Performance Evaluation of Solar Assisted Heat Pump Water Heating System

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Abstract : The application of solar thermal energy in water heating system has received more attention in recent years. The solar water heaters is used both in domestic and industrial use. The variation of solar intensity and atmospheric condition is key issue in determining the performance of solar water heater. The conventional thermosyphon solar water heaters fail to provide hot water supply round the clock in low temperature regions. The use heat pump with solar water heating system provides better water management. The COP of heat pump increases with increase in solar intensity and is energy efficient compared to conventional solar water heaters with electric or gas boosters as auxiliary heat source.

The main objective of this paper is to compare the performance of heat pump assisted solar water heater to conventional solar water heating system for low ambient temperature application. The theoretical analysis of solar water heater with heat pump integration is presented which shows that the collector efficiency and output water temperature can be increased compared to conventional solar water heaters under same solar intensity and ambient condition.

Keywords: *Solar energy, Heat pump, CO_2 refrigerant, Water heater*

I.   DIRECT EXPANSION SOLAR ASSISTED HEAT PUMP (DX-SAHP)

In direct system solar collector serves as the evaporator of heat pump and refrigerant is circulated through the solar collector. DX-SAHP systems use the solar collector as one potential evaporator for the heat pump. Therefore the refrigerant is passed through a throttling valve just before entering the collector in order to drop its pressure to allow it to evaporate when it collects the solar energy. The refrigerant leaves the collector as a vapor and passes through the compressor causing it to become superheat vapor. This high temperature and pressure vapor then flows through the condenser heat exchanger where it transfers energy into the domestic water tank. The solar panel is usually only one or more sources utilized by the system as evaporator. An air source heat exchanger may also be used when sufficient solar energy is not available.
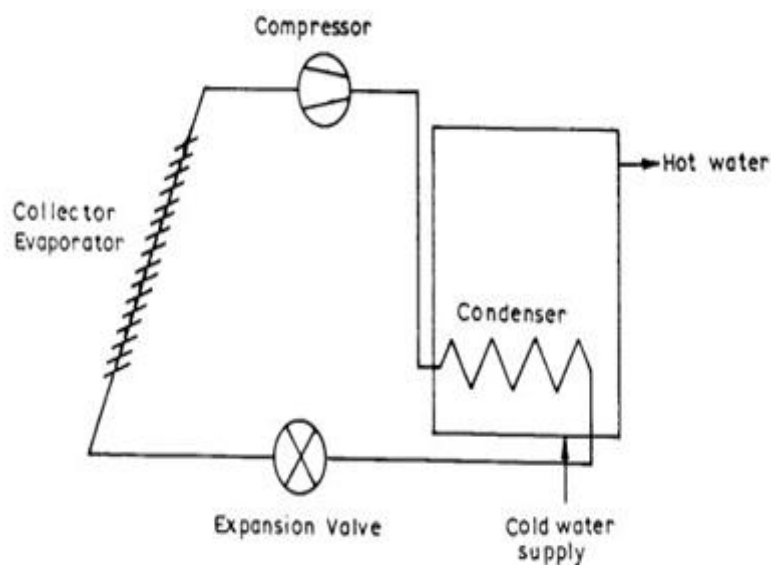

Fig 1. DX-SAHP water heating system

NOMENCLATURE			n	Polytropic index	
Ac	Area of the collector	m^2	Pred	Pressure ratio	bar
C_w, C_f	Specific heat of water, refrigerant	J/kgK	Pr	Prantal number	
D	Diameter of the copper tubes	m	t_m	Mean evaporative temperature	°C
d	Plate thickness	mm	t_a	Ambient temperature	°C
E	Correction factor		u_w	Wind speed	m/s
I_T	Solar irradiation	W/m^2	u	Average velocity	m/s
K	Thermal conductivity, absorber plate	W/m^2K	v	Kinematic viscosity	m^2/s
L	Length of the copper tube	m			
M	Molar mass		α	absorvity	
m_f	Mass flow rate of refrigerant	kg/m^2	ϵ	emissivity	
m_w	Mass flow rate of water	kg/m^2	σ	boltzman constant	
N	Number of riser tubes		Φ	latitude angle	

