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Experimental Studies on Direct Expansion Solar Assisted Heat Pump: An Energy Point View

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ABSTRACT

Paper presents experimental and theoretical performance investigation of direct expansion solar assisted heat pump (DX-SAHP) in Solar Energy Center at National Institute of Technology Calicut India. And the effect of various parameters such as solar insolation, ambient temperature, collector area, wind speed and as well as design parameters such as pitch of the tube and collector plate thickness are has been theoretically analyzed to understand the system performance. The system mainly includes hermetic compressor for R22, air cooled condenser, expansion value and a flat-plate solar collector of total are 2 m^2 acting as an evaporator with refrigerant R22. The experimental values were agreed well with simulation predicated results with average error of 1%. Performance parameter of DX-SAHP shows that compressor power consumption various from 1100 to 1302W, condenser heating capacity of 2.0 to 3.6 kW and system performance EPR in the range of 1.85 to 2.75. Effect of other metrological parameters also discussed.

Keywords - DX-SAHP, EPR, Parametric Studies, SEIR;

1. INTRODUCTION

In view of the growing global energy demand and concern for environmental degradation, the possibility of running thermal system using the energy from the sun has received considerable attention in recent years. Solar energy is clean and most inexhaustible of all known energy sources. The low temperature thermal requirement of a heat pump makes it an excellent match for the use of solar energy. The combination of solar energy and heat pump system can bring about various thermal applications for domestic and industrial use. Since from last 25 years many researchers reported the performance of the solar assisted heat pump by experimentally and theoretically for water heating, desalination, solar drying, refrigeration, space heating and many other applications.

Combing the solar energy with heat pump technology initially started with Ambrose from in West Virginia in the year 1955. Further studies are carried out by O'Dell et al. [1] and presented the general procedure to improve the system performance about 15%. Similar Kind of work is extended by the Ito et al. [2] on bare flat plate collector. Result presented on the investigation of bare plate collector indicate system performance various from 2.2 to 5.3. The computational results are well agreed with experimental results. Morrison [3] developed the TRNSYS simulation package to predict the performance of solar assisted heat pump system. Morgan [4] presented the simulation and experimental of DX-SAHP system using R11 as the working fluid. Their results concluded that system performance is improved with integrating the solar energy and overll system performance was found to be about 3.5. Chaturvedi et al. [5] performance the experiments on direct expansion solar assisted heat pump system with R12 as working fluid. For integration of solar energy unglazed type solar collector was used. Solar collector efficiency in the range of 40 to 70%, the system COP was in the range of 2 to 3.

Several investigators conducted the experimental and theoretical studies on the solar assisted heat pump system from the application point of view. Huang et al. [6] performed the experimental and simulation investigation of direct expansion solar assisted heat pump water heating (DX-SAHPWH). Their experimental results well agreed with simulation results. Similar kind of work for the assessment of direct expansion heat pump for water heating application was carried out by Hawladar et al. [7]. Results found that the collector efficiency is about 75% and system performance in terms of COP was found to be 9. Saldo et al. [8] investigated the direct expansion solar assisted heat pump system uing R134a as the working fluid and experimental results reported that solar collector efficiencies 60 to 85% and 4 to 9 system COP range. Mohanraj et al. [9] experimentally studied the performance of R22 and its alternative refrigerant mixture R407C– LPG and identified that RM30 (LPG10%+ R407C90%) as an optimum refrigerant composition, which has thermodynamic properties closer to that of R22 across the wide range of operating conditions.

