Numerical analysis of the use of R-407C in direct expansion solar assisted heat pump

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1. Introduction

Solar energy is an attractive energy source due to its availability, low cost and low environmental impact that could be effectively used to reduce energy dependence on fossil fuel and environmental pollution. Solar energy technology could be combined with heat pump technology to generate a Solar Assisted Heat Pump (SAHP), a non

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conventional water heater where the solar collector provides the heating capacity required to evaporate the refrigerant in the heat pump evaporator. Compared to a conventional solar system, the SAHP allows to produce high temperature hot water with two advantages: first, the surface of the solar field reduces, due to the presence of the heat pump, and, second, the solar collector efficiency increases, due to lower heat losses related to reduced collector to ambient temperature difference. Moreover, compared to a conventional heat pump, the SAHP generally allows to work at higher evaporation temperature, often higher than the ambient temperature, resulting in improved COP.

The coupling of a heat pump and solar field can generate two different systems: the conventional SAHP and the Direct eXpansion SAHP (DX-SAHP). In a conventional SAHP, the solar field and the heat pump are separate units and a secondary fluid (usually air or water) flows into the solar heat exchanger loop transferring the energy gained in the solar field to the refrigerant in the evaporator. In a DX-SAHP, the solar collector and the heat pump evaporator are combined together in order to form a collector/evaporator where the refrigerant evaporates absorbing the solar radiation. The advantages of the latter solution are the higher evaporation temperature, the lower solar collector energy losses and the improved collector lifetime. As a matter of fact, the direct expansion of the refrigerant inside the solar collector eliminates the intermediate heat exchanger loop, which is required in the convectional SAHP system, eliminating its inherent inefficiency. Moreover, the use of a refrigerant instead of a water-glycol mixture overcomes freezing and corrosion problems, resulting in solar field and system increased life. The main drawback of the DX-SAHP is the high extension of the refrigerant loop, which can result in refrigerant leakage and trapping of the oil in the evaporator, and the possible system instabilities due to large or sudden fluctuation of solar radiation.

Although the idea of a DX-SAHP was first proposed in mid Fifties [1], the studies on DX-SAHP systems are more recent and most of them are reviewed in [2] and [3]. The main issues related to this research field deal with the heat pump COP and solar collector efficiency as functions of solar collector technology, the heat pump working fluid and the heating capacity modulation.

Solar collectors generally used in DX-SAHP are bare flat plate collectors while only few studies refer to glass-covered or PV/T collectors. This choice arises from the request to reduce system costs while maintaining high heat gains through the evaporator, that is possible using unglazed solar collectors instead of glass-covered or selective surface solar collectors [3]. In fact, the refrigerant evaporation temperature is usually very close to ambient temperature, making the unglazed solar collector more efficient than the other ones. Although a simple graphical procedure to size the collector area for the DX-SAHP is proposed in [4], no information about the use of the surface of the solar field as a function of solar radiation or ambient temperature is generally given.

Refrigerants commonly investigated are R-12, R-22 and R-134a due to their better performance compared to R-404A, R-407C and R-410A [4]. However, the latter refrigerants are widely used in air conditioning and refrigeration industry and a more detailed analysis is worthwhile.

Finally, the need to use a variable speed compressor and/or a modular solar field in order to properly match the heat pump heating capacity (i.e. collector/evaporator load) with the building heat load is addressed by many authors [5-7].

The aforementioned studies provide valuable information about the performance of a DX-SAHP as a function of the main system parameters, but they refer to the DX-SAHP system without considering a real thermal load. As a matter of fact, there is lack of studies dealing with the energy feature of a DX-SAHP coupled with a building and related issues, such as the discrepancy between the building heating demand and heat pump heating capacity. The present study addresses this issue with particular attention to COP and heating capacity of the DX-SAHP, to compressor rotational frequency and to the use of the solar field surface and collector efficiency.

