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Solar-Assisted Dual-Source Multifunctional Heat Pump: Field Tests Results and Thermodynamic Analysis

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The integration between heat pumps and renewable energy sources (i.e., solar energy) is a promising and recognised technology to reduce primary energy consumption for building cooling/heating. This paper contributes to the existing discussion concerning field performances of multifunctional solar-assisted heat pumps, for cooling/heating applications, and for the production of domestic hot water. The proposed system has been tested experimentally, in a detached house in Milan, to obtain the seasonal performances; in particular, based on experimental observations, energy and exergy analyses have been formulated and applied to the heat pump control volume and to the whole system control volume. The results of the energy analysis have demonstrated that the system was able to maintain high efficiency in the different seasons. The exergy efficiencies of the heat pump and of the whole system were similar in their values, thus suggesting that the heat pump control volume is the location where most of the exergy losses occur, thus pointing out where the future research activities should focus to improve the performance of the proposed system.

1. Introduction

European policies aim to reduce primary energy consumption and to increase the use of renewable energy sources, to achieve a sustainable low-carbon economy in the short-term, medium-term and long-term future. In this respect, particular attention is devoted to the cooling/heating sections in buildings, which are characterized by high primary energy consumption; its reduction is very important to achieve the European targets and might be achieved by acting on the demand side (e.g. building envelope) and/or on the supply side (e.g., energy conversion technologies), as discussed by Hansen et al. (2016) and by Connolly (2017). By considering the supplies side, the integration between heat pumps and renewable energy sources is a promising technology, also when considering the broader framework of the “total heat recovery” as shown in study conducted by Liew and Walmsley (2016) and the district heating shown in the heat roadmap Europe studies (EC, 2011). An interesting coupling between renewable energy and heat pumps is represented by the solar-assisted heat pumps (SAHP); this technology was proposed in the early study of Sporn and Ambrose (1955) and, since then, it has been widely studied (Scarpa et al., 2015). Among the different technologies proposed in the literature, a growing attention is devoted to multi-functional heat pumps, which are able to produce both space heating/cooling and domestic hot water (DHW), In this complex framework, this paper contributes to the existing discussion concerning multifunctional SAHP for heating and cooling applications, as well as for the production of DHW by field study and an exergy post-processing of the data. To this end, the present study investigates, experimentally and theoretically (by energy and exergy analysis), a multifunctional SAHP system, which has been first proposed by Croci et al. (2017) and, subsequently, installed and monitored in Milan (Besagni et al., 2017). It is worth noting that, despite, exergy analysis has been applied to different heat pumps by a number of researchers (Ozgener and Hepbasli, 2007), unfortunately, exergy analysis of multifunctional SAHP are still limited. The approach proposed in this paper is interesting as it couples a seasonal field test with a thermodynamic evaluation of the system: the seasonal field study is needed to verify on field the performance of the system, rather than based on theoretical approaches. Indeed, there is still a large uncertainty concerning the energy consumptions and performance of large-scale applications, as field measurements of real installations often have shown lower efficiencies compared with laboratory-scale experimentations (Caird et al., 2012). The aim of this paper is, thus, twofold: (a) assess and define the system performance relating input and output parameters, (b) provide a baseline approach to compare the proposed system performance to the other system layouts proposed by other research groups.

2. Experimental setup and methods

2.1 Experimental setup

The multifunctional heat pump was installed in a detached house located in Milan, at RSE Spa headquarter (Latitude 45.47°, Longitude 9.25°). The detached house consists of a prefabricated house with a heating/cooling area equal to 60 m^2, divided in four rooms (Madonna and Bazzocchi, 2013). The house is equipped with five fan coils used for space heating/cooling and has a nominal heating load equal to 4 kW_{th} (indoor temperature equal to 20 °C and outdoor temperature equal to -5 °C). Figure 1 displays the layout of the multifunctional heat pump system; the proposed system couples hybrid photovoltaic/thermal (PVT) panels with a multifunctional and reversible heat pump. The heat pump is equipped is classified as a dual-source, as it employs both “air-source” evaporator and a “water-source” evaporator, connected in series and operated alternatively, based on the ambient conditions, system parameters and operating modes (the reader may refer to the literature survey proposed by Croci et al., (2017) and to the influence of the source describe by Besagni et al. (2017)). The PVT panels are connected with the heat pump by two storage tanks, used either to produce DHW or in “water-source” evaporator. Further details concerning the different components of the system have been discussed in our previous papers (Besagni et al., 2017).

