Journal of Engineering Research and Applied Science
Available at www.journaleras.com
Volume 9 (2), 2020, pp 1546-1554
ISSN 2147-3471 © 2020

Dual source heat pump systems: operation and performance

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Accepted on 2 November 2020

Abstract
Dual source heat pump systems comprise of a main cold source heat pump that is supported by an additional heat source. In the present study, only one arrangement has been studied in detail: air source heat pumps combined with solar collectors. In addition to a situation where solar collectors are devoted solely to direct heating, the solar system can be used with the heat pump in either a series or a dual source scheme. When set up in series, a higher COP can be achieved, but there is often a lower free energy fraction. This is due to the lack of direct solar heating, meaning that auxiliary energy is required more frequently. A careful analysis of all the plant elements, including location, heating and cooling demand, solar collector area is fundamental for achieving the best outcome in terms of both good primary energy savings and profitable economical performance.

Keywords: heat pump; heat source; solar energy; solar heat pump.

1. Introduction

It is anticipated that the electricity cost will increase on the planet in the future, due to CO2 cost considerations and scarcity of energy resources. Solar photovoltaics might change the picture if the technology is massively adopted. But still, highly efficient heat pumps reducing the electricity demand will be needed to substitute the fossil heating solutions that dominate the world energy market in the 2010s. Combinations with solar collectors can increase the overall performance of a heat pump and will therefore also be an elegant solution of choice [1-4].When considering the possible use of a heat pump, the sensitivity of the system to low and high temperatures should be taken into account. It is also important to consider the temperature lift the heat pump can achieve in relation to the cold source temperature. In Fig. 1, the heat pump coefficient of performance (COP) is represented as a function of the temperature lift for a heating temperature of 60 °C. The COP is the ratio between the heating effect and the work necessary to drive the heat pump. Fig. 1 shows indicative COP values that are achievable in theory and practice, according to different sized and technically developed machines [5-8].

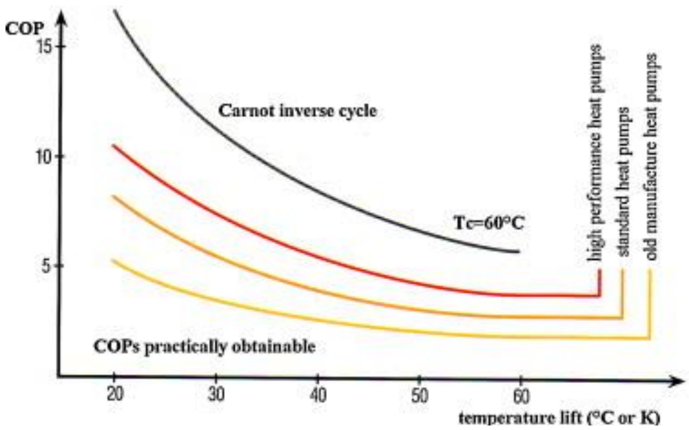

Fig. 1. Theoretical and practical COPs for heat pumps as a function of temperature increase.

The profile of the machine capacity is quite similar in most cases, which suggests two key areas that must be considered when designing a heat pump system [1-5]:

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- Careful selection of the heating system in order to lower heat supply temperature is required before looking for higher level heat sources. It is not logical to operate with systems that need the highest temperature attainable by the machine (usually around 60 °C), when systems are available which can distribute the heat at temperatures lower than 35 °C (i.e. heating panels or all air systems).
- The most common heat pump source is outside air, but this is the least favourable in terms of thermodynamic properties. Thermal load will increase as external air temperature decreases, resulting in a reduced system capacity and lower COP.

There are other reasons, besides thermodynamic performance, which may make it beneficial to look for alternative sources to the outside air. The external coils which are in contact with the outside air are often subjected to frosting at low temperatures, leading to the requirement to detect and eliminate frost. Conditions inside the building may become uncomfortable during the defrosting period. Also, air movement within the outside coil produces noise and it may not be possible to control this at an acceptable level. External coils can usually be easily placed, but with poor aesthetic results, and the energy cost of air movement can be considerable [917].

The main advantage of using air as a heat source is that it is free and immediately available. However, the potential advantages of alternative heat sources can be significant, so it is important that each is fully evaluated at the design stage. On the other hand, in a dual source system, as the name intrinsically suggests, the main heat pump cold source is aided by another source. Many combinations are theoretically possible [1], but only two arrangements has received full attention and have been studied in detail [2]:

- Air source heat pump and solar collectors;
- Ground source heat pump and solar collectors.