II. CO_2: PROMISING REFRIGERANT

The refrigerant characteristics have a greater impact on the performance of DX-SAHP. Though there are many conventional refrigerants being used widely in this application such as R22, R134a, R12 or combination of refrigerants. CO_2 (R744) is the natural refrigerant which imposes negligible effect on the environment. CO_2 has a very low Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) [1]. Carbon dioxide is colorless, odorless, naturally occurring gas. Carbon dioxide has played key role for sustainability of plants and human kind on this planet. Carbon dioxide has a very good thermo-physical and transport properties as compared to other refrigerants. The heat transfer properties of CO_2 are favorable especially near to its critical point compared to other conventionally used working fluids. CO_2 has a small change in saturation temperature for a given saturation paper and thus the efficiency of CO_2 heat pump does not affect much with large change in pressure [2]. It is environmental friendly nonflammable, chemically inactive.

III.   NUMERICAL ANAL YSIS OF DIRECT EXPANSION SOLAR ASSISTED HEAT PUMP (DX-SAHP)

The performance of direct expansion solar assisted heat pump water heating system with CO_2 as refrigerant is analyzed theoretically with U-pipe evacuated tube solar collector as an evaporator of area 2 m^2 and condenser tubes place inside the storage tank of 100L. Figure 1 shows the schematic view of the system considered for analysis.

The following assumptions were made for the theoretical analysis.
1.   Steady state heat transfer process
2.   Pressure drop in connecting pipes are negligible
3.   Isenthalpic expansion is considered
4.   The inlet water temperature is 30°C and the wind velocity of the ambient was being assumed as 5m/s.
5.   The collector is placed in a latitude angle of 13°

IV.   MODELLING OF COLLECTOR/EVAPORATOR

The energy gained by the collector/evaporator is given by [3]

$$Q_u = A_{cL} F'(S - U_L (t_m - t_a)) \qquad (1)$$

The value of S is the difference between the solar radiation absorbed by the collector/evaporator and the net radiation heat loss from the collector/evaporator surface at ambient temperature

$$S = \alpha I_T - \epsilon q_o \qquad (2)$$

The rate of heat transfer from the base of the fin to the tube is given by,

$$F = \frac{\tan h\left(\sqrt{\frac{U_L}{kd}} * \frac{W-D}{2}\right)}{\left(\sqrt{\frac{U_L}{kd}} * \frac{W-D}{2}\right)} \qquad (3)$$

Where W is the width of spacing between the riser tubes

The overall heat transfer coefficient solar collector is given includes the wind heat transfer coefficient and the ambient temperature and is given by

$$U_L = h_w + 4 \in \sigma T_a^3$$

$$(4)$$

V. HEAT TRANSFER COEFFICIENT OF CO_2

1. Two Phase Region

The two phase heat transfer is given by the sum of heat transfer coefficient in nucleate boiling(h_{NCB}) and the heat transfer in liquid phase (h_l) [4].

$$h_{TP} = Sh_{NCB} + Eh_l \tag{5}$$

$$h_{NCB} = 55 Pred^{.12}(-.4343 \ln Pred)^{-.55} \ M^{-.5} q^{.67} \tag{6}$$

$$h_l = .023 Re^{.8} Pr^{.4} \frac{k}{D} \tag{7}$$

2. Superheated Region

The Nusselt number is calculated as

$$Nu = \frac{\frac{f}{8}(Re - 1000)Pr}{12.7\sqrt{\frac{f}{8}}\left(Pr^{\frac{2}{3}} - 1\right) + 1.07} \tag{8}$$

The friction factor is given

$$f = (.79 \ln(Re) - 1.64)^{-2} \tag{9}$$

Reynold's number

$$Re = \frac{uD}{v} \tag{10}$$

VI. MODELLING OF COMPRESSOR

The specific work of compressor is given by

$$w = \frac{n}{n-1} \ P_1 v_1 \left(\left[\frac{P_2}{P_1}\right]^{\frac{n-1}{n}} - 1\right) \tag{11}$$

