Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 70 (2015) 394 – 401
Energy Procedia

International Conference on Solar Heating and Cooling for Buildings and Industry, SHC 2014

Performance comparison of direct expansion solar-assisted heat pump and conventional air source heat pump for domestic hot water

Xiaolin Sun[a], Yanjun Dai[a]*, V. Novakovic[b], J. Wu[a], Ruzhu Wang[a]

a Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, 200240, China
b Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, N-7491, Norway

Abstract

In this work, performances of conventional air source heat pump water heater (ASHPWH) and direct expansion solar-assisted heat pump water heater (DX-SAHPWH) under various operating conditions are analyzed to make comparison between the two systems. The DX-SAHPWH system in this study uses a plate type roll-bond solar collector with optimized flow channel as the evaporator, which can take both solar energy and ambient air as the heat source. Performances of both systems are investigated experimentally and numerically. The influences of operating conditions (air temperature, water temperature, solar radiation intensity, et al) are analyzed, and performance comparison under various operating conditions is made between the two systems. Results show that, in clear day conditions, the COP of DX-SAHPWH is obviously higher that of ASHPWH because the solar energy can improve the evaporating temperature of the heat pump obviously; in overcast day conditions (without frost formation), COP of both systems are almost the same; and in night conditions, especially in clear night conditions, the DX-SAHPWH shows poor performance because of the poor convectional heat exchanging performance of the solar collector/evaporator and the radiative heat loss to the night sky. And annual performance analysis shows that the average COP of the DX-SAHPWH system is remarkably higher than the conventional ASHPWH system, especially in winter season.

Peer-review by the scientific conference committee of SHC 2014 under responsibility of PSE AG

Keywords: solar; heat pump; water heating; COP

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: yjdai@sjtu.edu.cn

Peer-review by the scientific conference committee of SHC 2014 under responsibility of PSE AG
doi:10.1016/j.egypro.2015.02.140

1. Introduction

Nowadays, the building sector accounts globally for about 40% of the society energy consumption. And domestic hot water, after air conditioning, has become the second largest contributor to residential building energy consumption. So, for the last decades of years, as energy shortage draws attention of the whole world, building energy conservation has become a focus of researchers. Consequently, study on high-efficiency domestic hot water also becomes an important topic. New systems as well as new energy sources are proposed to take place of the conventional electrical or fossil fuel water heater to improve energy efficiency and reduce energy consumption. Among those water heating systems, air source heat pump water heater is one of the most promising technologies.

The air source heat pump water heater (ASHPWH), operating following a simple mechanical refrigeration cycle, takes the ambient air as heat source. Since the ambient air can provide heat stably, the heat pump system can operate reliably. Compared to electric resistance water heater, the electric-driven ASHPWH can save power consumption by 40%-60% [1]. While since the performance of ASHPWH is significantly influenced by the ambient temperature, poor performance caused by low ambient temperature has become the main obstacle to the application of ASHPWH in high latitudes.

Direct expansion solar-assisted heat pump water heater (DX-SAHPWH), first proposed by Sporn and Ambrose [2], is the combination of solar heating and heat pump technology. As mentioned above, the ASHPWH shows good operating stability but poor performance under low temperature situation. In contrast, solar water heating is totally free, though the supply of energy is unstable. The DX-SAHPWH combines the advantages and overcomes the disadvantages of both ASHPWH and solar water heating system [3]. In a DX-SAHP system, the solar collector works as the evaporator of the heat pump system simultaneously, and solar is taken directly as the heat source for the heat pump system to improve operating performance [5-11]. When a bare solar collector is used, the collector/evaporator can abstract heat from both solar radiation and ambient air, thus the combined system can operate in all weathers conditions all day [4].

In this work, performances of ASHPWH and DX-SAHPWH under various operating conditions will be investigated experimentally and numerically to make comparison between the two systems. Results show that, in clear day conditions, the COP of DX-SAHPWH is obviously higher that of ASHPWH; in overcast day conditions, COP of both systems are almost the same; and in night conditions, especially with low ambient temperature, the DX-SAHPWH shows poor performance.