Of course, the two options can be used in different situations according to available storage capacity, or the potential for interaction between the two sources. For example, solar collectors can charge the ground in summer [2]. Heat pump systems with more than one source can be classified as: series and dual [3].

In a series system, the two sources are aligned in series so that the former raises the temperature before that heat is taken from the latter. In a dual source configuration, the heat pump takes heat either from the former or the latter according to the temperature levels [3], [4]. The inclusion of more than one source implies a more complex and expensive system, which may need to be justified in terms of either economic performance or energy savings. It is assumed that the COP of the heat pump will be increased by having an additional source. In practice, there are usually some advantages, but it is difficult to evaluate the extent to which such benefits are significant and worthwhile in different applications. Several mathematical and experimental studies have provided some analysis of the available system options. Discussion of these findings will be presented in this paper, firstly considering the combination of air and solar collectors, before assessing ground and solar systems [1-7].

2. Dual source (air & solar) heat pumps system

The use of a solar source in addition to outside air in heat pump systems has been questioned, as both elements perform poorly during the coldest months. Outside air temperature is lowest during the winter, and solar collectors function inefficiently due to low levels of insolation and cold external temperatures. The performance of the solar collector is relative to direct utilisation of solar energy. However, if thermal levels are lowered to a point that is not suitable for direct utilisation but is high enough for the heat pump evaporator to function, then the solar collector could present a useful addition to the heat pump system and enable increased overall performance levels [1-3].

In this simple example, a flat plate solar collector is considered with the following parameters:

$F_R(\tau\alpha) = 0.88$ and $F_R U_c = 7.8$ W m^{-2} K^{-1}.

In the case of a low insolation, say of 100 W m^{-2} and a working temperature of 35 °C for an outside temperature of 0 °C, the solar collector efficiency would be zero:

$$Q = (300\times0.88) - (35-0) \times 7.8 \approx 0 \text{ W/m}^2$$

The same collector, operating at a temperature of 5 °C, which is an excellent value for the heat pump, could provide instead [2]:

$Q = 300 \times 0.88 - (5-0) \times 7.8 \approx 230\ \text{W/m}^2$

In this scenario, the solar collector would be useful with an efficiency of 66%, whereas it would be otherwise idle. The operating temperature would also be 5 °C higher than the outside air alone would permit, and there is no need to consider frosting/defrosting cycles.

Due to the more favorable heat transfer properties of liquid with respect to a gas at the same temperature of 5 °C, the behaviour of a liquid heat pump is more than 10% better than for an air source heat pump, in respect of both COP and capacity. A possible example is shown in Fig. 2, where the COP is given for liquid or air cold source as a function of temperature [2].

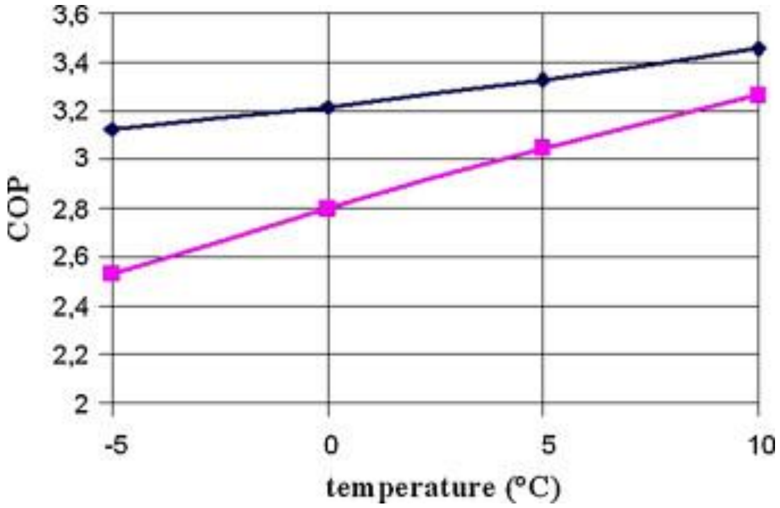

Fig. 2. COP of liquid and air heat pumps as a function of cold source temperature.

As an alternative to series or dual source systems, it is also possible to install the heat pump and solar collector in a parallel arrangement. In this situation, the solar collector provides direct heating when possible, and the air source heat pump aids the solar collector when insolation levels are low. Auxiliary heating would be required at low outside air temperatures, as the heat pump capacity is poor in this case [2].