Where P_2 and P_1 are are the saturation pressure in condenser and evaporator .
The compressor work can be obtained from the mass flow rate of the refrigerant (m) as
The compressor work W = m * w

VII. MODELLING THE CONDENSER

In this case one turnover period, t_T of stratified storage tank is very small and this can be easily achieved in a horizontal storage tank with high circulating CO_2 flow rate, well mixed storage might seem to be inherently less efficient due to high temperature of the fluid leaving storage tank. This loss is compensated by the high heat transfer factor attainable with large flow of fluid through the collector.

$$q_T = \frac{F_x[(\epsilon\alpha)I_T \quad - U_L(T_S - T_a)]t_T}{1 + \frac{F_x U_L t_T}{2m_s C_s}} \tag{12}$$

1. Heat Removal Factor

The factor F_R reduces the useful energy gain from the expected value is given by

$$F_R = \left[\frac{mC_f}{A_c}\right]\left[1 - \exp\left(-\frac{A_c U_L F'}{mC_f}\right)\right] \tag{13}$$

2. Heat Exchanger Factor

If q is the net heat flux collected per unit collector area, then the heat transferred through the heat exchanger to the water of insulated tank is $h = \Delta U_x$

$$U_x = 52.7 \left[\frac{q\left(\frac{Ac}{Ax}\right)}{Lo}\right]^{\frac{1}{5}} \tag{14}$$

Since the heat loss in the connecting pipe between the storage tank and heat exchanger is negligible and the equation is given by

$$F_x = \left[1 + \frac{F_R U_L}{m_f C_f}(\epsilon - 1)\right]^{-1} \tag{15}$$

Where $m_f C_f$ are the mass flow rate and specific heat of the refrigerant
The effectiveness of the heat exchanger is

$$\epsilon = 1 - \exp(-NTU) \tag{16}$$

3. Output Temperature
The output temperature of the system represents by T_{so},

$$T_{so} = T_{si} + \frac{q_T}{m_w C_w} \qquad (17)$$

Where T_{si} is the input water temperature and $m_w C_w$ are mass flow rate and specific heat of water in the water tank.

4. Condenser Heat Gain
The heat gained by condenser with temperature difference of the input and output water temperature of the storage tank/ condenser as following

$$Q_c = m_w C_w (T_{wo} - T_{wi}) \qquad (18)$$

VIII.   SYSTEM PERFORMANCE
The efficiency of the collector/evaporator is given by

$$\eta = \frac{\text{net energy obsorbed by the collector}}{\text{solar energy on absorber of collector}} = \frac{Q_u}{A_c I} \qquad (19)$$

The COP of the heat pump system is expressed as

$$COP = \frac{\text{Heating Capacity}}{\text{Total Energy Input}} = \frac{Q_C}{W} \qquad (20)$$

