International Journal of Latest Engineering and Management Research (IJLEMR)
ISSN: 2455-4847
www.ijlemr.com || Volume 02 - Issue 03 || March 2017 || PP. 44-50

An Investigation on Comparison of Direct Expansion Solar Assisted Heat Pump Water Heater with an Air-Source Heat Pump Water Heater

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Abstract: The investigation on comparison of direct expansion solar assisted heat pump and air source heat pump water heater is detailed. This system consists flat plate collector as an evaporator surface area of 2.23m^2, a small R134a reciprocating-type compressor rated input power 245 W, an insulated hot water tank volume of 30L and capillary expansion tube bore of 0.036”. The use of heat pump or solar water heating, particularly the solar-assisted heat pump options, is not popular. The paper explains the potential application of direct-expansion solar-assisted heat pump water heater (DESAHPWH) system. Experimental studies measure the solar intensity, water inlet temperature, water outlet temperature, ambient temperature, time step, and heat gain at the condenser for finding out the coefficient of performance, also a performance comparison between DESAHPWH and Air Source HPWH was done. The COP for the DE-SAHPWH built in the present study lies in the range 3–5 depending on operating conditions. It was an increase of 47% in COP when compared with HPWH.

NOMENCLATURE

I Solar radiation intensity (W/m²)
$\mathbf{T_a}$ Ambient air temperature (°C)
$\mathbf{T_w}$ Temperature of water in the storage tank (°C)
$\mathbf{m_r}$ Mass flow rate of the refrigerant (kg/s)
h Specific Enthalpy (kJ/kg)
$\mathbf{c_{pw}}$ Specific heat of water (kJ/kgK)
$\mathbf{M_w}$ Mass of the water in water tank (kg)
$\mathbf{P_s}$ Pressure at suction (kg/cm^2)
$\mathbf{P_c}$ Pressure at condenser (kg/cm^2)
t Time (min)
$\mathbf{Q_w}$ Heat gain at condenser

Introduction

Hot water can be used in number of applications such as large scale hot water usage for bathing and laundry applications in hostels, hospitals and high rise apartment buildings, pre feed for boilers for steam generation, for various industrial applications, milk dairies for applications such as pasteurization, condensation, cleaning, leather processing industry for drying and tanning. Hot water also used in metal finishing industry for degreasing and phosphating, resin emulsification in polymer industry, drying and related processes in pharmaceutical industry, solar drying through air heating is an area of growing interest and swimming pool heating is a popular concept in India and abroad. Hot water form an integral part of various industrial and commercial applications and with rising oil prices, there has never been a better time to look at heating water by harnessing energy from the sun.

In the direct expansion solar assisted heat pump water heater (direct SAHP) system, the solar collector serves as an evaporator where the refrigerant absorbs the incident solar energy and energy rejected by the condenser contributes to water heating. Since the solar collection system can supply energy at temperatures higher than the ambient outdoor air, the capacity and coefficient of performance improves. In virtue of its above mentioned advantages, the direct SAHP is expected to have a huge potential market in daily life especially in areas where ambient temperature is low. In the direct SAHP, condenser can be arranged as an external heat exchanger supplying a hot water or arranged as an immersed coil in the hot water storage tank. The main advantage of direct SAHP as compared to SAHP is the better thermal performance due to direct expansion and evaporation of the refrigerant in the collector. In direct SAHP, long supply and return lines are required between roof mounted solar collector and the thermal storage located in the heated interior of the building. As these lines are charged with refrigerant and require specialized mechanics, this makes the installation difficult. The study however concluded that this system configuration offered significant performance and cost benefits over the solar assisted heat pump water heater. In this paper, we will discuss and compare the performance of direct expansion solar assisted heat pump and air source HPWH.

The concept of the DESAHP was firstly considered by Sporn and Ambrose in 1955 [1]. The DE-SAHP principle is one of the most promising techniques, so much research has focused on DE-SAHP systems, including system structure ,thermal performance, working fluid characteristics , operational control, numerical simulation, economic analysis ,etc. since the overall performance of a solar system is influenced significantly by the changes in the climate conditions and load demands, the real system matching in a whole year is hardly realized without the guide of a reasonable theoretical analysis.[2]

Chaturvedi (1980) [3] carried out a theoretical analysis for the instantaneous operation of a SAHP and shows that the evaporating temperature of a SAHP, T_e, depends on the solar radiation *I* and the ambient temperature T_a. T_e may be higher than T_a (heat dissipated to the ambient air from the collector) or lower than T_a (heat gained from the ambient air), depending upon the design and the operating conditions.