An overview of a potential parallel system is shown in Fig. 3, taken from an interesting paper by Kaygusuz [11]. The system incorporates a storage tank to store heat when solar energy is available and supply exceeds low levels of heating demand.

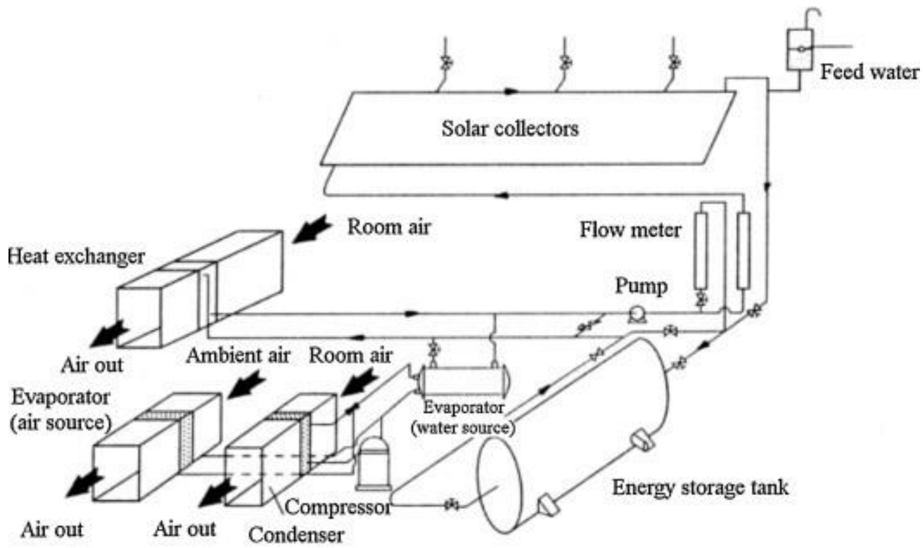

Fig. 3. Schematic of a dual source heat pump system (air + solar).

Attempting to predict the performance of the three system types is not straightforward. The parallel set-up is the simplest to assess, as the solar collector control is bound to the minimum supply temperature and the heat pump will operate according to the ambient temperature set by the thermostat. When the internal temperature falls below required by the thermostatic control, the heat pump will function. When the heat pump alone cannot achieve the desired temperature, supplementary energy will be provided by electric resistance heating or an auxiliary boiler [2].

In a series system, there is a requirement to predefine the temperatures at which the transfer from direct solar heating to use of the heat pump occurs, and vice versa. It is essential to select the two temperatures with care, as direct solar heating could be prevented if the range is not adequately wide. For example, in a case where the solar collector could provide a temperature of 28 °C, this would be too low even for a radiant floor heating system. If the solar system is then devoted to the heat pump, it would take a great amount of the time for the value to return to a level suitable for direct heating. Such a situation could be prevented if the temperature at which switch-over occurs is set sufficiently below the minimum required for direct heating. It may be possible to obtain optimum performance by fixing the solar radiation thresholds for direct heating and switch-over via a microprocessor. The solar collector efficiency curve should be loaded into the processor, as a function of insolation, outside temperature and operative temperature. Fig. 4 contains insolation threshold data required to maintain a useful temperature of 30 °C for different outside temperatures, in the case of flat plate non-selective and selective solar collectors. The strategies utilised by different authors, in both simulation and experimental work, are generally bound to a particular switch-over temperature, usually close to 300 K [2, 5, 11, 12].

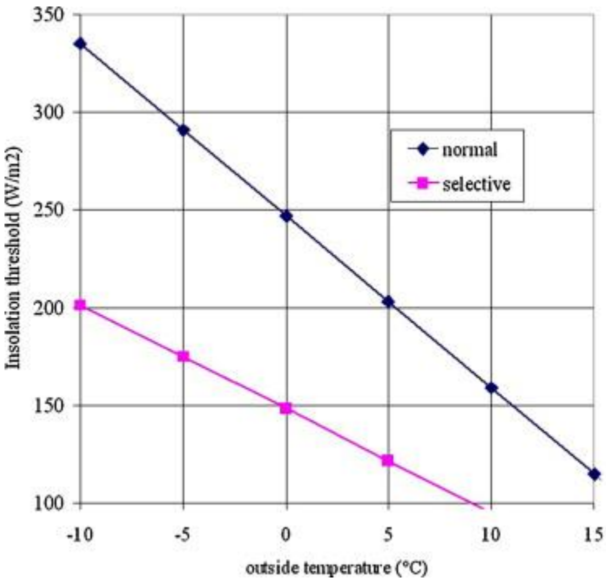

Fig. 4. Insolation thresholds for an output temperature of 30 °C at different external air temperatures.