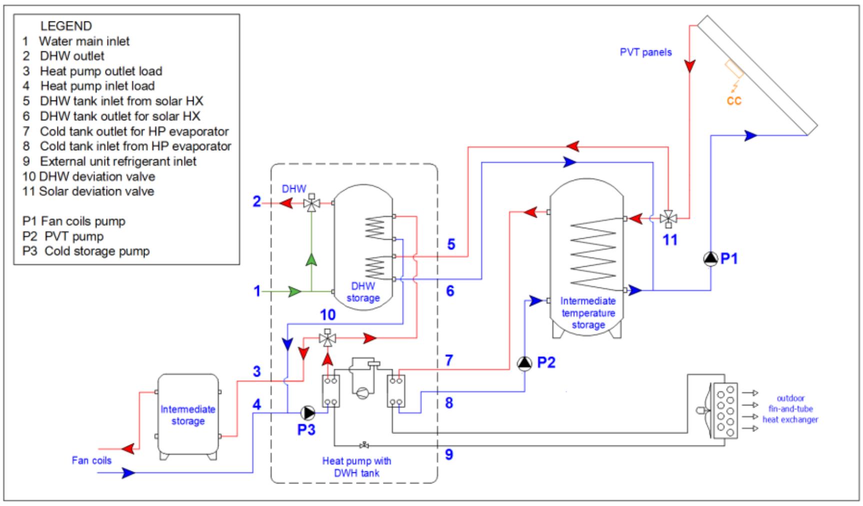

Figure 1: Solar-assisted dual-source multifunctional heat pump: the experimental layout

2.2 Experimental methods

The flow rate in each circuit has been measured by an electromagnetic flowmeter meter (E&H Promag P50, ±0.2% read value). All the inlet and outlet temperatures of the main equipment, the supply and return water temperatures of the different locations, were measured by RTD Pt100 4wire 1/5DIN, inserted inside the pipes. The indoor and outdoor (near the PVT panels) temperature and humidity were measured by an Pt100 4wire hygrometer (Siap+Micros). The solar radiation intensity has been measured by a thermopile pyranometers (pyranometer Kipp&Zonen CMP11), mounted at a 45° inclined angle near the PVT panels. The power consumption of the heat pump and the circulating pumps (solar pumps, intermediate-storage tank, fan-coil pump) were measured by multifunction electric meters (Shark 100, ±0.1 %, and FRER MonoNano, ±0.5 %). Evaporating and condenser pressures were measured by pressure transducers (Keller series 21Y). All data were recorded automatically at every 6 seconds.

2.3 Operation modes

The multifunctional heat pump has been operated in four different sessions. The first operation mode (mode#1) concerns heating without DHW production (from 17/01/2017 to 13/03/2017). The internal set-point temperature was set to 22 °C, with night attenuation of 4 °C. The temperature of the water produced by the heat pump and sent to the fan-coils was set by using a climatic curve (e.g., T_3 = 45 °C with T_{amb} = 0 °C and T_3 = 40 °C with T_{amb}

= 15 °C – Refer to Figure 1 for details on the subscripts). In this operation mode, valve V1 was set to deviate all thermal energy produced by the PVT panels to the "intermediate-temperature" storage tank. The "intermediate-temperature" storage tank, is used as the "water-source" for the heat pump when T_{amb}, is low and the resulting COP would decrease, as discussed by Besagni et al. (2017). Changes from "air-source" evaporator to "water-source" evaporator are obtained by switching on/off the pump P2 and switching on/off the outdoor "air-source" unit. The second operation mode (mode#2) concerns heating with DHW production (from 13/03/2017 to 24/05/2017). In this case, the previous operation mode was modified as follows: (a) a daily profile of DHW production was set to produce 150 l (corresponding to, approximately, 4 KWh); (b) valve V1 was set to deviate the glycol-water mixture, at the outlet of the PVT panels, depending on the temperature of the storage tanks (a) towards the "intermediate-temperature" storage tank ($T_{intermediate\text{-}temperature}$ < 38 °C), (b) towards the DHW tank ($T_{intermediate\text{-}temperature}$ ≥ 38 °C) or towards the "intermediate-temperature" storage tank ($T_{DHW,tank}$ ≥ 58 °C); (c) the DHW storage tank set-point temperature was set to $T_{DHW,set\text{-}point}$ = 48°C and its lower temperature has been set $T_{DHW,mantenance}$ = 42°C. If the temperature of the DHW storage tank fell below $T_{DHW,mantenance}$, the heat pump would be used to increase the DHW tank temperature. The thirds operation mode (mode#3) concerns cooling with DHW production (from 24/05/2017 to 16/10/2017). The internal set-point temperature was set to 24 °C. The outlet water temperature was set at 7°C In addition, the operation mode mode#2 was modified as follows: (a) a daily profile of DHW production was set to produce 150 l; (b) valve V1 was set to deviate the glycol-water mixture, at the outlet of the PVT panels, depending on the temperature of the storage tanks towards the DHW storage tank ($T_{intermediate\text{-}temperature}$ ≥ 36 °C) or towards the "intermediate-temperature" storage tank ($T_{DHW,tank}$ ≥ 57 °C). Pump P1 was activated from 19:00 until 24:00, to lower the temperature of the "intermediate-temperature" storage tank and, thus, to increase the PVT performances. The fourth operation mode (mode#4) concerns heating without DHW production (from 22/10/2017 to 14/12/2017) and was operated with the same settings as the mode#1. Please note that, owing to technical maintenance in the area of the facility, we were forced to stop the monitoring activities in the period between the 16/10/2017 and the 22/10/2017.