Experimental and analytical investigation of direct expansion solar assisted heat pump system for water heat system was carried out by Kuang et al. [10]. The results are presented in terms of solar collector efficiency and COP the system. Their results indicate that the collector efficiency varied from 40 to 60%, and COP of the system various from 4 to 6.5. The DX-SAHP system thermal performance was carried for the water heating and drying applications by Hawlader et al. [11]. Experimental and simulation results are well agreed with in the limited range. The COP values are found to be 6 and 7 for experimentation and simulation respectively. Li et al. [12] proposed the optimization of solar assisted heat pump for water heating applications. Their experimental energy and exergy analysis of DX-SAHP system helps to for the optimization of the existing system. Maximum exergy destruction was found in in the compressor and solar collector and followed by the condenser and expansion valve with total exergy destruction of 0.593 kW. Kong et al. [13] presented a simulation model to predict the thermal performance of direct expansion solar assisted water heater (DX-SAHPWH).Simulation results are well agreed with experimental results and simulation model also capable to effect of various parameters on the system performance. Mohanraj et al. [14] proposed the modeling technique for the performance predication of the direct expansion solar assisted heat pump system.

In this study, an attempt has been made to recover the condenser heat and utilize it in space heating with renewable heat sources: solar energy and ambient energy by developing experimental set up model of a direct expansion solar-assisted assisted heat-pump system. Results obtained from the experimentation are well agreed with the devolved simulation model. The simulation model can predict the system performance under various weather conditions and it can able to examine the effect of solar insolation, ambient temperature, wind velocity and collector area on the system performance. The influence of collector plate thickness and pitch of the tube on system performance also discussed based on the simulation results.

2. EXPERIMENTS

2.1. Experimental Set Up

The DX-SAHP system (suitable for space heating applications) experimental setup, schematic diagram is shown in Fig. 1. Experimental set up mainly consists of a solar collector (glazed type) which act as the evaporator of the system and as well as the heat source device with a total area of 2.0 m2 (2 x 1 m). Copper tubes which act as the fins having 0.8 mm thick and 10 mm length are attached to the solar collector. In order to improve the solar collector absorptivity of the incident solar insolation its surface has selective coting. R22 hermetic sealed (reciprocating type) compressor with a rated power of 1020W is used. An air cooled condenser (forced type) having copper tube coils (9.52 mm diameter) with a maximum face velocity of 4.75 m/s. The sight glass and liquid receiver are mounted downstream of the condenser to measure the refrigerant flow and moisture content a turbine type flow meter and drier are installed in the circuit. The refrigerant flow in the solar collector/evaporator is controlled by using the thermostatic expansion valve. The system is adapted to face south in order to maximize the solar insolation incident on the solar collector/evaporator. The solar collector is titled to 200 with respect to horizontal.

2.2. Data Acquisition System

The temperatures, pressures, flow rate of working fluid (refrigerant) and velocity of the air are measured at the different points in the experimental set up as shown in Fig. 1. Also, the metrological parameters such as relative humidity, ambient temperature, solar insolation and wind velocity rre measured. Compressor and expansion value inlet and outlet pressure and were measured with the help of bourdon type pressure gages and pressure transducers respectively.

Resistance thermometers (RTDs) are used to measure the refrigerant temperature at compressor inlet and outlet, exit of the condenser and well as the refrigerant after expansion in the expansion valve. The condenser inlet and outlet air temperature are measured using the similar set of Resistance thermometers. The ambient temperature is measured with the help of a thermometer. Vantage-Pro weather station which is installed in the Solar Energy Center at National Institute of Technology Calicut, India is used to measure the wind velocity, relative humidity and parameters. Duct air velocity at the exit of the condenser is measured with the help of velocity sensor and vane type anemometer. A pyranometer is placed on the glazed type evaporator to record solar insolation. Refrigerant flow rate in the circuit is measured using the turbine type flow meter. Compressor power consumption was continuously recorded in the digital type, multi-function single phase energy meter. All parameters recorded in the computer based data acquisition system.

