Technology Review of Solar Assisted Heat Pump System for Hot Water Production

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Abstract:- This paper reviews past research on solar assisted heat pump systems (SAHP) technologies for hot water production. SAHP technologies are basically conventional vapour compression cycle system (VCS), assisted by solar energy. These technologies are proposed as an alternative to the conventional air source heat pump (ASHP) and hot water boiler (HWB) due to higher energy efficiency and smaller building footprint requirement. In this paper, the characteristics of SAHP and comprehensive technology review of SAHP are investigated.

Key -words: -Solar assisted heat pump, Vapor compression

1 Introduction

Basic factor for the growing interests of heat pump based water heating system is the availability of abundant and free heat source for the evaporator. Heat pump operates between two (2) temperature level, pumping heat from low temperature heat source to high temperature heat sink. The energy required to pump the heat is proportional to the difference of these temperature levels. Since higher evaporation temperature dictates significantly higher COP, coupling heat pumps with free and abundant solar energy is very promising. In hot and humid countries with abundant solar radiation, utilising solar as a heat source for water heating is a sensible choice. STC system is a logical choice, but beside higher setup cost compared to ASHP and electric heating, STC based water heating requires higher building or roof footprint and this impedes the market penetrations of STC.

Generally, SAHP is preferred for producing hot water in the temperature range between 40^oC to 70^oC [1]. In tropical countries where space heating is not required, hot water in this temperature range is suitable for domestic hot water (DCS) and dehumidifier.

SAHP has gain interests from the researcher all over the world since 1950.

Most research have focused on improving energetic and exergetic efficiency, operational flexibility and minimizing capital cost [1-8].

2 Principal of SAHP

SAHP is a type of heat pumps that integrates with solar thermal collectors which supply heat directly or indirectly to the evaporator. The former is called direct expansion solar asssisted heat pump (DX-SAHP) and the latter is indirect expansion solar asssisted heat pump (IX-SAHP). Both type are categorised as series system. In parallel system, conventional heat pump typically air sourse (ASHP) is utilise in parallel with solar collectors. In this configuration, the solar collector provides direct heating whenever the available solar radiation exceeds the critical radiation level of the collectors, and assisted by heat pump if the solar heat absorbed is insufficient to increase the water temperature up to the desired temperature.

The main concept of SAHP is the utilization of solar heat to increase the evaporation temperature or reduce the condenser load of the heat pumps and thus increases the heat pump coefficient of performance (COP).

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2.1 Classification of SAHP

Series system can be further categorised into two (2) types; a) direct expansion (DX-SAHP) and b) indirect-expansion (IX-SAHP)[9-10] as shown in Fig. 2 and Fig. 3. IX-SAHP utilises water loop heat pump system where the evaporator side of the heat pump is connected to the hot water produced by the solar collector. The heat collected by the solar collectors is transferred indirectly to the evaporator of the heat pump. In DX-SAHP, two (2) phase solar collector/evaporator is used as an evaporator of the heat pump. The refrigerant is pumped directly by the compressor and thus eliminate the requirement of additional water loop circuit to transfer heat from the collector the evaporator.

