Performance Optimization of Solar-Assisted Heat Pump System for Water Heating Applications

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ABSTRACT

This research paper presents a comprehensive study on the performance optimization of a solar-assisted heat pump (SAHP) system for water heating applications. The integration of solar energy with heat pump technology offers an efficient and sustainable solution for domestic and industrial water heating needs. The primary objective is to enhance the system's overall efficiency by maximizing the utilization of solar energy while minimizing electrical energy consumption.

A detailed thermodynamic analysis of the SAHP system is conducted to understand the key parameters influencing performance, including solar collector area, heat pump capacity, refrigerant type, and water storage tank size. The optimization process involves both experimental investigations and computational simulations to identify the optimal configuration for various climatic conditions.

In the present study, we performed parametric optimization based on an experimental model of a solar-assisted heat pump system for water heating (SAHPSWH) in the context of colder climatic regions receiving minimal solar radiation. Various parameters were investigated, such as the different glazing arrangements, the distances between fluid-circulating tubes, and the absorber sheet arrangement.

The results showed that double glazing was more efficient than single glazing, with average COP values of 3.37 and 2.69, respectively, and with similar heat gain rates. When the evaporator tube was soldered below the absorber plate, the COP was 1.19 times greater than when the tube was soldered above the absorber plate. We also analyzed whether the collector efficiency factor F' has an inverse relationship with the tube distance and a direct relationship with the absorber plate thickness. Through this experimental study, we verified that the SAHPSWH is reliable if designed judiciously. This promising energy-saving system is particularly suitable for areas abundant in solar radiation, such as in India, where the needs for space conditioning and water heating are constant.

Keywords:—thermal performance; renewable energy; heat pump; solar radiation; flat plate collector.

I. INTRODUCTION

The demand for energy-efficient and environmentally friendly water heating solutions has grown significantly in recent years, driven by the global push to reduce

carbon emissions and reliance on fossil fuels. Traditional water heating systems, which primarily depend on electricity or gas, are associated with high energy consumption and increased greenhouse gas emissions. Solar-assisted heat pump (SAHP) systems present a promising alternative by harnessing renewable solar energy to meet the thermal energy requirements of water heating applications. These systems combine the advantages of solar thermal technology and heat pump efficiency, leading to reduced energy consumption and operational costs.

A solar-assisted heat pump system typically consists of a solar collector, a heat pump, a water storage tank, and a control mechanism. The solar collector captures solar energy, which is then used to enhance the heat pump's performance by preheating the refrigerant or water before it enters the heat pump. The heat pump further increases the water temperature, utilizing electrical energy at a significantly reduced rate compared to conventional systems. This combination leads to higher system efficiency, especially when operating in regions with abundant solar radiation.

Despite the potential of SAHP systems, optimizing their performance poses several challenges. Key factors that influence the overall system efficiency include the size and type of the solar collector, the heat pump capacity, the selection of refrigerant, and the storage tank's thermal capacity. Additionally, the interaction between solar energy availability and heat pump operation requires careful consideration, as mismatched components or inappropriate control strategies can lead to inefficiencies and increased operational costs.

The purpose of this study is to explore various strategies for optimizing the performance of solar-assisted heat pump systems for water heating applications. By analyzing the system's thermodynamic behavior and operational parameters under different climatic conditions, this research aims to identify the most effective design and operational practices. Specific objectives include evaluating the impact of solar collector area, heat pump configuration, and storage tank size on energy savings and system performance. Additionally, this study investigates the potential of advanced control algorithms and predictive models to improve system efficiency by better aligning heat pump operation with solar energy availability.

To construct energy-efficient sustainable buildings in compliance with the emerging regulations for global warming and greenhouse gas (GHG) emissions, several changes are required [1, 2]. The use of renewable sources of energy to achieve this goal has largely been endorsed [3]. Among the renewable sources, solar energy is the most readily available source of clean energy, with minimal costs and environmental impacts [4]. Applications based on solar thermal energy have gained massive attention from 1970's onwards, following the beginning of the energy crisis [5]. The process of collecting solar arrays in the form of energy and converting them into useful heat for water heating, space conditioning, or agricultural or industrial applications is the basis of solar thermal applications [6]. Solar water heating accounts for a major proportion of all applications in the market; however, various technical flaws, such as uncertainty related to the heat gain efficiency and heat loss, act as barriers to its promotion [7]. The integration of heat pumps for thermal applications can potentially rectify such issues [8]. The solar-assisted heat pump system for water heating (SAHPSWH) has advantages over conventional solar water heaters in terms of performance and initial