2.4 Energy and exergy analysis

The performance of the multifunctional heat pump has been evaluated, on a daily-averaged point of view, based on the experimental data acquired in the experimental tests. In particular, both the heat pump performance (by energy and exergy approaches) and the whole system performances (by an exergy approach) have been computed. The energy performance of the heat pump has been evaluated by the COP (during heating mode, Eq. (1)) and the EER (during the cooling mode, Eq. (2)), as follows:

$$COP = \left.\frac{E_{HP\rightarrow fan\text{-}coil} + E_{HP\rightarrow DHW\text{-}tank}}{E_{el}}\right|_{daily} \tag{1}$$

$$EER = \left.\frac{E_{HP\leftarrow fan\text{-}coil} + E_{HP\rightarrow DHW\text{-}tank}}{E_{el}}\right|_{daily} \tag{2}$$

In Eqs. (1-2) E_{el} is the electrical energy provided to the system, $E_{HP\rightarrow fan\text{-}coil}$ and $E_{HP\leftarrow fan\text{-}coil}$ refer to the thermal energy provided by the heat pump to the fan-coils (heating mode) and vice-versa (cooling mode); $E_{HP\rightarrow DHW\text{-}tank}$ refers to the thermal energy provided by the heat pump to the DHW storage tank. The exergy performance of the heat pump (Eq. (3)) and the exergy performance (Eq. (4)) of whole system have been computed as follows:

$$\eta_{EX,HP} = \left.\frac{EX_{HP\text{-}fan\text{-}coil} + EX_{HP\rightarrow DHW\text{-}tank}}{EX_{el}}\right|_{daily} = \left.\frac{EX_{HP\rightarrow fan\text{-}coil}(1+T_0/T_{in}) + EX_{HP\rightarrow DHW\text{-}tank}(1+T_0/T_{DHW\text{-}tank})}{E_{el}}\right|_{daily} \tag{3}$$

$$\eta_{EX,System} = \left.\frac{EX_{HP\rightarrow fan\text{-}coil} + EX_{DHW}}{EX_{el} + EX_{PVT}}\right|_{daily} = \left.\frac{E_{HP\rightarrow fan\text{-}coil}(1+T_0/T_{in}) + E_{DHW}(1+T_0/T_{DHW})}{P_{el} + E_{PVT}(1+T_0/T_{PVT})}\right|_{daily} \tag{4}$$

In Eqs. (3-4), EX_{el} is the exergy related to the electrical energy, $EX_{HP\rightarrow fan\text{-}coil}$ and $EX_{HP\leftarrow fan\text{-}coil}$ refer to the exergy of the thermal energy provided by the heat pump to the fan-coils or vice-versa; EX_{DHW} refers to the exergy of the thermal energy provided by the heat pump to the DHW tank; EX_{PVT} refers to the exergy of the thermal energy produced by the PVT panels. In addition, T_0 = 273 K is the reference temperature for the exergy analysis, T_{in} is the internal temperature of the detached house, T_{PVT} is the PVT operating temperature, $T_{DHW\text{-}tank}$ is the DHW storage-tank temperature and T_{DHW} is the temperature of the DHW produced. The daily-averaged performances have been considered and, in this respect, the different temperatures in Eqs. (3-4) have been computed as daily-averaged values. In the above equations, E_{el} considers all the auxiliaries: (a) solar circulating pump (approximately 4.1 % of the total energy consumption); (b) "intermediate-temperature" circulating pump (approximately 1.2 % of the total energy consumption); (c) Fan-coil circulating pump (approximately 3.7 % of the total energy consumption), (d) DHW circulating pump and all other auxiliaries (approximately 14.2 % of the total energy consumption). Based on the experimental uncertainties the energy and exergy performances are computed within the range of ± 0.2 % of their actual value.