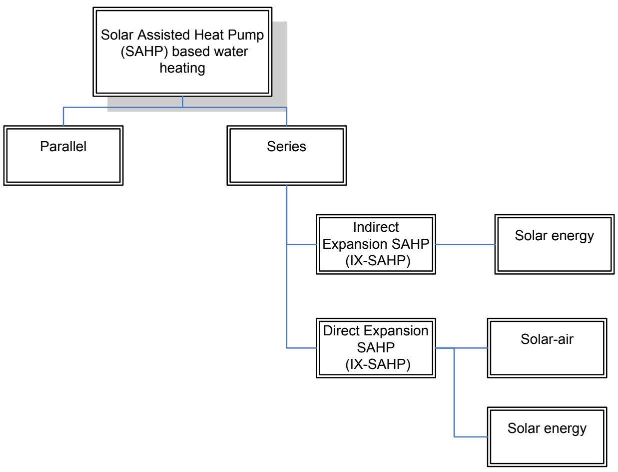

Fig. 1 Classification of SAHP

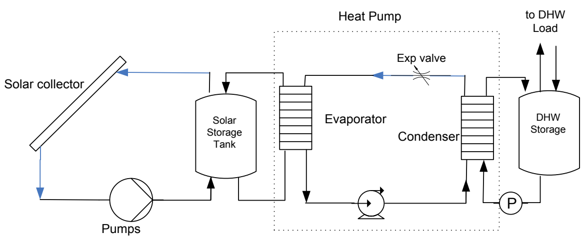

Fig. 2 Series system- Indirect Expansion SAHP (IX-SAHP)

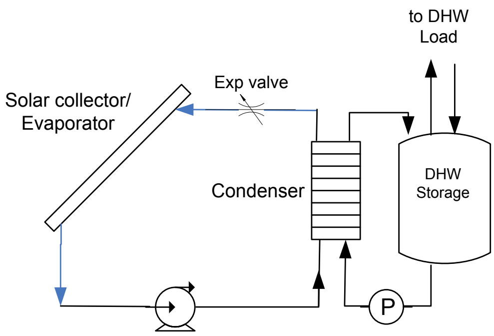

Fig. 3 Series system- Direct Expansion SAHP (DX-SAHP)

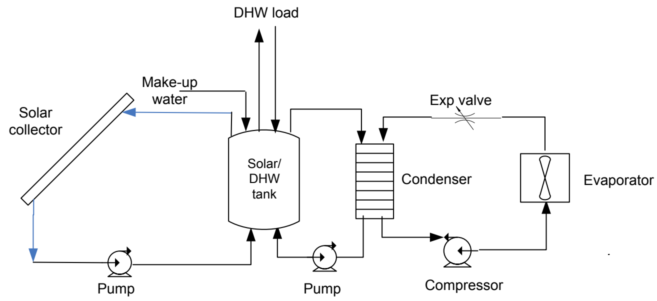

Fig. 4 Parallel System

In general, SAHP offers the potential for significant improvement over Air Source Heat Pump (ASHP) [11-12]. Higher evaporation temperature from direct exposure to solar radiation relative to ambient temperature resulted in higher COP of SAHP.

DX-SAHP advantageous over IX- SAHP are listed below:

a. The direct vaporization of the refrigerant in the solar collector– evaporator leads to higher heat transfer coefficients [10].
b. The use of the solar collector as the evaporator reduces overall system cost because the need for an additional evaporator in the traditional SAHP system is eliminated [10].
c. Problems, which may occur in water collectors (i.e. corrosion, night freezing), are eliminated due to the use of refrigerants as the working fluid, leading to longer system life [4, 10, 13].

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d. Utilization of refrigerants as the working fluid in the heat pump cycle results with low temperature during the evaporation process in the solar collector, which leads to lower system losses since the collector loss value is a function of the collector to ambient temperature difference [10].
e. The collector, including bare flat-plate collectors, works at high efficiency values based on the low collector to ambient temperature differences, which also reduces collector cost [10, 14].
f. DX-SAHP can be envisaged to run on photovolatic [14].
g. Reduction of number of components (resulting in improved reliability, simpler control and less maintenance)[4, 15-16].
h. DX-SAHP required around half of the collector panel required for traditional solar panel for water heating [14].

Although DX-SAHP is generally more efficient relative IX-SAHP, lack of direct solar heating (radiation), meaning that auxiliary energy is required more frequently [17].

3 Solar collector/evaporator

Among the distinct characteristics of DX-SAHP is the application of solar collector as the evaporator of the heat pump. Refrigerant-filled, two-phase solar collectors have been used as an evaporator to DX-SAHP. Flat plate collectors are well suited for low temperature domestic hot water heating applications (<60^{o}C) since the solar collector temperature and application temperature are roughly matched. Solar collector is more efficient at low collector temperature due to lower collector heat loss.