investment, even under changing conditions and uneven weather. The conventional systems contain water as the working fluid, while hybrid water heating systems use a refrigerant as the working fluid, which transfers heat to the water [9]. The SAHPSWH solves the common issues of conventional systems regarding the high investment costs for collector components and the problems that arise due to corrosion. In contrast, the SAHPSWH is able to work under moderate climatic conditions with solar radiation, enhancing the energy efficiency of buildings [10]. A plethora of research studies have experimentally and numerically [11] evaluated the potential of solar thermal hot water collectors and their combination with heat pumps to reduce site energy consumption in heating applications.

Jose et al. analyzed a SAHPSWH experimentally for sub-zero temperature conditions and observed a COP value of 3.01 when heating 300 L from 14 to 55 °C at an ambient temperature of 21.9 °C over 638 min, along with observing a transient increase in the heating process during the first 15 min before reaching a trans-steady-state [12]. A study based on an economic comparison between a solar-assisted heat pump system for water heating (SAHPSWH) and a conventional system for tropical and sub-tropical regions showed decreased annual operating costs, with a notable payback time and the need for different configurations based on climatic variations [13].

By modifying solar collectors with corrugated metal roofing and a copper tube, along with a compressor speed of 20 rps and mass flow rate of 0.01 kg/s, the COP values obtained were between 2.5 and 5.0. The suitable mass for the storage tank was 400 kg with a payback time of 2.3 years [14]. A combined SAHPSWH with serial and parallel modes was experimentally and numerically validated, with the results suggesting the use of the serial mode in winter and parallel mode in summer, with an annual average COP of 5.7 [15]. A numerical study validated the performance of the SAHPSWH under frosting conditions, showing reliable heating performance with an average COP of 2.75 and delayed frost formation in comparison with a traditional system. This clearly showed that with decreased ambient temperature and increased solar radiation intensity, frost formation can be prohibited [16].

In [17], an experimental setup involving a SAHPSWH was structured for the purpose of both water and space heating, resulting in a COP of 2.1 for water heating and an average COP of 2.5 for space heating under variable climate conditions. Tagliafico et al. [18] showed the SAHPSWH approach to be very efficient, even for uneven weather conditions, proving the approach to be environmentally friendlier than a traditional solar heater integrated into a gas burner. The average savings in energy consumption based on different glazing configurations were also analyzed.

Cutic et al. [19] determined that COP levels are significantly altered by alterations in solar radiation based on convection theory, enabling the absorption of heat due to higher ambient temperatures and lower evaporation temperatures. Bastos et al. [20] studied the solar-assisted heat pump system for water heating (SAHPSWH) prototype for the purpose of heating residential water via numerical simulations and experimental validation, proving that the power consumed by the compressor varied due to radiation and wind speed. Additionally, a decrease was observed in the COP because of a pressure

loss in the evaporator and due to the compressor not being thermally insulated.

Buker and Riffat [21] studied a system in which solar thermal collectors were combined with heat pumps in a single solar-assisted heat pump system for water heating (SAHPSWH), which can be used for various purposes. They reviewed various systems from the past and present using visualizations, systematic representations, and component classification. They experienced challenges in classifying the systems based on a variety of parameters, configurations, and performance criteria, which increased the level of complexity. Additionally, they found that there were separate effects of solar heat energy on the collector efficiency and heat pump, concluding that the SAHPSWH has great potential and could be an alternative for various purposes and different climatic zones around the world.

Chaturvedi et al. [22] studied a sustainable SAHPSWH for low-temperature water heating applications, analyzing the energy savings and economic feasibility of the system. The thermal performance of the system was simulated with the help of computer software, which embedded location-based irradiation, collector, heat pump, and other data. The economic feasibility was checked with the help of the life cycle cost (LCC) method. It was found that the direct expansion approach of the SAHPSWH when compared with a conventional electric water heater was economical, conserving energy by 60%. This system can fulfill the demands of low-temperature water heating applications.