Nomenclature

f_{COMP}	compressor rotational frequency, Hz
G	solar radiation, $W \cdot m^{-2}$
S_{CF}	use of the solar field surface, %
T_E	ambient temperature, °C
η_{CF}	Efficiency of the solar collector, dimensionless

2. Model description

The analysis of the DX-SAHP is carried out through a steady-state mathematical model of each component as explained further in the text. It is worth specifying that DX-SAHP performances are inherently dynamic due to daily or sudden variation of ambient temperature or solar radiation. Nevertheless, a steady state analysis could provide valuable information about the system working condition and energy performance that are the basis for further development and refinement. The heat pump supplies the heating capacity of a building whose design heating demand is equal to 7.5 kW when the indoor air temperature is equal to 20 °C and the outdoor air temperature is equal to -5 °C. Fig. 1 schematically illustrates the system under consideration.

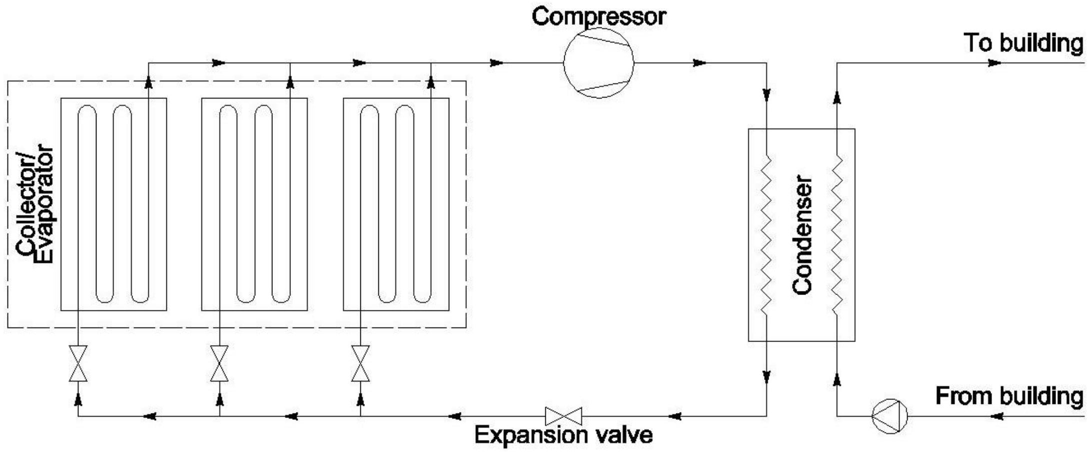

Fig. 1. Schematic diagram of the direct expansion solar assisted heat pump (the number of solar collectors shown is arbitrary).

The heat pump supplies only the heating capacity required for building space heating. In order to take into consideration building solar and internal gains in a simple way, according to EN 14825 [8] the building heating demand is supposed to vary linearly as function of the outdoor temperature, reaching the value of 0 kW when the outdoor air temperature is equal to 16 °C.

Flat plate unglazed collectors are chosen as DX-SAHP evaporator. The single collector main characteristics are listed in Table 1.

Table 1. Characteristics of the unglazed solar collector.

Plate material	Aluminum	Tube type	Smooth
Plate thickness [mm]	1.6	Tube external diameter [mm]	9.52
Coating absorptivity [-]	0.9	Tube thickness [mm]	0.3
Coating emissivity [-]	0.25	Tube spacing [mm]	112
Tube material	Copper	Tube length [m]	10
Number of tubes [-]	1	Insulation thickness [mm]	80

The evaporator is simulated using a 2D finite-difference model that modifies the model proposed in [9] in order to take into account that the fluid flowing into the tube undergoes a change of phase. The two phase flow heat transfer coefficient is calculated using the Wojtan et al. correlation [10] whereas the single phase one is calculated using the Gnielinski correlation [11]. Refrigerant pressure drop are calculated using the Moreno Quibén and Thome formulation [12] in the two phase flow and using the Konakov equation [13] in the single phase one.