The most common solar collector/evaporator used for DX-SAHP is flat unglazed/bare solar collector [3-4, 18-21]. The most common collector material is copper even though aluminium is sometime used for its light weight property [22]. Thermal performance flat unglazed/bare solar collector is not degraded substantially in a temperate climate [23]. Since convection and irradiation losses are low due to low evaporation temperature of the refrigerant relative to ambient temperature , neither glazed solar collector nor expensive vacuum tube are required. However, in upper latitudes, single or multiple cover collector systems must be employed for satisfactory system performance [3]. The bare collector can also be integrated with the roof so that elaborate supporting fixtures for the collector plate are not required [3].

Operation of DX-SAHP system requires consistent solar radiation. Due to inconsistency in available solar radiation, especially in rainy days and monsun season, Xu et.al [24] develop solar collector/evaporator using specially designed flat-plate heat collector/evaporator with spiral-finned tubes exposed directly to both ambient air and solar irradiation, absorbing both solar energy and ambient air energy simultaneously or either of the two. Another special type of solar collector/evaporator developed by Huang et.al [18] consisting of a bare, circular shape collector/evaporator surrounding a water tank. The collector is of tube-in-sheet type using copper tube. The evaporator/collector is designed in circular shape. Hence, it always absorbs both solar radiation and ambient air by the half part facing the sun and absorbs the ambient air energy only from the other half that is back the sun. In order to further reduce collector cost, Nuntaphan et.al [25] developed a solar collector, modified from corrugated metal roofing.

4 Energetic and Exergetic efficiency

Heat pump performance is a function of heat sink and heat source temperatures. For the designated heat sink/application temperature, the heat source temperature is a main factor dictating heat pump performance. The higher the heat source temperature the higher the performance. The heat pump performance parameters COP and the collector efficiencies are function of the collector operating temperature. As collector temperature (hence evaporator temperature) rises, the collector efficiency drops but with an increases in heat pump efficiency.

Exergy is the quantification of maximum useful work that can be done by a system interacting with the surrounding environment, at a constant pressure and temperature. Analysis of exergy flows in a solar-driven system can lead to identification of inefficient parts of the system and optimum operating conditions [26]. The goal of these analysis is to determine the optimized system design by maximizing exergetic efficiency at all components level. In recent years, first-law analysis (i.e. energy analysis) and second-law analysis (i.e. exergy analysis) of DX-SAHP have been carried out by many researchers [6, 9-10, 26-27].

Table 1 in Appendix 1 tabulates review of energetic and exergetic studies on DX-SAHP. Table 2 in Appendix 2 outlines the improvement strategies of exergetic efficiency.

4.1 Exergetic and Energetic Efficiency Model of DX-SAHP

The exergetic analysis is used to evaluate the exergetic efficiency of each system component and determine which component has the highest exergy loss or destroyed. Mathematical formulation for exergy analysis in differents components can be arranged in the following way [28]. DX-SAHP and its corresponding T-S diagram are as shown in Fig. 5 and Fig. 6.

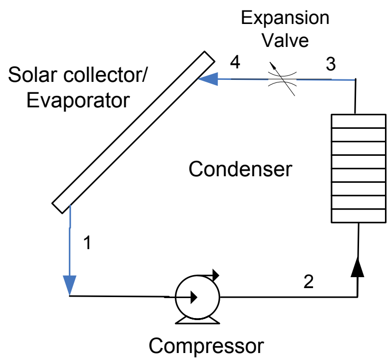

Fig. 5 Basic DX-SAHP Schematic and corresponding T-S diagram

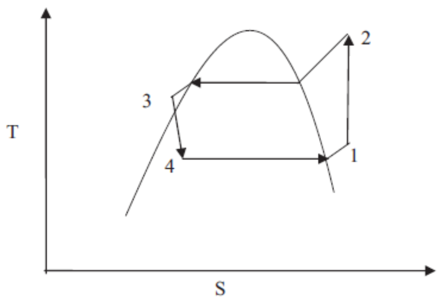

Fig. 6 DX-SAHP on T-S Diagram

Specific exergy in any state,

$$\psi = (h - h_o) - T_o(s - s_o) \quad (1)$$

For evaporator,

Heat addition in evaporator is given by:

$$Q_{ev} = \dot{m}(h_1 - h_4) \quad (2)$$

Exergy destruction,

$$I_{ev} = \dot{m}(\psi_4 - \psi_1) + Q(1 - \frac{T_o}{T_{ev}}) \quad (3)$$

$$I_{ev} = \dot{m}[(h_4 - h_1) + T_o(S_4 - S_1)] + Q(1 - \frac{T_o}{T_{ev}}) \quad (4)$$

For evaporator that receive heat from solar radiation (solar collector/evaporator),

$$I_{col/ev} = \dot{m}[(h_4 - h_1) + T_o(S_4 - S_1)] + \dot{Q}_{rad}(1 - \frac{T_o}{T_p}) \quad (5)$$

For compressor

Compressor work is given by:

$$W_c = \dot{m}(h_2 - h_1) \quad (6)$$

For non-isentropic compression,

$$h_c = \frac{(h_{2s} - h_2)}{\eta_c} \quad (7)$$

Electrical power,

$$W_{el} = \frac{W_c}{\eta_{mech} X \eta_{el}} \quad (8)$$

Exergy loss,

$$I_{comp} = \dot{m}(\psi_1 - \psi_2) + W_{el} \quad (9)$$

$$I_{comp} = \dot{m}[(h_1 - h_2) + T_o(S_1 - S_2)] + W_{el} \quad (10)$$

For condenser,

Heat released in the condenser is given by:

$$Q_{con} = \dot{m}(h_2 - h_3) \quad (11)$$

Exergy destruction,

$$I_{con} = \dot{m}(\psi_2 - \psi_3) + Q_{con}(1 - \frac{T_o}{T_{con}}) \quad (12)$$

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$$I_{con} = \dot{m}[(h_2 - h_4) + T_o(S_2 - S_3)] + Q_{con}\left(1 - \frac{T_o}{T_{con}}\right) \quad (13)$$

For expansion valve,

Exergy destruction for isoenthalpy process (h_4=h_1),

$$I_{exp} = \dot{m}(\psi_4 - \psi_3) = m(S_4 - S_3) \quad (14)$$

Total exergy destruction,

$$I_T = I_{col/ev} + I_{comp} + I_{con} + I_{exp} \quad (15)$$

The exergetic efficiency or exergy efficiency can be expressed as[29]:

$$\eta=1-\frac{\dot{E}_{xloss}}{\dot{E}_{Xi}} \quad (16)$$

The energetic efficiency for heat pump is expressed in the form of Coefficient of Performance (COP).

$$COP_{HP} = \frac{h_2 - h_3}{W_c} = \frac{Q_c}{W_c} \quad (17)$$

And to determine the COP for the whole heating system,

$$COP_{HPSYS} = \frac{Q_c}{W_c + W_p} \quad (18)$$

COP varies with varying evaporator and condenser temperature which are in turn subjected to available solar radiation and hot water output temperature. The higher the difference between condenser pressure and evaporation pressure, the higher the power of the compressor required. As for DHW application, hot water outlet temperature is typically set at a single temperature, evaporation pressure/temperature, T_{ev} at the solar collector/evaporator side can be manipulated to reduce system COP. Higher T_{ev} results in lower compressor pressure lift and corresponding power input, but when T_{ev} is higher than the ambient temperature, solar collector/evaporator loss is unavoidable and leads to overall system COP reduction. There exists an optimum T_{ev} that will ensure highest overall system COP for DX-SAHP.