The dual source system presents the most complex arrangement, as the heat pump incorporates two evaporators. The first is a liquid evaporator, which receives energy from the solar section, eventually via thermal storage. The second is an air evaporator that receives energy from the outside air. Whilst the system is more complicated, it should obtain higher performance levels as the heat pump is able to select the most favourable source to achieve the highest COP [2].

The dual source system has three possible modes of operation [2, 11, 12]:

Mode 1. Solar heating mode – the heat pump is off and the solar heat can be stored.

Mode 2. Heat pump utilises stored heat – this occurs when the storage tank temperature is not high enough to enable direct heating, but it is higher than the outside air.

Mode 3. Heat pump utilises air evaporator – this occurs when the storage tank temperature falls below a pre-determined outside air temperature. The solar section can continue to attempt to raise the storage tank temperature.

In the evaluation of a solar system, one fundamental parameter is the so called free fraction *F*. This is the fraction of annual load met by free energy, often represented as a function of the solar collector area. Fig. 5 illustrates the results of an interesting simulation carried out in [6]. It relates to a scenario where the heating of a laboratory building was evaluated utilising different heat pump systems. The two base curves are that of direct solar heating only and of the conventional heat pump. The free energy given by the conventional heat pump depends on the seasonal COP [2-14].

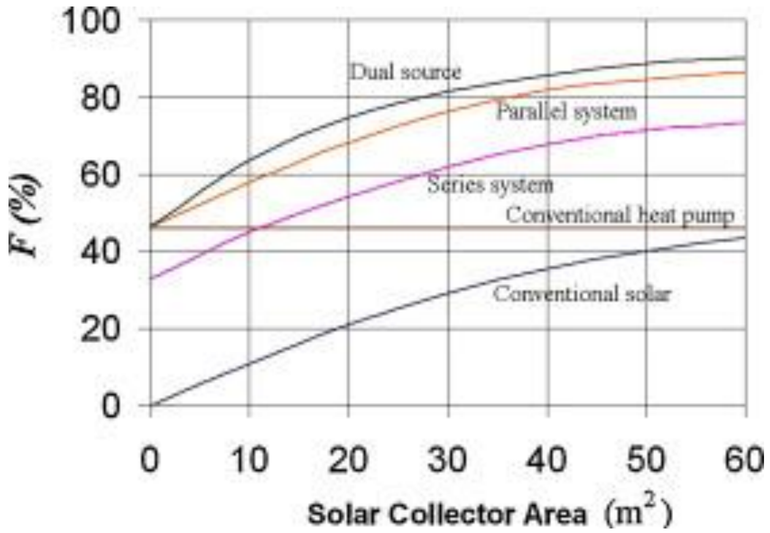

Fig. 5. Fraction of the annual load met by free energy as a function of the solar section area for the systems under consideration.

Whilst parallel and dual source systems consistently perform better than the conventional heat pump, this is not true for the series system. For a collector area of less than 10 m^2, there is not enough energy to satisfy the heat pump and auxiliary energy is often required. This situation is perhaps not as expected. When collector efficiency is considered, the series system presents the highest values, closely followed by the dual system (Fig. 6) [2]. Conventional solar and parallel systems behave quite similarly, so it appears that solar performance does not alter when a heat pump is present. The high efficiency achieved by the series system is due to the lower working temperature. It can collect more solar energy, but this is seldom available for direct heating. The efficient operation of the heat pump is limited by the frequent occurrences of insufficient solar energy availability. As a result, it is necessary to revert to the use of auxiliary systems on a regular basis [9-16].