From the above studies, it can be inferred that the solar-assisted heat pump system for water heating (SAHPSWH) is a good alternative for various climatic zones around the world in terms of cost-effectiveness and energy conservation. The COP values for the system vary with different structural arrangements or with variations in solar radiation intensity and ambient temperature. The economic analysis conducted for the system both numerically and experimentally validated its proficiency, showing that different meteorological conditions require specific configurations to achieve better performance. Although several studies have been presented in this review, the full range of applications of this technology is still to be shown, since laboratory-based experiments and real-world conditions are different. This study represents one such real-world scenario, involving different optimization strategies. To the best of our knowledge, as highlighted in the literature, there is no evidence of experimental optimization based on permutations and combinations of tube arrangements and different glazing layers for a composite climate. In this study, an experimental effort is made to optimize the design parameters and identify the best design strategies that may help in reducing the complexity while classifying the system.

An experimental study is performed in a composite climate in India at 29.8543° N, 77.8880° E, during the winter season, with an average temperature range of 15–20 °C. This is done in order to tune the conditions to the colder climatic zone of India, so that the results of this study can be used by designers for colder climates. With the help of mathematical modeling, the system components are designed. The solar-assisted heat pump system for water heating (SAHPSWH) is essentially designed for domestic applications, but with further exploration could be used for commercial applications. The experiment is conducted in an ingenious manner by using a multiobjective optimization approach, resulting in different seasonal arrangements

with certain permutations and combinations. Minute effects of plate and tube arrangements in accordance with suitable weather are observed. An extensive glazing and tube arrangement study is performed in the present experiments. Firstly, the effects of different configurations of evaporator tubes on the collector performance are evaluated, while simultaneously the effects of glazing on the overall performance of the system are observed, showing that this technology is sustainable for water heating applications.

The remainder of the paper is as follows. Section 2 describes the case study and methodology employed for the experiment. Section 3 provides insights into the experimental setup and instruments used. Section 4 presents the results of the experimental investigation, while the last section provides concluding remarks.

II. METHODOLOGY

The solar water heater's performance can be enhanced either by reducing the top heat loss or by improving the convective heat transfer coefficients by changing the working fluid and extracting that heat via a heat exchanger. In this study, the primary concern was the enhancement of the thermal performance of the SAHPSWH. The effects of different parameters, such as the configuration of the collector tubes, glazing material, ambient conditions, and solar intensity on the flat plate collector efficiency, were assessed to expand its commercial applications. An experimental setup was constructed as shown in Figure 1, in which necessary parameters and component specifications, such as the absorber plate thickness, the distance between the collector tubes, and tube diameter, were first optimized using mathematical models, along with climatic variations measured by various measurement devices. The experiment was performed in a composite climate in India in a low-cost bamboo house to completely replicate the winter climatic conditions in the country, which was then supported by theoretical analysis. The readings during the experiment were taken at five-minute intervals.

2.1. Mathematical Modeling

For the prediction of the thermal performance, a 1-D mathematical model was built to predict the thermal performance, which was grounded on certain assumptions:

- ❍ The system is at a quasi-steady state within the chosen time interval;

- ❍ Negligible pressure drops occur in the evaporator, condenser, and piping;

- ❍ Both at the exits of the condenser and the evaporator, the refrigerant is considered to be saturated;

- ❍ Compression of the refrigerant vapor is assumed to follow a polytropic process;

- ❍ Expansion of the refrigerant liquid is considered to be isenthalpic;

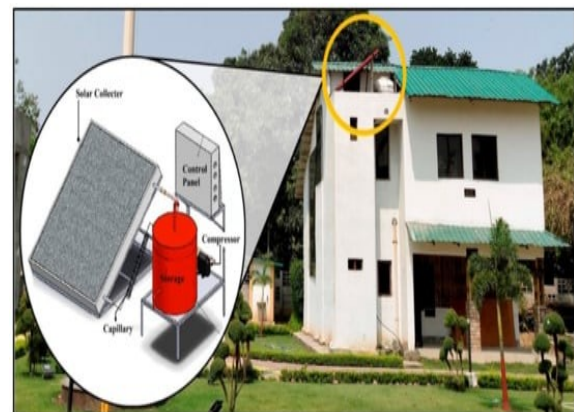- ❍ The hot water storage tank is assumed to be non-stratified [23, 24, 25, 26, 27, 28, 29].

Figure 1. In-field experimental setup (location: 29.8543° N, 77.8880° E).