2. system schematic and operating principles

2.1. system schematics and experimental set up

Fig.1 shows the structure of typical ASHPWH and DX-SAHPWH systems. Both systems operate according to a simple mechanical refrigeration cycle. The only difference is that the DX-SAHP system uses a solar collector to replace the fan-coil unit evaporator, thus solar energy could be exploited as the heat source of the heat pump. In clear day conditions, the DX-SAHPWH will show better performance because the solar radiation increases evaporating temperature of the system [2-4].

Plate-type solar collector with or without glass cover can both be used as the collector/evaporator of the DX-SAHPWH system. In clear day conditions, the glazed collector/evaporator performs higher heat collecting efficiency and lower heat loss. While when the solar radiation cannot supply enough heat for the evaporator, the glass cover will stop the collector/evaporator from extracting heat from the ambient air, unless an extra fan is used, which will increase the structure complexity and initial cost of the collector. In comparison, a bare collector/evaporator, with simple structure and low cost, can exploit heat from both solar and air easily. And operating at a temperature lower than the ambient most time, heat loss rate of a bare plate collector/evaporator is actually low [5]. Thus, in this work, a bare plate roll-bond solar collector made of aluminum is used as the evaporator of the DX-SAHPWH system. And the flow channel of the roll-bond panel has been optimized to enhance the performance of the collector/evaporator [4, 6]. Parameters of the experimental set up for this work is listed in table.1.

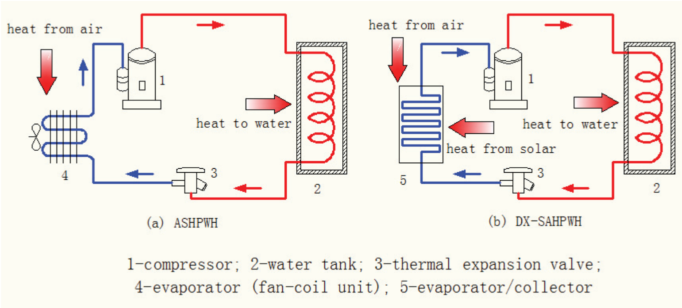

Fig.1 schematic diagram of typical ASHPWH/DX-SAHPWH system

Table. 1 parameters of experimental set up

	DX-SAHPWH	ASHPWH
Compressor	Reciprocating type, 8.8cm3/rev	Reciprocating type, 16.7cm3/rev
Evaporator	Roll-bond collector, unglazed, 2m2	Fan-coil unit
Expansion valve	Thermal	Electronic
Water tank	Volume of 150L, with copper-coil heat exchanger inside as the condenser	

2.2. Operating principles

Both the DX-SAHPWH system and the ASHPWH system operate according to a compressing-condensing-throttling-evaporating cycle. No water pump is used in either system, and water is charged into the tank by means of tap water pressure. For the DX-SAHPWH system, the compressor is the only power-consumption component, thus the input electric power

$$W_{in} = W_{comp} \tag{1}$$

While for the ASHPWH system, which uses a fan-coil unit as the evaporator, electric power has also to be supplied to the fan, and the input electric power

$$W_{in} = W_{comp} + W_{fan} \tag{2}$$

As mentioned before, the ASHPWH system takes the ambient air as heat source, and heat exchanging capacity of the evaporator (fan-coil unit) is calculated by

$$Q_{evap} = A_{evap} K_{evap} \Delta T_m \tag{3}$$

Where A_{evap} is the heat exchanging area of the evaporator; K_{evap} is convectional heat exchanging coefficient; and ΔT_m is the mean temperature difference of convectional heat exchanging.