The choice of optimum evaporatoring upon the design and weather condition. Chaturvedi et al [19] found a variation of the evaporator temperature from 0°C to 10°C under favourable solar conditions to ensure high collector efficiency. Another study by Li et al. [22] found maximum exergy efficiency at evaporation temperature 5-8°C above ambient. Chata et al. [13]suggested that evaporation temperature shall be maintained at 5-10°C above ambient by properly matches heat pumping (evaporative) capacity of the compressor and the collector capacity. Operating evaporator at this temperature leads to low collector heat loss and improved heat pump performance. Utilizing variable speed compressor to maintain the temperature level can significantly improve DX-SAHP COP performance[13, 15, 21, 24-25, 30-32]. However, according to Huang et al [5], operating at higher evaporation temperature will cause higher compressor discharge temperature possibly beyond its operating range leading to lower compressor reliability. He then suggested that operating evaporator at temperature lower than ambient will cause lower compressor discharge temperature and abling the collector to absorp heat both from the ambient and solar radiation without significant collector heat loss.

Optimum evaporation temperature is factor of available solar radiation, ambient temperature and collector characteristics and given by [3];

$$\left(T_f - T_a\right)_{optimal} = T_a\left[\left(1 + \frac{I_{coll}(\tau\alpha)}{U_L T_a}\right)^{1/2} - 1\right] \quad (19)$$

Exergetic analysis carried out by many researcher have concluded that the highest exergy loss occured at the compressor, followed by solar collector/evaporator, condenser and expansion valve [6, 22].

5 Review of previous research

The continues rising of energy cost and environmental concerns are the driving force of all research in any energy related field. Improving energy conversion efficiency and at the same time alleviating economic barriers to such technology is the prime concerns.

Huang et.al [18] studied a heat-pipe enhanced solar-assisted heat pump water heater (HPSAHP) that works with dual heat sources that combines the performance of conventional heat pump and solar heat pipe collector. An outdoor test for a HPSAHP in the present study has shown that COP of the hybrid-mode operation can reach 3.32, an increase of 28.7% as compared to the heat-pump mode COP (2.58).

Gorozabel Chata et.al [13] analysed the thermal performance of a DX-SAHP for several refrigerants using two collector configurations, namely a bare collector and a one cover collector. He found that R-12 produces the highest value of COP_H, followed by R-22 and R-134A. For mixture refrigerants, R-410A is shown to be more efficient than either R-407C or R-404A but 15-20% lower than obtained with R-134A.

Kuang and Wang [30] reports on the long-term performance of a multifunctional DX-SAHP system for domestic use. Daily average heat pump COP (space heating) from 2.6 to 3.3 and for DHW heating at 50^{o}C, system COP achievable from 2.1 to 3.5 and for space cooling at night, COP heat pump is 2.9. It shows that, the multi-functional DX-SAHP system could guarantee a long-term operation under very different weather conditions and relatively low running cost for a whole year.

Xu et.al [24] carried simulation study on solar air source heat pump water heater (SAS-SAHP) using specially designed flat-plate heat collector/evaporator with spiral-finned tubes to obtain energy from both solar irradiation and ambient air for hot water heating.

Li et.al [22] investigated DX-SAHP using DX-SAHP with constant speed rotary compressor, immerse condenser coil, aluminium plate collector/evaporator. COP of the DX-SAHPWH system can reach 6.61 during daytime and 3.11 at a rainy night. The seasonal average value of the COP and the collector efficiency was measured as 5.25 and 1.08, respectively.

As heat sink temperature rises above 60^{o}C, COP of single stage SAHP deteriorates. Chaturvedi [33] proposed two stage DX-SAHP systems with R-134a refrigerant and one cover collector in meeting loads with high temperature requirement in the range of 60^{o}C to 90^{o}C. He proved that two stage DX system had higher performance than single stage DX at high condensing temperature.