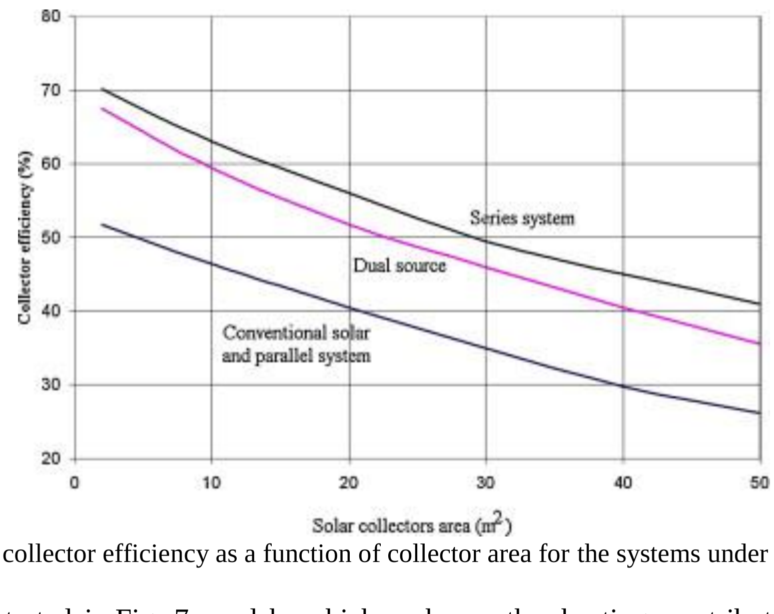

Fig. 6. Solar collector efficiency as a function of collector area for the systems under consideration.

This situation is illustrated in Fig. 7a and b, which shows the heating contribution from the various sources for a solar collector area of 30 m^2. Fig. 7a represents the fraction of the load satisfied by purchased energy, be it the energy for driving the heat pump compressor or auxiliary energy. Fig. 7b represents the fraction of the load satisfied by free energy, be it energy taken from the outside air or solar energy. The conventional solar contribution accounts for approximately 25%, which means that 75% is sourced from auxiliary energy. The parallel system takes a similar contribution (25%) from the solar collectors and about 50% from the outside air. Therefore, the remaining 25% must be provided by purchased energy. At the claimed seasonal COP of 3.0, this is composed of 17% of work to the compressor and 8% from auxiliary sources [2].

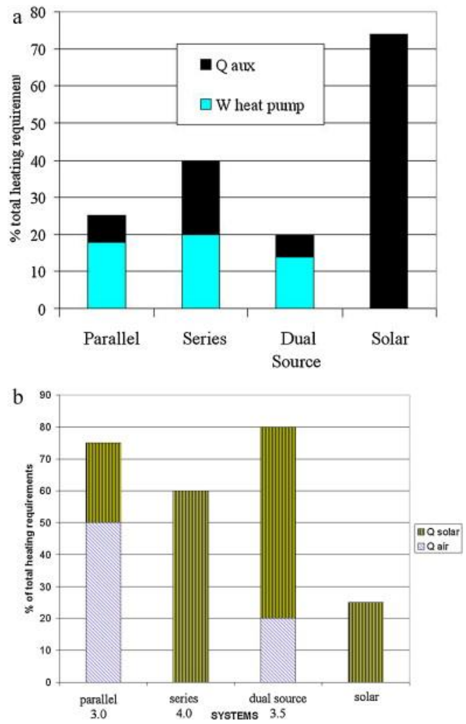

Fig. 7. (a and b) Fraction of the total heating requirement attributable to purchased energy and free energy.

In a series system, the total free energy used comes from the solar contribution of 60%. This means that 40% of purchased energy is required. The heat pump COP is the highest achieved (4.0), but the contribution of auxiliary energy is about 20%. Finally, in the dual source system, the contribution of solar energy is comparable to the series system, but this energy is composed of direct solar heating and heat pump cold source provision [9-16]. The total free energy is approximately 60%, with 20% derived from the outside air. Therefore, even if the seasonal COP is intermediate between the parallel and series systems (i.e. 3.5), the auxiliary energy contribution is only 6% [2].

The analysis of the operational frequency of the heat pump at various temperatures supports these conclusions. The parallel system operational distribution is centred at the lowest temperature, whilst the dual source system has two different temperatures depending on the type of source in use. The series system shows a distribution with a maximum frequency recorded at a temperature falling between the two values observed for the dual source [2].

There is no straightforward answer to the question of which system performs most favourably in terms of overall efficiency, as it is dependent on a number of variables. These include the heat pump and solar collector performances, heat pump capacity, and solar collector area. It should also be noted that a wide solar area supplies energy in excess, except for during the winter season. Therefore, it is important to fully consider climatic conditions and demand profiles in the design process. A reasonable approach could be to select a solar collector area that will meet plentifully the need for domestic hot water supply, operating in conjunction with dual system according to the specific climate and user demand characteristics [1-3, 8-12].