While the heat exchanging capacity of the DX-SAHPWH system, consisting of convectional and radiative heat exchanging, is calculated as following

$$Q_{evap} = A_{evap}(K_{evap}\Delta T_m + \alpha R - \varepsilon F_{e-s}\sigma({T_{evap}}^4 - {T_{sky}}^4)) \tag{4}$$

Where $\propto$ and ε are absorptivity and emissivity of the collector/evaporator surface; R is the intensity of solar radiation; T_{evap} is mean surface temperature of the collector/evaporator; T_{sky} is the equivalent sky temperature; F_{e-s} is the evaporator-sky view factor; and σis Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8} W/(m^2 \cdot K^4)$.

Since the working fluid entering the collector/evaporator is low-temperature refrigerant, the surface temperature of the collector/evaporator is also low. So, in clear day conditions, the radiative heat loss of the collector/evaporator is small enough to be ignored, and the equation above could be simplified as following

$$Q_{evap} = A_{evap}(K_{evap}\Delta T_m + \alpha R) \tag{5}$$

While in night conditions, especially clear night condition when the equivalent sky temperature is low, the radiative heat loss of the collector/evaporator, which has significant effect on performance of the system, can no longer be ignored.

The performance of a heat pump water heating system is usually evaluated by two critical parameters: COP and heating capacity (Q_h).

When the hot water temperature is T_w, instant heating capacity of the heat pump system is calculated by

$$Q_h = c_w m_w \frac{dT_w}{dt} \tag{6}$$

Where c_w and m_w are specific heat capacity and gross mass of water in the tank.

For an electric-driven heat pump water heater, COP of the system is calculated by:

The instant COP

$$COP_i(T_w) = \frac{Q_h(T_w)}{W_{in}(T_w)} \tag{7}$$

And the average COP with water temperature rising from the initial value to T_w is

$$COP_m(T_w) = \frac{\int Q_h dt}{\int W_{in} dt} = \frac{c_w m_w (T_w - T_{w0})}{\int W_{in} dt} \tag{8}$$

Where T_{w0} is the initial temperature of water.

3. results and discussion

To make a comparison between the performances of the two systems, experimental study under various operating conditions has been made.

3.1. Clear day condition

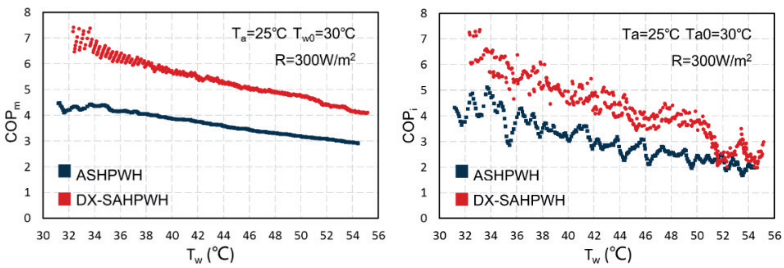

Fig.2 COP comparison under clear day condition

Under the clear day condition with environmental parameters of $T_a = 25$℃, $T_{w0} = 30$℃ and R $= 300W/m^2$, COP_i and COP_m of both systems with increasing water temperature are compared in fig.2.

Experimental results show that, in clear day conditions, with hot water temperature varying from 30 ˚C to 55 ˚C, the DX-SAHPWH system performs higher average COP than the conventional ASHPWH system. And fig.2 shows that, the instant COP of DX-SAHPWH system decreases more rapidly than that of conventional ASHPWH system. With hot water temperature up to 55 ˚C, the DX-SAHPWH system still performs higher instant COP, though the advantage gets less significant as the water temperature increases.

As shown in fig.3, with solar radiation intensity of 300W/m2, when the water temperature increases from 30 ˚C to 55 ˚C , evaporating temperature of the DX-SAHPWH system keeps more than 5 ˚C higher than that of the convectional ASHPWH system. And in this study, in order to keep a high heating capacity of the system, the DX-SAHPWH system is designed to take both solar and ambient air as heat source [4]. So, in most conditions, the evaporating temperature of the system keeps lower than the ambient temperature (unless the solar radiation intensity in extremely high).