The compressor chosen is a variable speed scroll compressor whose swept volume is equal to 7.3 m^3/h (rotational frequency equal to 50 Hz) and whose rotational frequency can vary in the range 15 Hz ÷ 60 Hz. The compressor is modeled regressing performance data supplied by the manufacturer trough third order polynomials that are able to provide refrigerant mass flow rate and compressor power consumption as function of evaporating temperature, condensing temperature and rotational frequency.

According to [14] the condenser is modeled as a constant condensation temperature heat exchanger, with condensation temperature set to 50 °C, high enough to supply hot water at a temperature equal to 45 °C that is required for heating purpose. The subcooling of the refrigerant at the outlet of the condenser is considered equal to 5 °C. Pressure drop across the condenser are neglected.

The expansion valve is modeled imposing that the refrigerant undergoes a constant enthalpy process while passing through this devices and that the valve is able to guarantee a refrigerant superheating equal to 5 °C at the evaporator outlet in any evaporator load condition.

3. Results

The analysis of the energy performance of the DX-SAHP is carried out considering four different solar fields. Each field is sized in order to allow the DX-SAHP to supply the design heating demand when the solar radiation is above a minimum value. Table 2 shows the characteristics of the four solar fields and the minimum solar radiation required by the system to properly satisfy the building heating demand. It is worth specifying that each solar field is sized considering an evaporation temperature of the R-407C equal to 258.15 K, a vapor superheating at the evaporator outlet equal to 5 °C and an outdoor air temperature equal to -5 °C, as previously mentioned.

Table 2. Number of solar collectors, surfaces and minimum solar radiation of the four solar fields considered.

Collector field	n_{COLL} [-]	S [m^2]	G_{MIN} [$W \cdot m^{-2}$]
CF#1	36	40.32	50
CF#2	26	29.12	100
CF#3	20	22.40	150
CF#4	15	16.80	200

Each solar collector is assumed to be completely excludible from the refrigerant circuit (see Fig. 1). This choice arises from the need to provide a variable heating capacity to the building, depending on ambient temperature and on solar radiation, and from the consequent variable evaporator load. The reduction of the heating capacity provided by the DX-SAHP is achieved reducing the compressor rotational frequency before excluding solar collectors.

Simulations are carried out to evaluate the influence of ambient temperature and solar radiation on the heat pump COP and heating capacity, on compressor rotational frequency and on the use of the solar field surface and collector efficiency. Simulation conditions are shown in Table 3.

Table 3. Ambient temperature and solar radiation used in the simulations.

T_E [°C]	-5; 0; 5; 10; 15
G [$W \cdot m^{-2}$]	50; 100; 150; 200; 250; 300; 350; 400; 450; 500; 550

Fig. 2 shows the heat pump COP as a function of ambient temperature and solar radiation for the four solar fields under investigation. As either the ambient temperature or the solar radiation increases, the COP becomes higher and reaches a plateau. The trend is qualitatively the same whatever is the size of the solar field but bigger solar fields allow to broaden the plateau extent obtaining, in this way, higher COP at lower ambient temperature or solar radiation values.