Nuntaphan et.al [25] carried research on the thermal performance of a IX-SAHP using a solar collector modified from corrugated metal roofing with a copper tube attached beneath. The refrigerant mixture used is R22/R124/R152a. The coefficient of performance (COP) of this system is between 2.5 and 5.0 The payback period for this system is 2.3 years.

Mohanraj et.al [34] investigated the suitability of artificial neural network (ANN) to predict the performance of a DXSAHP under the meteorological conditions of Calicut city in India.

Li, H. and H. Yang [35] investigated the application of the IX-SAHP systems for hot water production in Hong Kong. A mathematical model of the system is developed to predict its operating performance under specified weather conditions. They reckoned that system performance is governed strongly by the change of circulation flow rate, solar collector area and initial water temperature in the preheating solar tank.

Chow et.al [15] examined the potential application of a DX-SAHP with variable speed reciprocating compressor, immersed condenser coil, tube in plate heat exchanger and capillary tube. The system achieved a year-average coefficient of performance (COP) of 6.46 much better than the conventional heat pump system performance.

Xu et.al [36] developed novel low-concentrating solar photovoltaic/thermal integrated heat pump system (LCPV/T-HP) with both electricity and heat outputs. Fixed truncated parabolic concentrators was employed to reflect the incident sunlight onto the surface of PV cells also as the evaporator of the heat pump system.

Wang et.al [37] proposed a novel indirect-expansion solar-assisted multifunctional heat pump (IX-SAMHP) which integrates a domestic heat pump with a solar water heater.

Ahmet and Cemil [38] studied the performance of a solar-assisted heat pump with an evacuated tubular collector both theoretically and experimentally. The maximum value of the coefficient of performance of the solar assisted heat pump is obtained as 6.38 experimentally.

Tamasauskas et al [39] presents the modeling and optimization of a solar assisted heat pump using ice slurry. Solar collectors are used as the primary source of thermal energy, with two distinct loops allowing the collectors to operate in series with an ice tank, or a warm water tank. The proposed heat pump with ice slurry achieved 86% reduction over an electrical resistance heating system and 5%

reduction relative to SAHP using sensible storage only.

6 Summary & Conclusion

The structure and focus of previous research on SAHP can be categorised into three (3) main categories; a) improving energetic and exergetic efficiency, b) improving economics and c) extending application field of heat pumps.

a) Improving energetic and exergetic efficiency

Major studies had focused on evaporation temperature optimization by using variable speed compressor, improvement of collector/evaporator heat transfer characteristcs, refrigerant type, system level configuration, use of PV-T collector and PCM heat storage to improve net system COP.

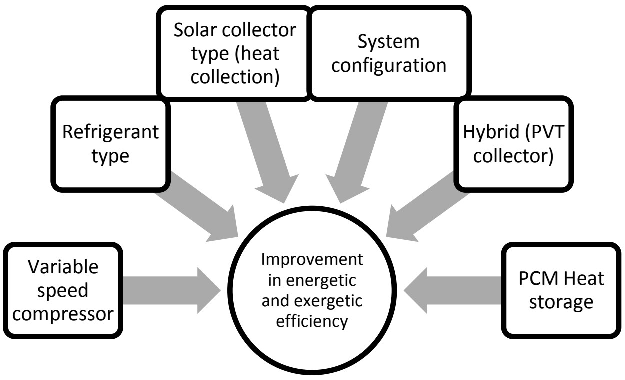

Fig. 7 Energetic and exergetic efficiency improvement strategies

b) Improving economics

One of the main cost factor in SAHP is the collector. Most direct expansion SAHP uses low cost bare flat solar collector as the optimum evaporation temperature is only 5°C to 10°C above ambient. Improvements are made to reduce the collector size by increasing its heat transfer performance and exploring cheaper collector such as corugated metal roof. Another strategy is to reduce the conventional hot water storage tanks capacity by using low volume high capacity phace change material (PCM) such as ice slurry.

c) Extending application fields

Efforts have been made to make SAHP more versatile in serving heating and cooling demand of buildings. Typically, SAHP is used to produce hot water for domestic and heating requirements but for tropical countries, cooling demand is dominant relative to heating. Studies have been conducted to extend the application of SAHP for space heating, domestic hot water and chilled water for air conditioning purposes. This make SAHP more versatile and attractive and open up more doors to commercialization.