IX.   RESULTS AND DISCUSSION
The variation of COP and heat output with ambient temperature is shown in fig 2. The COP of heat pump is greatly affected by the evaporator temperature which is influenced by solar intensity. The COP increases with increase in temperature. The speed of compressor is main factor in determining the COP of heat pump. Thus COP decreases with increase in speed of compressor and collector efficiency decreases. The heat output rejected to the storage tank is also influenced by the increase in ambient temperature.
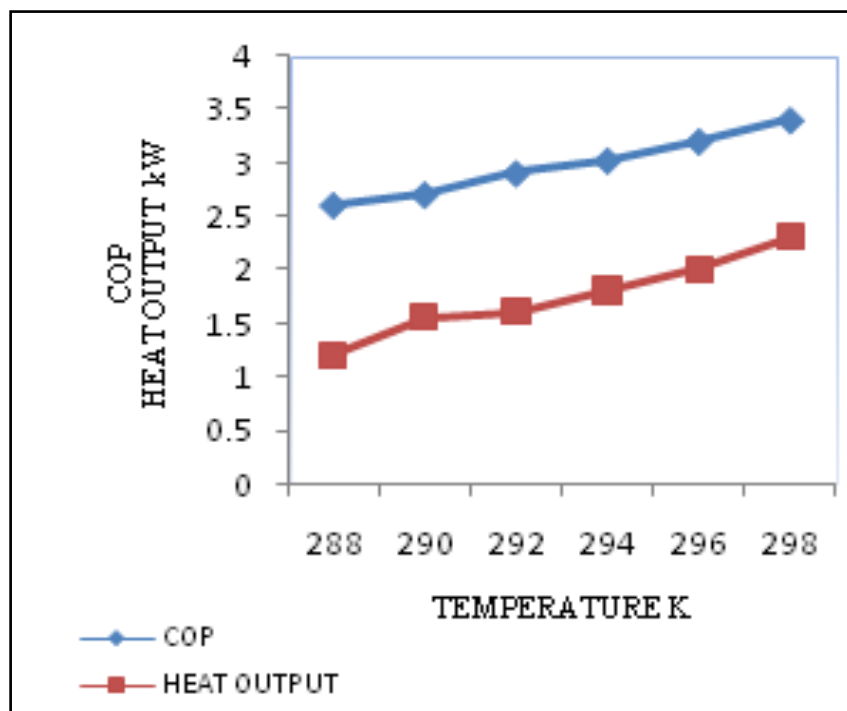

Fig 2 .COP and heat output Vs Ambient temperature

TABLE 1. Comparison of parameters of water heaters

PARAMETERS	DX- SAHP WATER HEATER	THERMOSYPHON WATER HEATER
Heat transfer coefficient, h	$512\ W/m^2K$	$213.77\ W/m^2K$
Collector efficiency, η	0.65	0.40
Heat removal factor, F_R	8.34	0.54
Net rate of useful heat energy per m^2, Q_u	$627.5\ W/m^2$	$392.6\ W/m^2$

The variation of collector efficiency with ambient temperature is shown in fig 3. The heat transfer coefficient of the CO_2 is more in two phase region is more than the superheated region causing effective heat transfer in collector/evaporator region and increasing the collector/evaporator efficiency further. The collector efficiency increases with increase in the solar radiation intensity
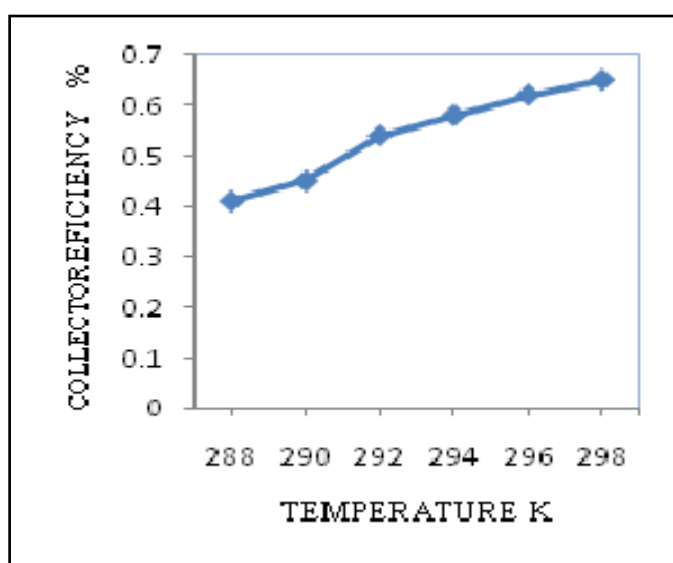

Fig 3. Collector efficiency Vs Ambient temperature

The specific work of compressor decreases with increase in solar radiation. This causes lower energy consumption. The variation of compressor speed increases the COP of the system which increases with increase in solar radiation. This is due to varying loading conditions with variation in solar intensity.