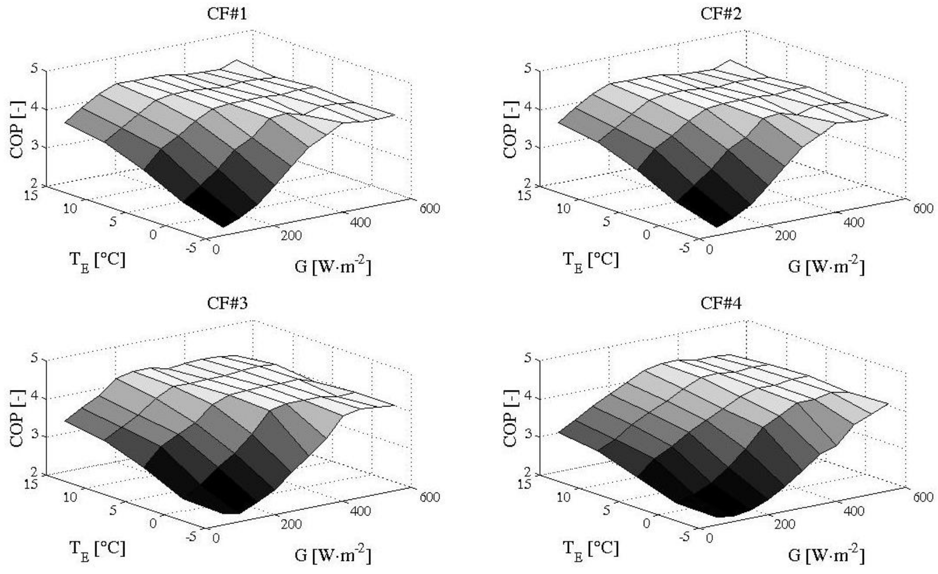

Fig. 2. DX-SAHP COP as a function of ambient temperature and solar radiation.

The heating capacity provided by the heat pump as a function of ambient temperature and solar radiation for CF#1 and CF#4 is shown in Fig. 3 where, for the sake of comparison, the building heating demand is depicted too. As previously mentioned, the DX-SAHP heating capacity is obtained varying the compressor rotational frequency and excluding some solar collectors in order to try to properly match the building heating demand (see Fig. 4 and Fig. 5).

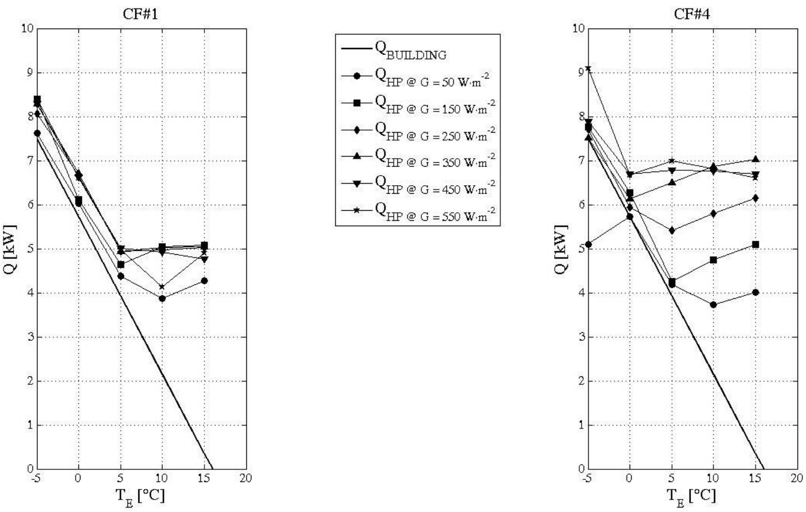

Fig. 3. Heating capacity as a function of ambient temperature and solar radiation for CF#1 and CF#4.

Simulation results show that, for both solar fields, the DX-SAHP is able to supply the building heating demand when the ambient temperature is lower than a threshold value (0 °C or 5 °C, depending on the number of collectors in the solar field) and for any solar radiation. When the ambient temperature increases, the heating capacity becomes higher than the building heating demand despite the compressor rotational frequency is variable and the solar field is modular. Moreover, when the surface of the solar field is low (CF#4), the heating capacity supplied by the DX-SAHP in the range of low ambient temperature and low solar radiation is lower than the building heating demand, requiring a back-up heating system. The trend for CF#2 and CF#3 is similar and, for this reason, it is not shown.

More details about the compressor rotational frequency and the use of the solar field surface are given in Fig. 4 and Fig. 5 where these parameters are plotted against ambient temperature and solar radiation. The use of the solar field surface is calculated as the ratio of the number of collectors required by the heat pump to supply the building heating capacity with respect to the total number of collector. As either the ambient temperature or the solar radiation increases, both the compressor rotational frequency and the use of the solar field surface show a decreasing trend due to the reduction of building heating demand and, consequently, the reduction of evaporator load. Again, the trend is qualitatively the same whatever is the size of the solar field but, in this case, smaller solar fields provide higher uses whereas the compressor rotation frequency does not seem vary much with it.