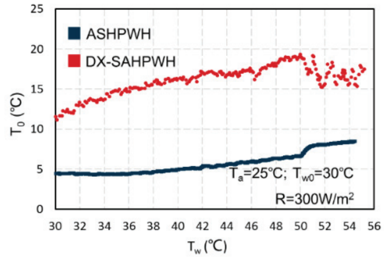

Fig.3 T_0 of both systems under clear day condition

3.2. Overcast day condition

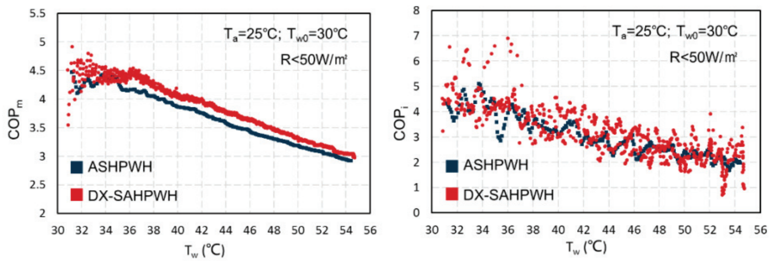

Fig.4 COP comparison under overcast day condition

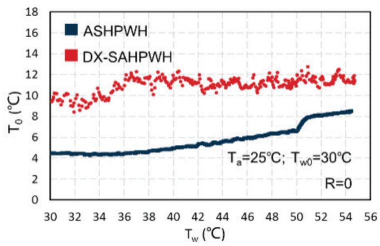

Fig.5 T_0 of both systems under overcast day condition

In overcast day condition that the solar radiation intensity is less than 50W/m2, experimental study is taken with environmental parameters of $T_a = 25°C$, $T_{w0} = 30°C$. As shown in fig.4, both instant and average COP of the DX-SAHPWH system is very close to those of the ASHPWH system. It could be inferred that, even in overcast day conditions, because of the effect of scattered radiation, the performance of DX-SAHPWH system is still as good as, or even slightly better than that of conventional ASHPWH system. And as shown in fig.5, the evaporating temperature of the DX-SAHPWH system is still higher than that of the ASHPWH system.

3.3. Overcast night condition

In overcast night condition, the value of solar radiation intensity is zero. Since the convectional heat exchanging performance of the roll-band collector/evaporator is not as good as the fan-coil unit, COP of the DX-SAHPWH system is lower than that of the conventional ASHPWH system, as shown in fig.6. And fig.7 shows that evaporating temperature of DX-SAHPWH system is also lower than that of the ASHPWH system.