X. CONCLUSION

The theoretical analysis of DX-SAHP water heater with CO_2 as refrigerant is done. For ambient temperature of 25ºC the collector efficiency of about 0.65 is obtained which is 0.05 higher than the collector efficiency obtained for conventional solar water heating system under same amient condition. The heat output ranges from 1.2-2.3kW for 15-25ºC . The compressor work increases with increase in solar intensity. The COP of heat pump from (3.2 – 4) is achieved. The performance of DX-SAHP water heater is evaluated theoretically and is found that the collector efficiency and output water temperature are high compared to conventional thermosyphon solar water heater under same conditions.

REFERENCES

[1]   Kuang, Y.H., et al.," Study on direct expansion solar assisted heat pump water heater" Int. J. Energ. Res., vol. 27, pp. 531-548, 2003
[2]   Onder Ozgener and Arif Hepbasli "A review on the energy and exergy analysis of solar assisted heat pump systems" Renew. Sust. Energ. Rev., vol. 11, pp. 482-496, 2007
[3]   Li,Y.W., et al., "Experimental performance analysis and optimization of direct expansion solar assisted heat pump water heater" Energy, vol. 32, pp. 1361-1374, 2007

[4]   Seok Ho Yoon, et al.," Characteristics of evaporative heat transfer and pressure drop of carbon dioxide and correlation development" Int. J. Refrig., vol. 27, pp. 111-119, 2004

[5]   Srinivas.S.Pitla, et al., "New correlation to predict the heat transfer coefficient during in-tube cooling of turbulent supercritical CO2" Int. J. Refrig. , vol. 25, pp. 887-895, 2002

[6]   Tiwari, G.N., "Solar energy, Fundamentals, design modeling and applications".

[7]   Anderson, T.N. and Morrison, G.L. " Effect of load pattern on solar boosted heat pump water heater performance" Sol. Energy , vol. 81, pp.1386-1395, 2007

[8]   Arif Hepbasli and Yildiz Kalinci "A review of heat pump water heating systems" Renew. Sust. Energ. Rev., 2008

[9]   Axaopoulous, P., et al., "Experimental comparisons of solar assisted heat pump Vs conventional thermosyphon solar system" Int. J. Energ. Res., vol. 22, pp.1107-1120, 1998

[10]   Aydin Dikici, Abdullah Akbulut "Performance characteristics and energy-exergy analysis of solar assisted heat pump system" Build. Environ., vol. 43, pp.1961-1972, 2008

[11]   Aye. L, et al., " Solar heat pump system for domestic hot water" Sol. Energy vol. 73, pp. 169-175, 2002

[12]   Xu Guoiying, et al., " A simulation study on operating performance of a solar air source heat pump water heater", Appl. Therm. Eng., vol. 26, pp. 1257-1265, 2006

[13]   Xu, G. et al., " A simulation study on the operating performance of solar air source heat pump water heater" Appl. Therm. Eng., vol. 26, pp. 1257-1265, 2006

[14]   Huang, B.J. and Lee, C.P., " Performance evaluation method of solar assisted heat pump water heater" Appl. Therm. Eng., vol. 27, pp. 568-575, 2007

[15]   Huang, B.J. et al., " Heat pipe enhanced solar assisted heat pump water heater" Sol. Energy, vol. 78, pp. 375-381, 2005

[16]   Ito,S., et al.," Performance of heat pump using direct expansion solar collectors" Sol. Energy, vol. 65, pp. 189-196, 1999

[17]   Ito,S., et al.,"Studies of heat pump using direct expansion type solar collectors". J. Sol. Energ. Eng., vol. 127, pp. 33-44, 2003

[18]   Yamaguchi, H., et al., " A solar energy powered Rankine cycle using supercritical carbon dioxide" Appl. Therm. Eng., vol. 26, pp. 2345-2354, 2006

[19]   Zhang, X.R. and Yamaguchi, H. " An experimental study on evacuated tube solar collector using supercritical CO2" Appl. Therm. Eng., vol. 28, pp. 1225-1233, 2008

[20]   Zhang, X.R. et al., " Analysis of a novel solar energy powered Rankine cycle for combined heat and power application using supercritical carbon dioxide" Renew. Energ., vol 31, pp. 1839-1854, 2006