2.1. Advantages of solar heat pump (SHP) systems

The success on the market of heating and cooling technologies determined mainly by the satisfaction of users. In principle, a good energy system should be cheap and easy to operate and should have limited operation costs, a low maintenance effort, and a long lifespan. In the last few decades, users have become more sensitive to environmental problems; however, they adequately weighted on the energy costs yet, even if clearly motivated. Most of the time, a customer is more attracted by a system with relatively low investment cost rather than a more environment-friendly solution [1, 2, 4, 8].

Heat pumps and solar thermal collectors are preferential solutions for meeting new restrictive standards on the reduction of CO_2 emissions in new or refurbished residential buildings and, in this sense, SHP systems represent a valuable solution. The large number of ready-to-use SHP systems available on the European market confirms this statement. Kits and turnkey standardized solutions commercialized in order to reduce the investment costs and the risk of mistakes during installation and to pursue compactness. In order to achieve these results, the standardization of the SHP system layout is fundamental and, thanks to a better design process. Simulations accomplished by using SOLSIM simulation program [8] and obtained resuls given in Figs. 8-12.

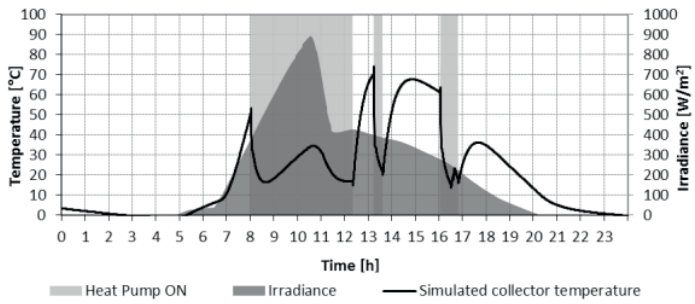

Figure 8. Solar irradiance, simulated collector temperature and HP operating period

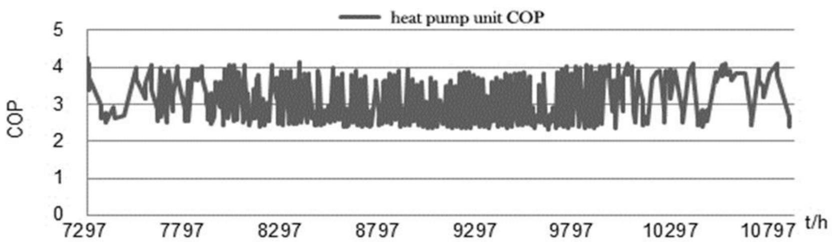

Fig. 9. The dual heat pump unit COP hourly variation in heating season.

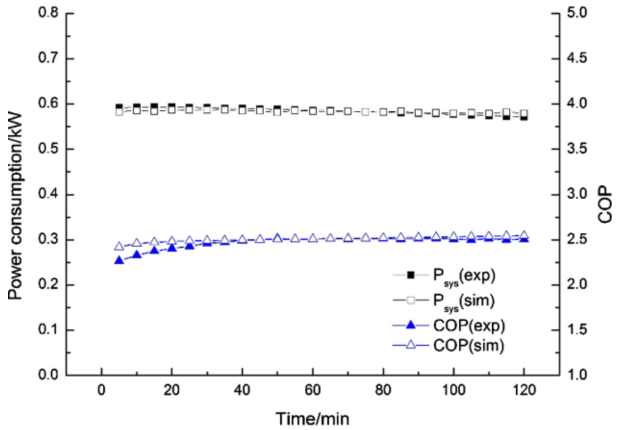

Fig. 10. Comparison between the experimental and simulation results in solar space heating mode-power consumption and COP.

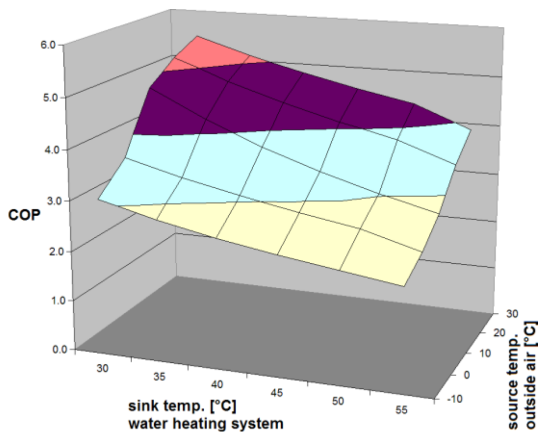

Figure 11. Exemplary COP performance map of an air-to-water heat pump.