SAHP technologies have huge potential as a green tools to reduce the world carbon footprint and energy cost reduction relative to other conventional technologies. They can serve many application for residential and commercial sector including space heating, water heating and cooling. Their ability to utilize ubiquitous low and high grade heat make them an indispensable technology that can contribute towards a cleaner environment. Much work has been done but more is still required to further improve SAHP and ease its penetration into commersalization. It is hoped that this review will help increase awareness and excite efforts in maximizing the potential of SAHP for the greener world.

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Appendix 1

Table 1 Selected energetic/exergetic studies on DX-SAHP (Extended from [10])

Year	Investigator	Location	Collector type	Collector area (m^2)	Type of refrigerant	COP	Collector efficiency (%)	Type of study		Type of analysis	
								Theory/Sim	Exp	Energy	Exergy
2006	Kuang and Wang [30]	China	1	10.5	R-22	2.6–3.3	N/A			⁄	
2007	Li et al[22]	China	1	4.2	R-22	5.3	1.08	⁄	⁄	⁄	⁄
2008	Nuntaphan et al [25]	Thailand	3	4.0	R22/R124/R152a	2.5-5.0	N/A	⁄		⁄	
2009	Chow et al[15]	Hong Kong	1	12.0	R-134a	6.5	N/A	⁄		⁄	
2009	Liu et al[31]	Tibet	4	4.6	N/A	6.0	47.9	⁄	⁄	⁄	
2010	Scarpa et al [14]	Italy	1	2.0	N/A	8.1	60.0-80.0	⁄	⁄	⁄	⁄
2011	G.Y. Xu et al.[36]	China	5	1.6	R-134a	4.8	N/A	⁄	⁄	⁄	
2011	X. Zhao et al.[40]	UK	6	10.0	R-134a	N/A	50.0	⁄		⁄	
2012	Ahmet and Cemil [38]	Turkey	7	N/A	R407C	5.6-6.4	72.8-80.7	⁄	⁄	⁄	
2012	Fu et al [41]	Hong Kong	8	12.1	R134a	2.5-4.9	N/A	⁄	⁄	⁄	⁄

Note

Collector type

1 Bare flat collector

2 Single glaze flat collector

3 Corrugated metal roofing with a copper tube attached beneath

4 PV-Bare-flat plate

5 PV/T collector with fixed truncated parabolic concentrators

6 Roof integrated PV/T collector

7 Evacuated Tube collector

8 Heat Pipe PV/T collector

Appendix 2

Table 2 Improvement strategies of exergetic efficiency

Components	Strategy	Researcher
Compressors	Regulation of evaporation temperature by using variable speed drive compressor.	Chaturvedi et al [2-3]
	Reduction of compressor power input by operating DX-SAHP at time with highest solar radiation and set hot water temperature not more than 60^{o}C.	Li et al [22]
Solar collector/evaporator	Evaporative capacity of collector must match heat pumping capacity of compressor (achievable via VSD).	Kuang et al [30, 42], Chaturvedi et al [2-3]
Expansion valve	Use of Electronic Expansion Valve (EXV) together with VSD.	Li et al .[22, 31]
Condenser /storage tank	Increase thermal insulation performance of water tank walls,	Li et al .[22]
	Enhancing heat exchange and optimizing the configuration and position of the condenser in the water tank	Li et al. [22]

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