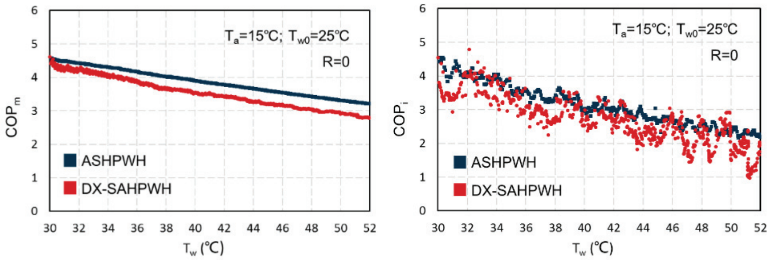

Fig.6 COP comparison under overcast night condition

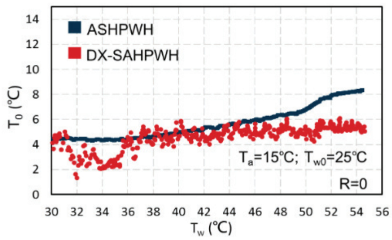

Fig.7 T_0 of both systems under overcast night condition

3.4. Clear night condition

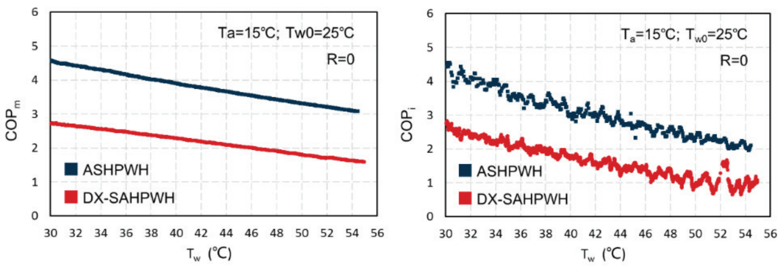

Fig.8 COP_m comparison under clear night condition

In clear night condition when there is no cloud cover, the equivalent temperature of the sky is low, thus the radiative heat loss of the collector/evaporator to the sky has significant effect on the performance degradation of the DX-SAHPWH system. Results in fig.8 to fig.9 indicate that, evaporating temperature as well as COP of the DX-

SAHPWH system is obviously much lower than that of the conventional ASHPWH system, on which the effect of sky radiation is negligible.

And it could be concluded from the results of instant COP as well as evaporating temperature (shown in fig.8 and fig.9) that, compared to the daytime situation and cloudy night situation, in clear night condition without the influence of solar radiation fluctuation and cloud cover movement, the operating parameters variation of the DX-SAHPWH system with increasing water temperature is more stable.

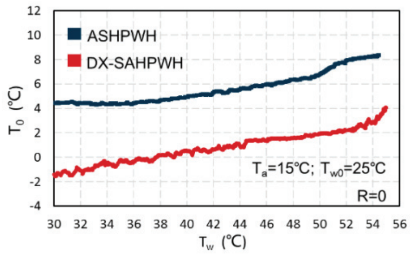

Fig.9 T_0 of both systems under clear night condition

3.5. Annual performance analysis

Numerical model of both DX-SAHPWH system and ASHPWH system are established to make annual performance analysis and comparison of the two type of systems. In this work, both experimental and numerical study are taken under the climate situation of Shanghai, China. As shown in fig.10, the ambient temperature as well as city water temperature differences are obvious from month to month, and over cast/rainy/snowy days take more than 1/3 of the whole year.

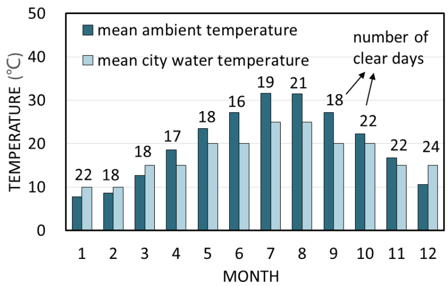

Fig.10 monthly average environmental parameters of the whole year

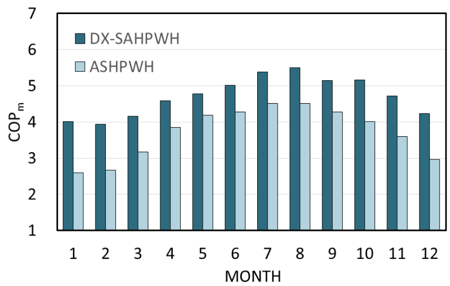

Fig.11 monthly average COP of the whole year

Fig.11 shows monthly simulation results of average COP for both DX-SAHPWH and ASHPWH system. In this simulation, city water is set to be heated from the initial temperature (as shown in fig. 14) to 55 ˚C, and only day-time operations are considered. The results indicate that the monthly average COP of the DX-SAHPWH system keeps higher than convectional ASHPWH system all over the year. Especially in winter season, when the ambient temperature is low, the ASHPWH system shown poor performance, the advantage of DX-SAHPWH system is more significant. This is because, in high ambient temperature situation, the evaporating temperature of conventional ASHPWH system is already high, and for DX-SAHPWH system, since there is an upper evaporating temperature limit of the compressor, the improvement of evaporating temperature cause by solar is also limited. While in low ambient temperature situation, when the evaporating temperature of conventional ASHPWH system is low, for the DX-SAHPWH system, solar radiation can increase the evaporating temperature more remarkably.