Chaturvedi (1998) [4] further shows theoretical and experimentally that a SAHP using a bare collector and a variable-frequency compressor has an optimum performance provided the collector temperature (related to the evaporating temperature T_e) is maintained in a temperature range of 5–10^{o}C above ambient. Ito *et al*. (1999) also designed a SAHP with a bare collector operating at $T_e - T_a$.

Theoretical and experimental studies were made by *Ito, Miura and Wang [5]* on the thermal performance of a heat pump that used a bare flat plate collector as the evaporator. The analysis used empirical equations to express the electric power consumption of the compressor and coefficient of performance (COP), as functions of temperature of evaporation at the evaporator and that of the heat transfer medium (water) at the inlet of the condenser. The model having been established, the influence of the collector area, the pitch of the tube for the refrigerant flow, and the collector plate material were also investigated analytically.

It should be noted that refrigerant R-12 R-22 was used in those experiments. On the other hand, the analysis of the paper can be applied in the same way to heat pumps using other kinds of refrigerants. Our experimental analysis is based on R-134a.

System Description

Fig.1 shows the schematic diagram of the DE-SAHPWH system. The system consists of detachable glazing flat plate solar collector which acts as an evaporator, a hot water storage tank with an immersed heat exchanger as condenser, a capillary expansion tube and a small hermetically sealed reciprocating compressor. The figure also shows the pressure gauges and temperature probes as and where located in the system.

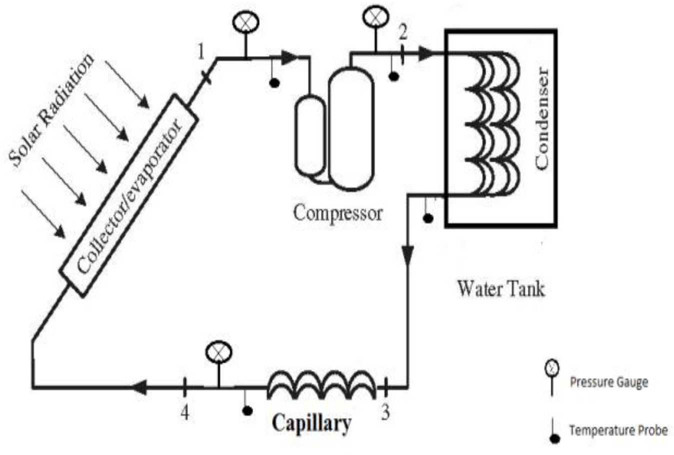

Figure 1. Schematic Diagram

Flat plate solar collector/evaporator

The DE-SAHPWH uses a detachable glazing flat plate solar collector with total area 2.23m^2. It consists of a copper absorbing plate of 0.3mm thickness. Copper tubes of OD 5/16 inches soldered to the plate with a pitch of 100mm. Collector has an aluminium sheet at the back, glass wool insulation in between with aluminium foil wrapped over it.

Compressor

A small R-134a reciprocating type hermetically sealed compressor with piston swept volume 5.79cc and rated input power 245W is adopted. The compressor has the self-protection circuit to prevent coil overheating and over current.

Condenser/hot water storage tank

The condenser is made up of a copper tube OD 3/8" with length 32ft, which is immersed in the domestic hot water tank 30 litres capacity. In order to improve the system performance factors such as heat conduction within the tank as well as side losses are considered and the storage tank is thus designed to minimize such losses.

Capillary Tube

The expansion device used in the system is a capillary tube of 0.036inches OD and length of 10ft. Two parallel 5ft capillaries are used with a copper filter. Use of capillary has an advantage that, when the compressor stops the refrigerant continues to flow into the evaporator and equalizes the pressure between the high sides and low side of the system this considerably decreases the starting load on the compressor. Thus a low starting torque motor can be used to drive the compressor, which is an advantage. Also the refrigerant charge in the capillary tube section is critical, therefore no receiver is necessary.
The photograph of the setup is shown in the figure 2.

Figure 2. Experimental setup

System Modification

For a comparison analysis to a Air Source heat pump water heater (HPWH), the present system is modified into a heat pump by replacing the solar collector/evaporator with a same length and diameter copper tube coil (i.e. copper tubes of OD 5/16" with length 6.4m (21ft)) as incorporated inside the collector. Now the system runs as an air source HPWH as shown in fig.3 and performance characteristics are thus analyzed and compared.