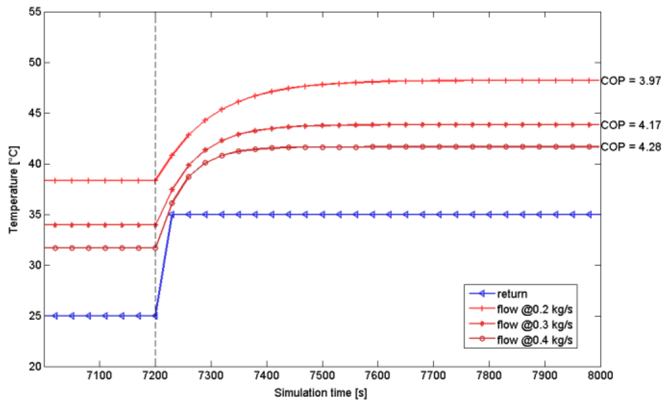

Figure 12. Outlet temperature and COP for a given step of the inlet temperature.

Among all these advantages of SHP systems, energetic and environmental aspects have a leading position. The combination of solar thermal and heat pump technologies contributes to increasing the system SPF and consequently in reducing the final energy (FE) consumption of the system and consequently the CO_2 emissions.

The additional ΔSPF induced by solar collectors is variable and dependent upon the SHP system configuration (series and parallel), the heat source typology, the surface area of the solar field, and the building loads. A value of ΔSPF per m^2 of solar field given according to parallel and series SHP system layouts. The benefit in terms of FE savings is dependent on the SPF_{ref} of a reference system and on the consequent ΔSPF [4].

$$SPF_{ref} = \frac{\int (Q_{SH} + Q_{DHW})\, dt}{\int (\Sigma P_{el})\, dt} \quad (1)$$

$$FE(\%) = \frac{FE_{ref} - FE_{SHP}}{FE_{ref}} = \left[\left(\frac{1}{SPF_{ref}} - \frac{1}{SPF_{SHP}} \right) / \left(\frac{1}{SPF_{ref}} \right) \right] \quad (2)$$

According to this equation and assuming a reference SPF_{ref} value of 2.7 for air source heat pump system and an SPF_{SHP} value of 4.5, the final energy savings amount to 40%. Since final and consequent primary energy savings reflected in an equivalent reduction of the CO_2 emissions by using a conversion factor, the same value of ΔCO_2 achieved. In this sense, SHP systems represent a ready-to-use solution for achieving a renewable energy concept in new or existing residential buildings [10-16].

3. Conclusions

The nature and performance of a dual source heat pump system carefully considered when a building heated by a heat pump combined with solar collectors. The addition of solar collectors can result in lower costs attributed to the ground thermal probes, as it may be possible to reduce the length of probe required. Moreover, solar collectors can recharge the ground in summer when the cooling demand is low, preventing possible overheating of the solar collectors. It is also important to take into account pumping costs within the primary energy analysis, as increased pumping costs may reduce the financial advantages of a dual source system, particularly in mild climates.

When the sun is shining, the collectors will be the primary source of energy for the domestic hot water preparation and for the space heating. Furthermore, the daily solar production can be stored for future use during a few days. When the sun is less abundant or when the solar storage is empty, the heat pump will take over the duty. The source of the primary low-energy “heat” for the heat pump to operate can be air, ground, or water from a river or an aquifer. A nice feature of the hybrid combination is that the solar collectors used as the provider of the primary heat for the heat pump. The two components will then operate in the so-called serial mode.

Combining solar and heat pump technologies is relevant in several aspects: a high renewable fraction can be achieved (solar + the heat pump heat source) and the safety of the solution makes it a good choice for many homeowners. The solar heat can help enhance the performance of the heat pump by raising the evaporation temperature. And the solar heat can be stored at low temperatures (0-80 °C) thus making good use of the collectors even during the cold season, cloudy days or at night.

Acknowledgement

The author greatly acknowledged to the Turkish Academy of Science (TÜBA) for financial support of this study.

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