4. Conclusion

In this study, experimental and numerical study on the comparison of DX-SAHPWH system and conventional ASHPWH system is taken in various environmental conditions under the climate situation of Shanghai, China. Results show that:

(1) In clear day condition, the DX-SAHPWH system takes both solar and ambient air as heat source. Compared to conventional ASHPWH system, the DX-SAHP system performs higher COP.

(2) In over cast day condition, the DX-SAHPWH system takes ambient air as the main heat source. While because of the scattered radiation, performance of the DX-SAHP system is still as good as that of the conventional ASHPWH system, even though the convectional heat exchanging performance of the fan-coil unit is much better than that of the roll-bond collector.

(3) In night conditions, compared to the ASHPWH system, the DX-SAHPWH system always shows poor performance. While there is a remarkable difference between clear night and overcast night conditions. In overcast night condition, the existence of the cloud cover improves the equivalent temperature of the sky efficiently and thus reduce the radiative heat loss of the collector/evaporator of the DX-SAHPWH system. While in clear night situation, the equivalent sky temperature is low, resulting in great heat loss of the collector/evaporator and poor performance of the system.

(4) Annual simulation analysis indicates that, all through the year, the monthly average COP of the DX-SAHPWH system keeps higher than that of the conventional ASHPWH system. Especially in clear winter day condition, when the ambient temperature is low, the advantage of DX-SAHPWH system gets more remarkable.

Acknowledgements

This work was supported by National Science and Technology Support Project of China under the Contract No. 2012BAA05B04.

References

[1] A. Hepbasli, Y. Kalinci. A review of heat pump water heating systems. Renewable and Sustainable Energy Reviews; 2009; 13: 1211–1229

[2] P. Sporn, E.R. Ambrose. The heat pump and solar energy. Proceedings of the World Symposium on Applied Solar Energy. Phoenix, Ariz; November 1–5, 1955

[3] O. Ozgener, A. Hepbasli. A review on the energy and exergy analysis of solar assisted heat pump systems. Renewable and Sustainable Energy Reviews; 2007; 11: 482–496

[4] Xiaolin Sun, Jingyi Wu. Experimental study on roll-bond collector/evaporator with optimized channel used in direct expansion solar assisted heat pump water heating system. Applied Thermal Engineering; 2014; 66: 571-579

[5] S. K. Chaturvedi, D. T. Chen, et al. Thermal performance of a variable capacity direct expansion solar-assisted heat pump. Energy Conversion and Management; 1998; 39: 181-191

[6] A. Bejan, S. Lorente. Constructal theory of generation of configuration in nature and engineering. J. Appl. Phys.; 2006; 100: 041301-041327.

[7] M. N. A. Hawlader, S. K. Chou, et al., The performance of a solar assisted heat pump water heating system. Applied Thermal Engineering; 2001; 21: 1049-1065

[8] B. J. Huang, C. P. Lee. Long-term performance of solar-assisted heat pump water heater. Renewable Energy; 2004; 29: 633-639

[9] Y. W. Li, R. Z. Wang. Experimental performance analysis on a direct-expansion solar-assisted heat pump water heater. Applied Thermal Engineering; 2007; 27: 2858-2868

[10] Y. H. Kuang, K. Sumathy. Study on a direct-expansion solar-assisted heat pump water heating system. International journal of energy research; 2003; 27: 531-548

[11] A. Moreno-Rodríguez, A. González-Gil, et al. Theoretical model and experimental validation of a direct-expansion solar assisted heat pump for domestic hot water applications. Energy; 2012; 45: 704-715