Figure 3. Modified Experimental setup

Experimental Procedure

In order to investigate the different parameters of DE-SAHPWH, experiments were performed in two stages. In the first stage, a DE-SAHPWH was experimentally investigated and all the data was recorded. In the second the collector of DE-SAHPWH was dissembled and replaced with a copper tube coil with equivalent dimensions as the solar collector tube coil and all the data was recorded. Experiments were performed on different days, in different solar intensity at different ambient temperatures with replication. The observations were recorded at the interval of 10-15 minutes during the day time in the month of May.
Ambient temperature, solar radiation, condenser water temperature, refrigerant temperatures and pressures at various points were recorded. The experiment was stopped as soon as the condenser water temperature reached about 50°C. The test conditions for different sets of experiment were conducted without water draw off from the storage tank (constant mass).

Energy balance with the immersed condenser yields

$$Q_w = M_w C_{pw} (dT_w/dt) \qquad (1)$$

where Qw is the heat gain at the condenser, which is also the heat transfer rate released to water in the tank by the condenser. $\mathbf{M_w}$ is the total mass of the water in water tank, $\mathbf{C_{pw}}$ is the specific heat of the water, $\mathbf{T_w}$ is the temperature of the water, **t** is the time.

The Coefficient of performance is defined as ratio of heat gain ($\mathbf{Q_w}$) in the condenser to the compressor electric power consumption. Compressor consumption is found energy-meter reading.

Calculation of COP:

$$COP = Q_w/W_{cm} \qquad (2)$$

Results and Discussion

For the purpose of analysis and comparison, average of replicates of two sets of experiments taken.
In case of DESAHPWH experimental tests were conducted. Data was recorded for all replications and averages as depicted in table 1.1 & 1.2
Similarly for HPWH replication experimental tests were conducted. Data was recorded for replication and average as depicted in table 2.1 & 2.2 and analyzed to calculate COP.

Table 1.1 Experimental results of DESAHPWH between 7:00 AM to 8:25 AM

I (W/m^2)	t (min)	Ta (°C)	Tw (°C)	P_C Kg/cm^2	P_S Kg/cm^2	Qw (kWh)
54	0	27	29			
58	10	27	32	9.0	1.5	.10449
70	25	27	35	9.7	1.65	.20898
115	40	27.5	38	10.4	1.85	.31347
250	55	28	42	11.2	2.05	.45279
325	70	28	45	12.0	2.3	.55728
423	85	28	49	13.0	2.5	.6966

Table 1.2. Experimental results of DESAHPWH between 7:00 AM to 8:25 AM

t (min)	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)	Energy Consumption (kWh)	COP_{act}
0						
10	23	49	32	-3	0.03	3.483
25	25	60	34	-2	0.07	2.985
40	25	67	36	0	0.11	2.849
55	26	71	39	2	0.15	3.018
70	27	73	41	4	0.19	2.933
85	28	76	47	6	0.23	3.028

Table 2.1 Experimental results of HPWH between 10:05 AM to 11:25 AM

t (min)	Ta (°C)	Tw (°C)	P_C Kg/cm^2	P_S Kg/cm^2	Qw (kWh)
0	39	30			
15	39	33	10.4	2	.10449
30	40	37	11.7	2.6	.24381
45	40	41	12.9	2.8	.38313
60	41	44	13.9	3.0	.48762
75	41	48	15.0	3.2	.62694
80	41	49	15.4	3.4	.66177

Table 2.2. Experimental results of HPWH between 10:05 AM to 11:25 AM

t (min)	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)	Energy Consumption (kWh)	COP_{act}
0						
15	8	52	37	2	.06	1.742
30	9	63	40	8	.12	2.032
45	10	65	44	9	.18	2.128
60	11	64	46	11	.24	2.032
75	12	64	50	12	.3	2.09
80	13	65	51	12	.32	2.06

Variation of the evaporation temperature with the tank water temperature

Figure 4 compares the variation of the evaporation temperature with respect to the tank water temperature for a DESAHPWH and HPWH. It can obviously be seen in the figure that when the evaporation temperature increases, the tank water temperature (condenser) increases.

It means that the evaporation in the system takes place at a higher temperature if higher temperature is maintained in the evaporator, which in turn improves performance of the system. In case of HPWH the evaporation temperature could not exceed than 13°C which is much below ambient temperature, but in case of DESAHPWH the evaporation temperature equaled ambient temperature 28°C and hence better performance of DESAHPWH was achieved.

