indeed, when the air-source must be exploited, the heat pump performance drops by 21% and 15% for cases S1 and S2, respectively, whilst a smaller decrease of 9% and 1% is noticed for cases A1 and A2, respectively. However, the DSHP performance (COP_d) remains very high (+19% and +29% for cases S1 and S2, respectively) if compared to that of the air unit (COP_a). Regarding the mild day test (case study M1), results indicate that a single borehole 55 m long (undersizing of 73%) can be employed for 96% of the operating time. However, the operation in ground mode of a DSHP coupled to a strongly undersized borefield during the hotter part of the heating season is not suggested, even if technically feasible, since the heat pump performance in air-mode (4.89) could be higher (+13%) with respect to that achieved in dual-mode (4.31).

5. Conclusions

In this paper the prototype of an innovative DSHP, able to exploit both ground and air as external heat source, has been tested in ground-source mode with different configurations of the coupled BHE field which is composed by 4 in-line vertical boreholes having different lengths. Each BHE can be intercepted to reduce the total length of the field. Finally, two BHEs are instrumented by a DTS system by means of which the geothermal fluid temperature over the entire length of the borehole can be measured during the heat pump operation. Several experimental tests have been performed by varying the operating profile (continuous and intermittent operations) of the DSHP. In particular, the operating profiles of the heat pump, coupled to a reference residential building, during three typical days of the heating season characterized by mild, average and severe climatic conditions, have been calculated numerically. By the experimental campaign it has been demonstrated that the DSHP operated in ground-source mode and coupled to a borefield 50% undersized is able to meet completely the heating needs for most part of the season. On the contrary, the DSHP coupled to the shortest BHE field configuration (under-sizing of about 70%) is able to meet in ground-source mode only the thermal energy demand of the milder part of the season. However, experimental results show that the shortest BHE field configuration can be adopted with the tested DSHP even in the most severe part of the season. In fact, the DSHP can operate in geothermal mode until the BHE fluid temperature drops below a threshold value (linked to freezing risk or to an efficiency limit), below which the aerothermal energy source can be exploited. In this way, when the external air is used as source, 80% of the undisturbed temperature of the soil can be recovered in an hour. Therefore, the efficiency of the unit can be maintained high, whereas the investment cost is strongly reduced. Additional tests will be performed in further research activities to fully characterize the performance of the DSHP described in this paper.

6. References

[1] Corberán J M et al. 2018 Dual source heat pump, a high efficiency and cost-effective alternative for heating, cooling and DHW production *Int. J. Low Carbon Technol.* **13** pp 161–176

[2] Grossi I et al. 2018 Dynamic modelling and energy performance analysis of an innovative dual-source heat pump system *Appl. Therm. Eng.* **142** pp 745–759

[3] Natale C et al. 2022 Dynamic modelling of a dual-source heat pump system through a Simulink tool *J. Phys.: Conf. Ser.* **2385** 012090

[4] Naldi C et al. 2019 A new numerical method to determine isothermal g-functions of borehole heat exchanger fields *Geothermics* **77** pp 278–287

[5] Fujii H et al. 2009 An improved thermal response test for U-tube ground heat exchanger based on optical fiber thermometers *Geothermics* **38** pp 399–406

[6] Aranzabal N et al. 2020 Novel instruments and methods to estimate depth-specific thermal properties in borehole heat exchangers *Geothermics* **86** 101813

[7] Dongellini M et al. 2023 A new climate chamber for air-source and ground-source heat pump testing based on the Hardware-in-the Loop approach: Design and cross validation *J. Build. Eng.* **64** 105661

[8] Campana JP et al. 2019 BESTEST and EN ISO 52016 Benchmarking of ALMABuild, a New Open-Source Simulink Tool for Dynamic Energy Modelling of Buildings *Energies* **12** 2938

[9] ASHRAE Handbook 2007 – HVAC applications (ASHRAE, Atlanta, GA) chapter 32

[10] Conti P et al. 2016 Revised heat transfer modeling of Double U vertical ground-coupled heat exchangers *Appl. Therm. Eng.* **106** pp 1257–1267

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