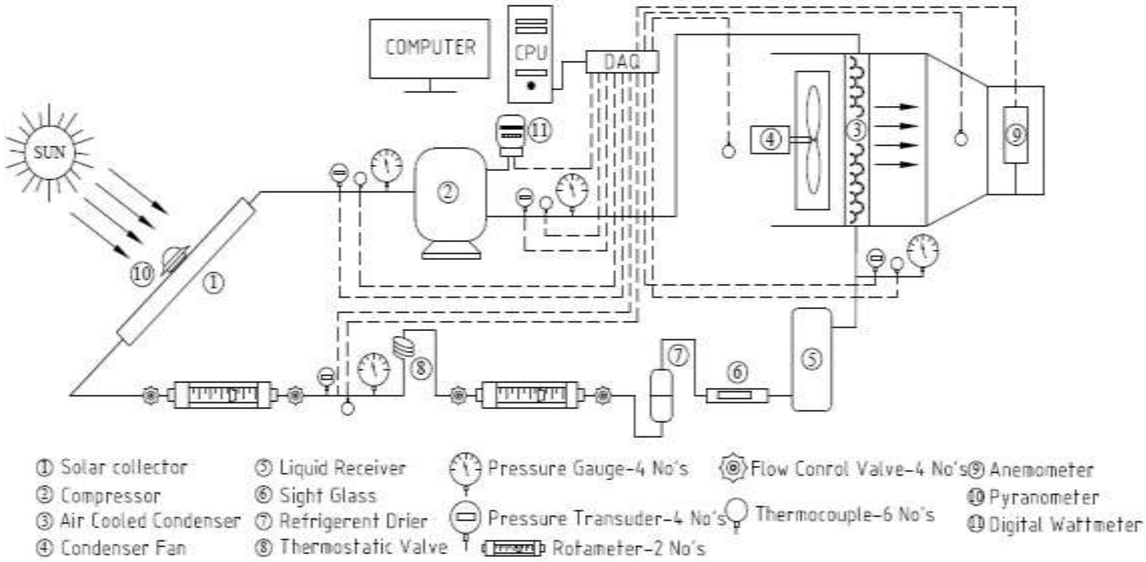

Fig. 1 Schematic diagram of the experimental set up

3. ENERGY ANALYSIS MODELLING

3.1. Assumptions

The energy analysis of a simple DX-SAHP system, based on the following assumptions:

- All the process in the circuit are assumed to constant
- Pressure drop in the circuit like condenser and in solar collector are assumed to constant
- Compression process is polytropic.
- Refrigerant expansion in the thermostatic valve assumed to be constant enthalpy process.

Based on the above assumption and the energy modelling of the DX-SAHP system components are modelled as follows.

For any thermodynamic system the mass and energy balance equation are given by as follows; as

$$m_i = m_e \tag{1}$$

$$q_e + P = q_c \tag{2}$$

Mass flow rate in the DX-SAHP system circuit assumed to constant, In the energy balance equation q_c is the condenser heating capacity, q_e heat gained in the evaporator or solar collector of the system P is the instantaneous work input of the compressor.

3.2. Compressor Power Consumption

In this system hermetically sealed reciprocation type compressor was used (Make: Emerson HKJ 50010 model). The cooling capacity of the compressor was 2700W and speed of the compressor 1500 RPM. The cooling capacity and the instantaneous power consumption of the constant speed compressor can be expressed in terms of their condensing and evaporating temperatures of the system. Similarly for The DX-SAHP system the compressor power consumption and the cooling capacity are expressed as follows (in terms of their condensing and evaporating temperature).

$$P = = -17854.2632 - 2381.4993t_e - 73.5881t_e^2 + 870.29110t_c - 9.9902t_c^2 - 110.8510\, t_e t_c + 3.45881t_e^2 t_c + 1.2900tc^2 t_e - 0.0404\, t_e^2 t_c^2 \tag{3}$$

$$q_e = -76112.1029 + 10754.2169t_e - 350.0243t_e^2 + 3345.3171t_c - 36.9126t_c^2 - 479.2131t_e t_c + 15.9065t_e^2 t_c + 5.4086t_c^2 t_e - 0.1809t_e^2 t_c^2 \tag{4}$$

Where t_e and t_c are the evaporating and condensing temperatures of the refrigerant in the DX-SAHP system respectively.