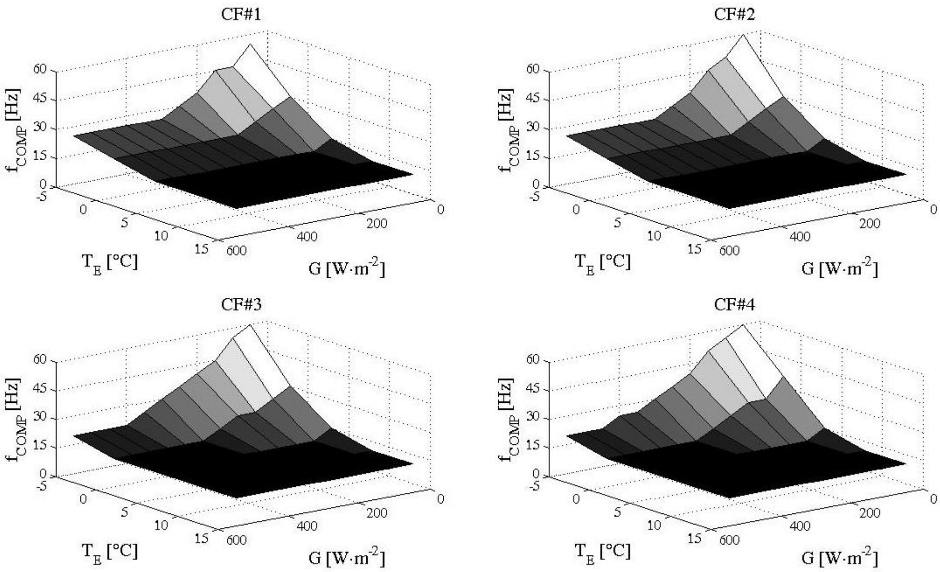

Fig. 4. Compressor rotational frequency as a function of ambient temperature and solar radiation.

The efficiency of the solar collector as a function of ambient temperature and solar radiation is shown in Fig. 6. According to [5] and [7], the efficiency is calculated as the ratio of the evaporator load and the overall solar radiation incident on the collectors. Data show that the collector efficiency is greater than 100% in the region of low ambient temperature and low solar radiation. As a matter of fact, in this condition the evaporation temperature is lower than the ambient temperature and, consequently, the heat exchanged between the ambient and the collector is a heat gain rather than a heat loss (the situation reverses as evaporation temperature increases). Moreover, for solar radiation lower than a threshold value (ranging from $G = 150\ W \cdot m^{-2}$ to $G = 400\ W \cdot m^{-2}$ depending on the number of solar collectors), the collector efficiency decreases as the solar radiation increase whereas the situation reverses for solar radiation higher than the threshold value. This is related to the fact as the solar radiation increases, the evaporation temperature increases as well, becoming greater than the ambient temperature, up to the maximum value allowed for compressor safety. Finally, for solar radiation higher than the threshold value the collector efficiency increases when the ambient temperature increase because in this situation the evaporation temperature and the ambient temperature are very close and this result in a reduction of collector heat losses.