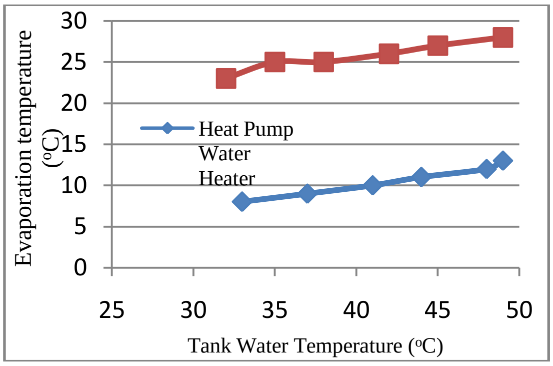

Figure 4

Variation of Energy Consumption with heat gain at condenser

Figure 5 compares the Energy Consumption with Heat gained by water in condenser for a DESAHPWH and HPWH. It is evident from the figure that for any particular value of heat gain (Q_w), HPWH consumes more energy than DESAHPWH. Therefore for same amount of water heating, HPWH will consume more electrical units than DESAHPWH.

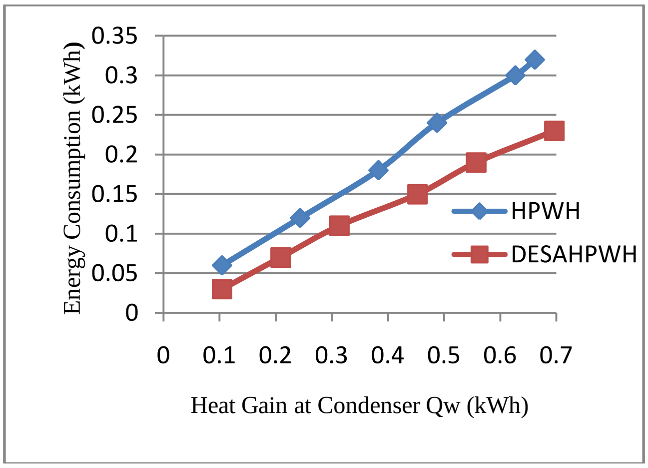

Figure 5

Variation of COP with time

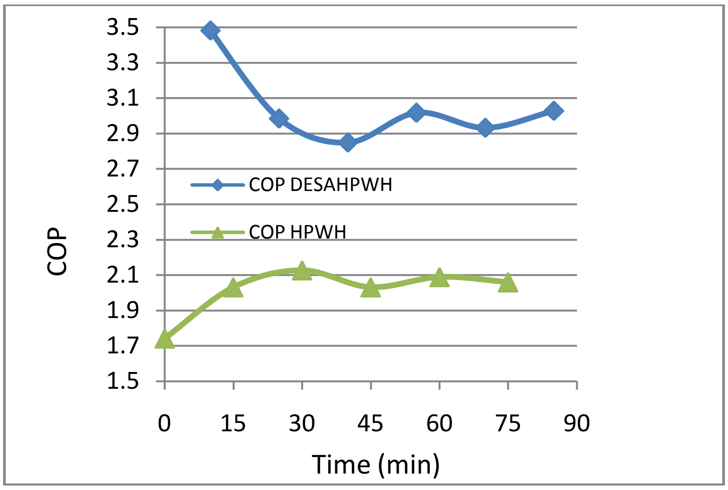

Figure 6

Conclusions

In this study our aim was to examine the performance of Direct Expansion Solar Assisted Heat Pump Water Heater and to find an improvement in existing conventional systems such as heat pump water heater. Experimental results show that there is considerable increase in the COP of the DESAHPWH in comparison to HPWH. Experiments were made between 28-50°C tank temperatures and a performance analysis of the system was carried according to the experimental results. The COP's of the heat pump were calculated.

The results showed that in the DESAHPWH 30 litres of water could be heated from 29°C to 49°C in 85 minutes and energy consumption is about 0.23kWh whereas in HPWH 30 litres of water could be heated from 30°C to 49°C in about 80 minutes and energy consumption is 0.32kWh.

The DESAHP system improves the COP of the heat pump from 2.06 to 3.028 i.e. an increase of 47% and Energy consumption is decreased from 0.32kWh to 0.23kWh i.e. a decrease of 28.13% which clearly states that performance of the system has increased. The experimental investigation also verified that for any particular value of heat gain at condenser (Q_w), HPWH consumes more energy than DESAHPWH.

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