3.3. Solar Collector/Evaporator

Useful solar energy absorbed in the glazed type collector ($q_{e)}$, for the DX_SAHP system for working at conditions expressed as follows as follows;

$$q_e = A_c F'\left(S - U_l(t_e - t_{amb})\right) \tag{5}$$

Where A_c evaporator/solar collector area, S is the total solar insolation on the glazed type collector. U_l is the overall heat loss coefficient due to convention and radiation losses from the solar collector to ambient. t_e is the average evaporating temperature in solar collector and t_{amb} ambient temperature respectively.

Neglecting the thermal resistance between the solar collector/evaporator absorber plate and tube materail. F' is given by

$$F' = F+(1-F)(D/W) \tag{6}$$

Where F is the fin efficiency, D is the external diameter of the tube and W is the pitch of the tube. The fin efficiency F can be calculated using the following correlation.

$$F = \frac{\tanh\left(\sqrt{U_l/k_p t_p}\;(W-D)/2\right)}{\left(\sqrt{U_l/k_p t_p}\;(W-D)/2\right)} \tag{7}$$

Where, t_p and k_p, are the thickness and thermal conductivity of the collector plate material, respectively. And Eq. (5), the symbol S is expressed as follows;

$$S = \alpha I_T \tag{8}$$

Where IT is the total solar insolation falling on the glazed type collector. α is the absorptivity of the solar collector plate material. In Eq. (5), the symbol U_l is the overall heat loss coefficient due to convention and radiation losses from the solar collector to ambient.

$$U_l = h_w + 4\sigma\varepsilon T^3 \tag{9}$$

Where σ is the Stefan Boltzmann constant, and h_w is the wind heat transfer co-efficient, is given by

$$h_w = 5.7 + 3.8u_w \tag{10}$$

Where u_w is the wind speed

3.4. Modelling of Condenser

Heating capacity of the condenser of a DX-SAHP system is the sum of instantaneous compressor consumption of the compressor and useful solar energy gain in the evaporator or solar collector of the system. Heating capacity of a direct expansion solar assisted heat pump system is one of the important parameter in in selecting the working fluid in the system. Hence the condenser modeling of DXSAP-system can be expressed as follows;

$$q_c = m_{air} C_{pa}(t_c - t_{amb}) \tag{11}$$

In the above equation the m is known as the mass flow rate of air through condenser air duct and experimentally it was found to be as 0.0228 kg/s. t_{amb} is the inlet temperature of the air for condenser and specific heat of air taken as 1.005 kg/kg.K with notation $C_{pa.}$

The system performance of direct expansion solar assisted heat pump system in terms of energy performance ratio or coefficient of performance (COP) cab be given as follows;

$$EPR = q_c/P \tag{12}$$

3.5. Method of System Simulation

In section 3 the energy modelling of direct expansion solar assisted heat pump system are presented. The DX-SAHP system components such as compressor, condenser thermostatic expansion valve and solar collector are separately modelled with help of energy and mass balance equations and as well as the governing equations.

The modelled system components such as compressor, condenser thermostatic expansion valve and solar collector are separately modelled with help of energy and mass balance equations and as well as the governing equations are solved with help of Matlab® (Version 9.1) program. The technique chosen for the mathematical simulation was Newton-Raphson method, which is the most popular technique for solving the simultaneous equations. The information flow diagram of the simulation program carried out is shown in Fig. 2. All the necessary input data such as solar insolation, ambient temperature, collector, wing speed, condensing and evaporating temperature are shown in the information flow diagram.