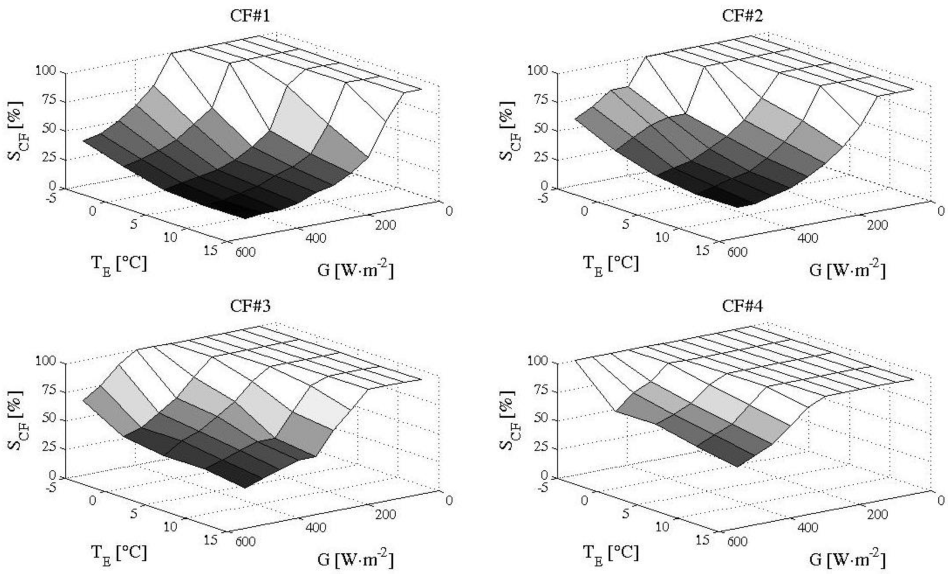

Fig. 5. Use of the solar field surface as a function of ambient temperature and solar radiation.

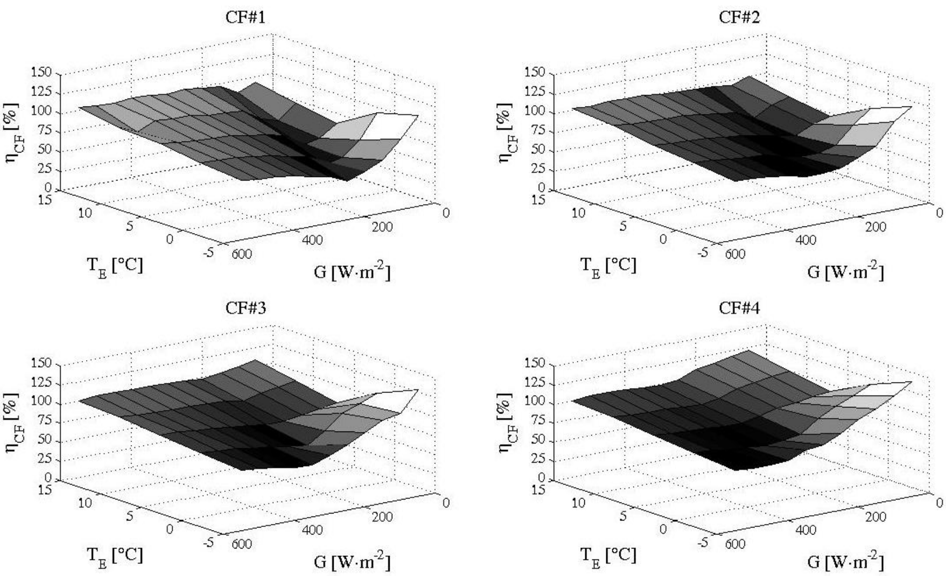

Fig. 6. Solar collector efficiency as a function of ambient temperature and solar radiation.

4. Conclusions

A numerical study of the energy performance of a direct expansion solar assisted heat pump working with R-407C was carried out through a steady state mathematical model. Four different sizes of the solar field were considered and the influence of ambient temperature and solar radiation on the heat pump COP and heating capacity, on compressor rotational frequency and on the use of the solar field surface and collector efficiency were investigated.

Simulation results show that the DX-SAHP works with quite high COP, ranging from 2.2 to 4.3 as a function of ambient temperature and solar radiation, that moves towards the higher value when the surface of the solar field increases, whatever are ambient temperature and solar radiation. The heating capacity provided by the DX-SAHP usually matches the building heating demand, especially if it is possible to vary the working conditions of the compressor and evaporator with the variation of ambient temperature and solar radiation. The solar collector efficiency strongly depends on ambient temperature and solar radiation and ranges from 50% to 149%.

As a general conclusion, in order to properly match the building heating demand with the heating capacity supplied by the heat pump, a variable speed compressor and a modular solar field are needed in the system, being their working conditions strongly influenced by the surface of the solar field.

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