3. Results

The results of the analysis are presented in Figure 2, Figure 3, Table 1 and Table 2. Figure 2 displays the daily-averaged energy performances of the multifunctional heat pump; Figure 3 displays the daily-averaged exergy performances of both the multifunctional heat pump and the whole system; in addition, Figure 2 and Figure 3 display the ambient temperature T_{amb}. Finally, Table 1 and Table 2 summarize the monthly-averaged (Table 1) and the operation mode-averaged (Table 2) energy and exergy performances.

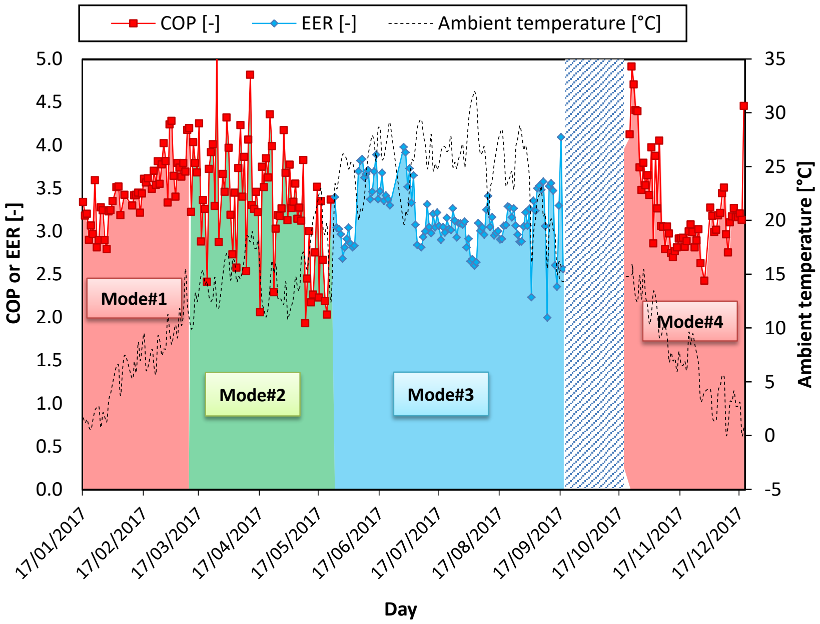

Figure 2: Daily-averaged energy performance of the multifunctional heat pump

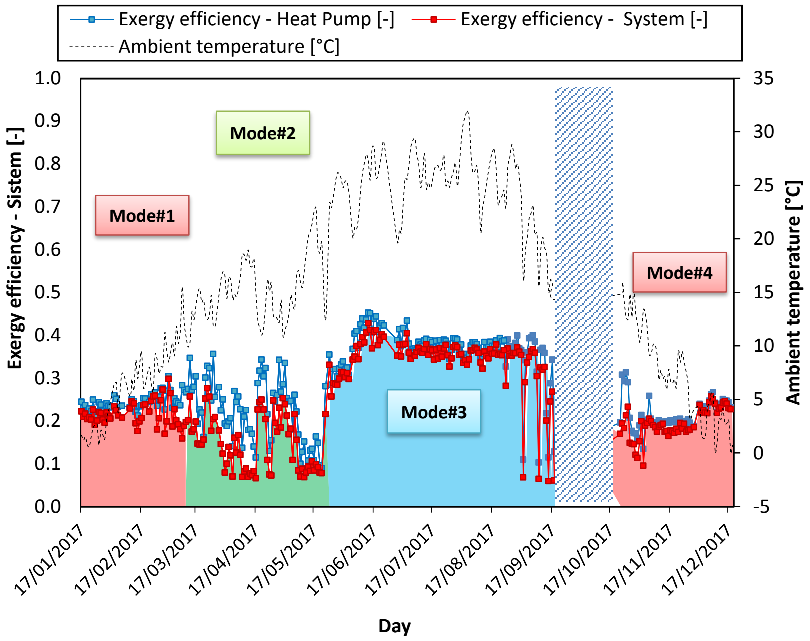

Figure 3: Daily-averaged exergy performance of the multifunctional heat pump

Table 1: Monthly-averaged energy and exergy performances (year: 2017)

Month	Operation mode	COP [-]	EER [-]	$\eta_{ex,HP}$ [-]	$\eta_{ex,System}$ [-]
January	mode#1	3.08	-	0.21	0.21
February	mode#1	3.51	-	0.24	0.23
March	mode#1	3.75	-	0.25	0.21
March	mode#2	2.74	-	0.27	0.19
April	mode#2	2.47	-	0.24	0.15
May	mode#2	2.55	-	0.20	0.14
May	mode#3	-	2.99	0.32	0.29
June	mode#3	-	3.45	0.41	0.38
July	mode#3	-	3.12	0.38	0.36
August	mode#3	-	3.02	0.37	0.35
September	mode#3	-	3.06	0.33	0.30
October	mode#4	3.53	-	0.21	0.17
November	mode#4	2.78	-	0.19	0.18
December	mode#4	3.05	-	0.23	0.23