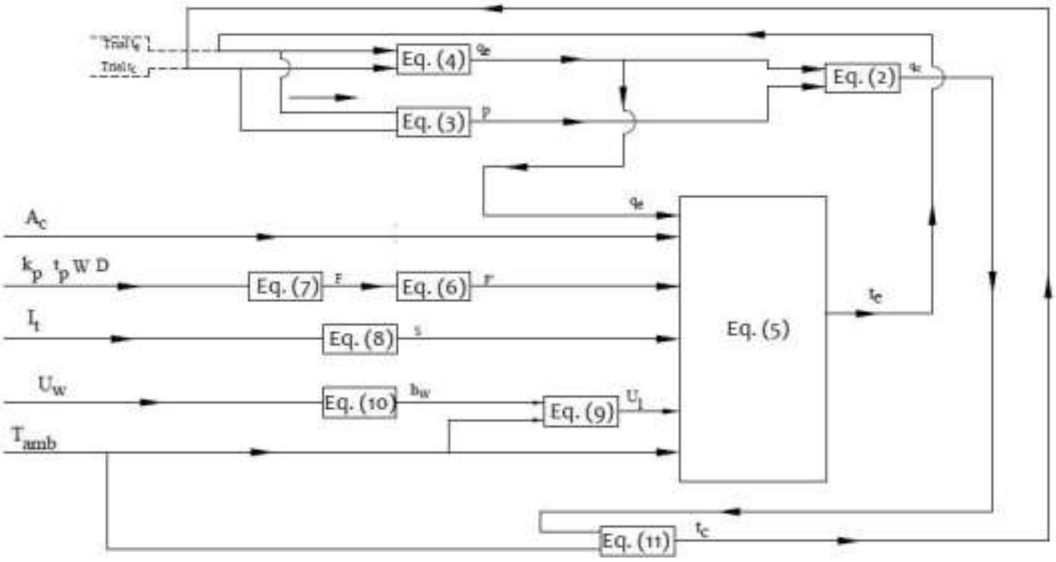

Fig. 2 Information flow diagram of the simulation

4. RESULT AND DISCUSSION

In this section after obtaining the experimental and simulation results of DX-SAHP system are discussed. The obtained experimental results are compared simulation results under the heading of experimental validation of simulation for compressor power consumption, condenser heating capacity, energy performance ratio and compressor discharge temperature. Further the effect of wind speed, collector area, solar insolation and ambient temperature are discussed with obtained system simulation results. Design parameter such as the effect of thermal conductivity and plate thickness also discussed with help of system simulation results.

4.1. Experimental Validation of Simulation

Condenser heating capacity of the DX-SAHP is system against solar insolation is plotted in Fig. 3. The condenser heating capacity is various from 2.1 to 3.6 kW. Experimental results are well agreed with simulation results with average of 2% error. Similarly the compressor power consumption against the solar insolation is shown in Fig. 4. Simulation and experimental results are well agreed with average of 1%. Compressor power various from 1095 to 1310W for given solar insolation range.

The energy performance ratio results are obtained by the experimentation and as well as the system results are closely agreed with an average error of 1%. Energy performance ratio values are in the range 1.82 to 2.75. In general the energy performance of heat system various from 2 to 3. Energy performance ratio for DX-SAHP system is shown in Fig. 5. The solar energy input ratio results are plotted against given solar insolation range from 55 to 935 W/m^2 in fig. 6. The compressor discharge temperature is also found to be in the range of 61.1 to 78.8^{0}C.

4.2. Parametric studies on the system performance

4.2.1 Effect Wind Speed and Collector Area

Figure.7, shows that effect of wind speed on the system performance, the increase in the wind speed enhances the heat transfer rate between collector and surroundings. When te is lower than ta, the rising the wind speed enhances the collector to obtain more useful energy gain from the surroundings and consequently increasing the system COP. It is observed that, the variation of wind speed from 1 to 4.5 m/s, for given solar intensity of 750 W/m2, the system COP increases from 2.42 to 2.49, which increase the average system performance about 0.5% Similarly Fig. 8, Shows that for given ambient temperature and solar intensity of 750 W/m2, varying collector area from 0.5 to 3.5 m2, enable to increase the solar and air source heat in the collector. Hence the system co-efficient performance increases from 1.50 to 3.05. And similarly about 11% average increment in the system performance.

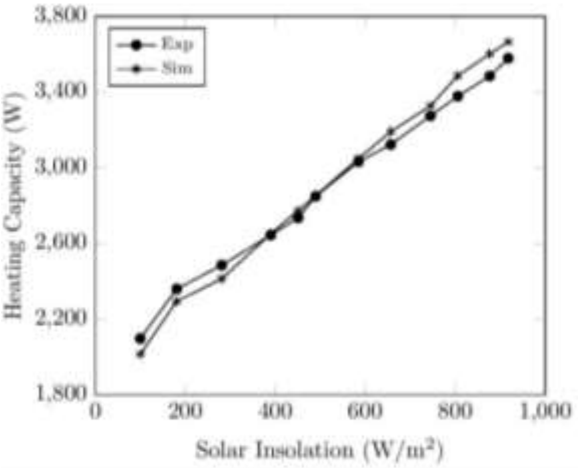

Fig. 3 Condenser heating capacity with respect to solar insolation

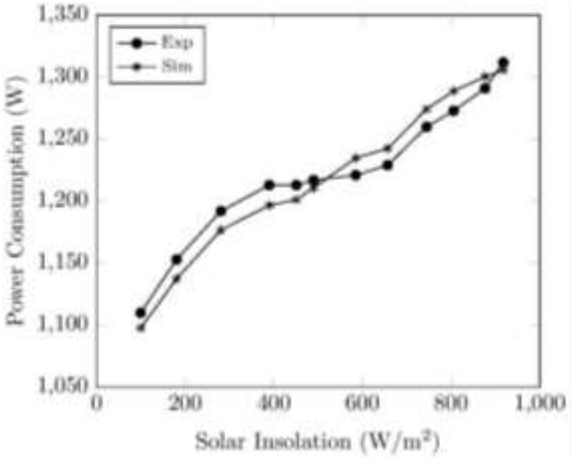

Fig. 4 Power Consumption with against to solar insolation

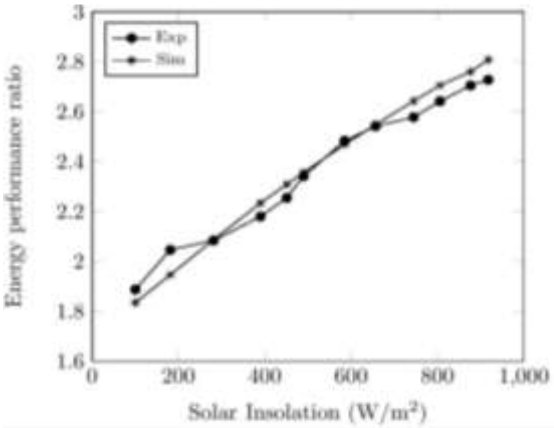

Fig. 5 COP against to solar insolation

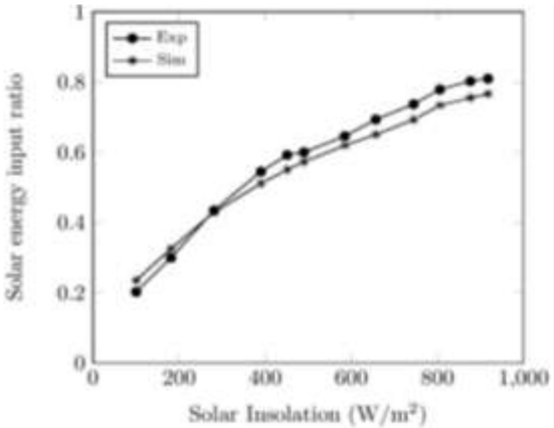

Fig. 6 Solar energy input ratio against solar insolation

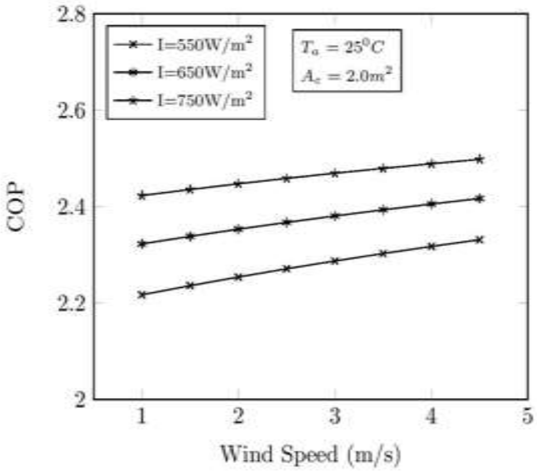

Fig. 7 Effect of wind speed on the system performance

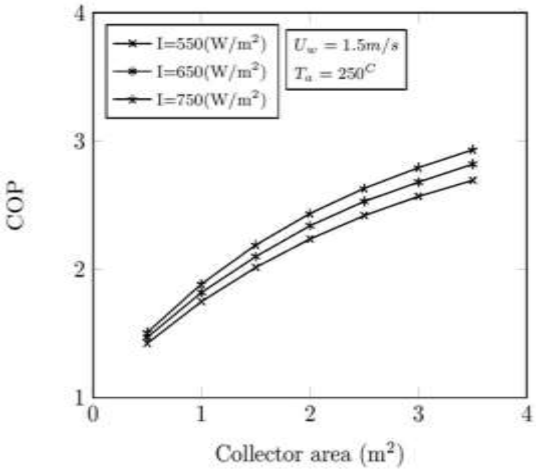

Fig. 8 Effect of collector area on the system performance

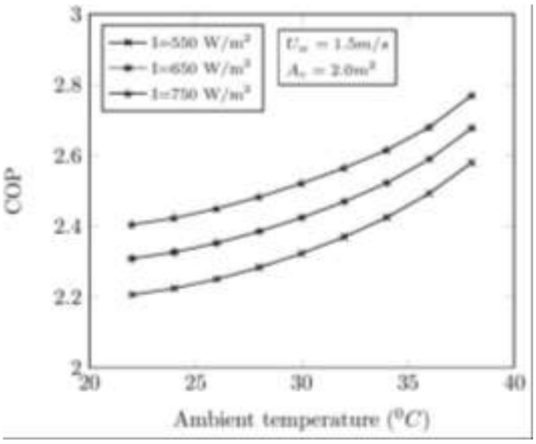

Fig. 9 Effect of ambient temperature on the system performance

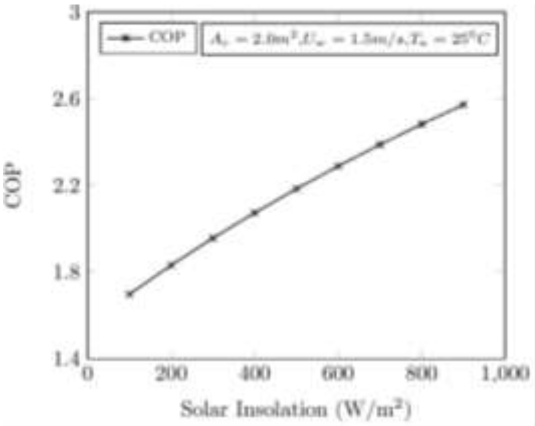

Fig. 10 Effect of solar insolation on the system performance

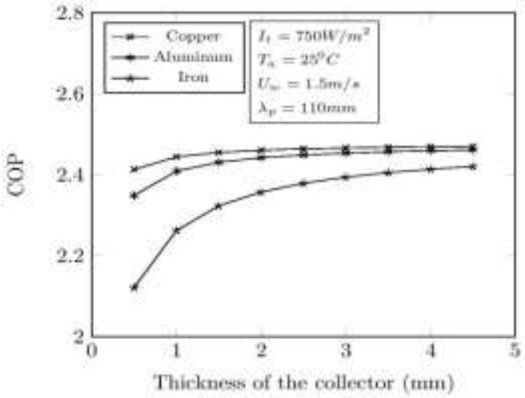

Fig. 11 Variation of COP with thickness of the collector plate

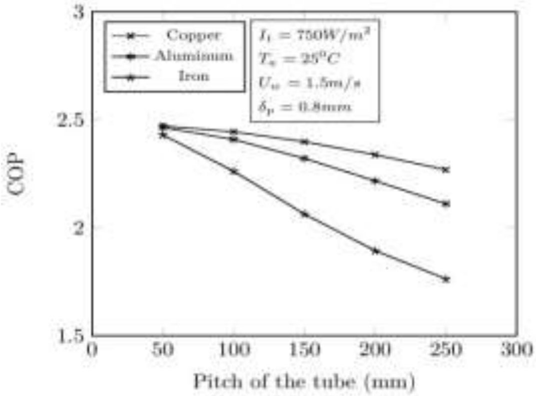

Fig. 12 Variation of COP with pitch of the tube

4.2.2 Effect Ambient Temperature and Solar Insolation

The system performance improves with increasing in the ambient temperature. This is because of rising the ambient temperature lower the heat loss from the collector and increase the evaporating temperature of the working fluid in the collector; (as shown in Fig. 9)., With increasing the ambient temperature from 22 to 38°C, for given solar intensity of 750 W/m2, the system