Table 2: Operation mode-averaged performances

Operation mode	COP [-]	EER [-]	$\eta_{ex,HP}$ [-]	$\eta_{ex,System}$ [-]
mode#1	3.34	-	0.23	0.22
mode#2	2.58	-	0.24	0.16
mode#3	-	3.14	0.38	0.35
mode#4	2.96	-	0.22	0.21

The averaged energy performances of the multifunctional heat pump are, approximately, 3.34 in the operation mode#1, 2.58 in operation mode# 2, 3.14 in operation mode#3 and 2.96 in operation mode#4 (Figure 2, Table 1 and Table 2). Of course, the performances of the heat pump are related to the ambient temperature T_{amb}, owing to the variable speed compressor and the electronic expansion valve discussed (see, for example, the daily profiles presented and discussed by Besagni et al. (2017)): a variation in the boundary conditions (i.e., internal/external temperature) reflects in a variation of the operating conditions of the compressor (viz. a variation of the suction/discharge pressure and temperatures) and the electronic valve opening (to maintain the super-heat set-point value, 5° C), On the contrary, the exergy performance of the multifunctional heat pump are, approximately, 0.23 in the operation mode#1, 0.24 in the operation mode#2, 0.38 in the operation mode#3 and 0.22 in the operation mode#4. The decrease in the energy and exergy efficiencies passing from the operation mode#1 to the operation mode#2 is related to the production of heat at high temperature, to maintain the DHW storage temperature set-point (see Section 2.3). It is interesting to observe that the exergy efficiencies of the heat pump and of the whole system (Figure 3, Table 1 and Table 2) are similar in values, thus suggesting that the heat pump is the component where most of the exergy losses occurs. In agreement with our observation, Kata et al. (2008) found that the exergy efficiency of the individual components of the solar assisted heat pump (without DHW production) ranged from 10.74% to 88.87% and the higher exergy losses are located in the heat pump systems (e.g., compressor and heat exchangers, …). For this reason, the future research activities should be devoted to developing, test and validate different heat pump system layouts (i.e., an ejector-based heat pump (Besagni et al. 2016) or other integrations with the solar system). In addition, it is interesting to observe the increase in the exergy efficiencies in the cooling mode, compared with the heating modes, suggesting that the proposed system is able to produce cooling effect and DHW is a more efficient and “reversible” way, compared with the heating mode. This behavior is likely to be related to the thermal energy provided by the PVT panels, which support the production of DHW and, thus, decreases the high-temperature operation of the heat pump. This observation suggests that future works should be devoted to improving the efficiency of the system in the heating mode. Compared with the previous literature, the proposed system has shown a better performance in terms of both energy and exergy performances. On the energy point of view, Li et al. (2007) experimentally studied a solar-assisted heat pump for DHW production and found COP in the range of 1.7 – 2.9; On the exergy point of view, Ito et al. (1999) studied an heat pump system only for cooling application and observed exergy efficiency in the range of 0.1 to 0.3 (Ito et al, 1999); instead, Li et al. (2007) studied direct expansion solar-assisted heat pump water heater, which does not accounted for space cooling and heating purposes, and observed exergy efficiency in the range of 0.2 to 0.5 (Li et al., 2007). Of course, the above-mentioned comparison is qualitative, as different authors studied different systems (in laboratory facility rather than in real field tests). Nevertheless, despite the comparison is qualitative only, the proposed heat pump system seems a promising technology, compared with the literature, reaching higher exergy efficiencies.

4. Conclusions

This paper investigates, experimentally and theoretically (by energy and exergy analysis), a multifunctional SAHP system. The results have shown that the system has been able to maintain high energy and exergy efficiencies in the different seasons and is a promising technology for primary energy saving in domestic applications study. In particular, the averaged energy performance of the multifunctional heat pump is approximately 3, in the three different operation modes; conversely, the averaged exergy performance is approximately of 0.23 in the heating mode and 0.38 in the cooling mode. These performances have been compared with the previous literature, suggesting that the proposed system is promising technology in the framework of energy saving. As far as future studies are concerns, the exergy analysis pointed out that the future research activities should be devoted to developing, test and validate different heat pump system layouts, especially to improve the heating performances.

Acknowledgments

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