COP increases from 2.4 to 2.8. This increases the average system performance by about 2%. From the Fig. 10, it is clear that increase in the solar radiation at given ambient temperature and collector area, there will be increase in the system performance. This is mainly because of an escalation in insolation allows to attain a higher evaporating temperature of the refrigerant and also enhance the collector to gain more beneficial solar energy, which results in a higher system COP. For a given ambient temperature 25°C and varying the solar insolation from 100 to 900 W/m2, the system COP increases from 1.7 to 2.6. And about 6% average increment in the system performance

4.2.3 Effect Collector plate thickness and pitch of the tube

Fig.11, Shows the variation of COP with the collector plate thickness. For copper plate thickness greater than 1 mm, the effect of the thickness on COP is small. Similarly plate thickness greater than 2 mm for aluminium and 3 mm for iron plate there will be negligible change in the system performance. Similarly Fig. 12 shows that Variation of COP with respect to effect of pitch of the tube. When the pitch was increased to 250mm from 50 mm, the reduction of COP was 2, 4 and 8% for copper, aluminium and iron plate respectively.

5. CONCLUSION

The results obtained from the system simulation and as well as the experimental results are discussed. The energy performance investigation of the direct expansion solar assisted heat pump discussed in terms pf performance parameters such as the Energy performance ratio (EPR) to be varying from 1.8 to 2.72 The instantaneous compressor is found to various from variation from 1100 to 1305W. The solar energy input ratio also found to in the 0.2 to 0.8.The condenser heating capacity is found to be 2.10 to 3.5 kW. All the obtained energy performance parameters results are closely match with the system simulation results. According to the simulations, the thermal performance of the DX-SAHP system for different parameters are studied, which is shows that system performance affected considerably by variation of solar collector/evaporator area, solar insolation, ambient temperature and followed by the effect of wind speed. And variation of COP with effect of pitch tube and collector plate thickness also studied and concluded that there is no significant effect on the COP. However, the thickness of plate (copper) could be made 0.5 mm without significant reduction in the COP. The results obtained from system simulation method helps for better understanding of system performance in various metrological parameters and as well as the design parameters. These system simulation results help to researchers to further studies of DX-SAHP system with different operating working fluid and conditions.

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