III. EXPERIMENTAL SETUP AND INSTRUMENTATION

The SAHPSWH shown in Figure 2 is a configuration that directly uses the solar collector in place of the evaporator in the cycle to reduce inefficient thermodynamic processes across eliminated components. Based on different studies and the present observations, the SAHPSWH has several advantages, which were attributed to the plate thickness being in the range of 1–5 mm, resulting in a significant increase in the COP by 0.5% but with no further increases found after 5 mm. Copper and aluminium are regarded as ideal materials for manufacturing solar collectors, as they have good K values and high ductility. Using R-134a as the refrigerant in the system can result in COP values at least 15% higher than those obtained using refrigerant mixtures (R-404a, R-407c, and R-410a). The critical design properties of the refrigerant allowing satisfactory system performance are the high thermal conductivity, evaporation enthalpy, and critical temperature. R-134a leads to minimum corrosion problems; thus, its life is typically ten times that of the collector carrying water as a fluid. The very low freezing point of the refrigerant can be advantageous in experiments. By eliminating the intermediate exchanger required in the conventional system, this improves the thermal performance of the SAHPSWH.
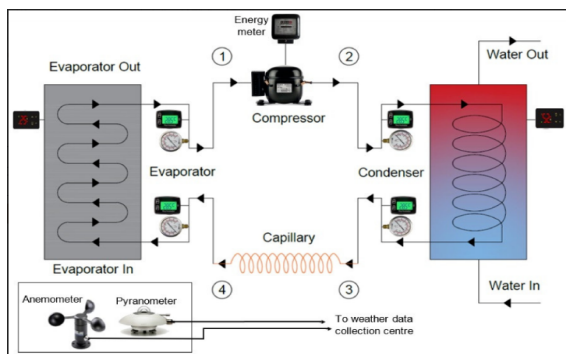

Figure 2. Schematic diagram of the SAHPSWH.

The system uses a solar collector for the evaporator–compressor to increase the system performance, using a condenser as the heat transfer unit and a capillary as the expansion device, with the following specifications for the main components.

Collector: In the study, we used a flat plate collector measuring 1.83 m (L) × 1.22 m (W) × 0.1 m (T) with transparent glazing as a cover on the top of a 0.3-mm-thick dark copper plate absorber incorporated in an extruded aluminium collector box. Different types of glazing were utilized to minimalize the heat from the absorber plate top. Fiberglass wool was used as insulation to minimize the heat loss from the bottom and side of the collector, along with an insulation cover for the probable exposure area responsible for the occurrence of heat loss. Solar radiation passes through the transparent glazing on the absorber plate over a 2.1 m^2 ± ± 0.1 m^2 absorbing area. The heat absorbed is then transferred to the R-134a refrigerant flowing in the tubes, with inner and outer diameters of 7.8 and 8.5 mm, respectively, brazed with an absorber plate. These absorber plates were layered with selective black chrome paint to absorb maximum radiation.

Compressor: A reciprocating hermetically sealed compressor with an input power of 245 W and a flow rate of 5.79 cc/rev was incorporated, working on the basic principle of increasing the pressure of the refrigerant by reducing the volume of the fluid. The compressor increases the refrigerant pressure, which significantly contributes towards increases in the refrigerant temperature.

Capillary: An optimized 0.91-mm-diameter copper capillary with a length of 3.048 m was used in the construction. Two parallel 1.52 mm capillaries were used with a copper filter. Before entering the evaporator again, it became necessary to

normalize the temperature and pressure of the refrigerant. Therefore, after losing latent heat, a reduction in pressure can be achieved via the diffusion action within the capillary, thereby increasing the volume of the refrigerant fluid, leading to a decrease in the pressure amongst the refrigerant.

Condenser: The condenser was used here to transfer heat to the water. The main function of a condenser is to condense a refrigerant from its gaseous state to a liquid state, after which its latent heat is moved to the storage tank. The condenser consisted of copper tubes with an outer diameter (9.525 mm) and length of 9.75 m immersed in the storage tank, which was assumed to be non-stratified, i.e., losses can be neglected while determining the coefficient of performance.

Instrumentation/Measuring Devices: The apparatus was in the appropriate arrangement to evaluate the system performance under different conditions. The measuring devices used to collect the necessary data were a 4-channel SZ-7504 temperature scanner, a SZ-7569-P temperature scanner, a pressure gauge, a pyranometer, an anemometer, a sling psychrometer, an energy meter, a voltmeter, and an ammeter, with a differential pressure switch as a safety device. To calculate the COP of the system, temperature readings were taken from 4 points, namely at the inlet of the evaporator –collector, the outlet of the evaporator– collector, the discharge port of the compressor, and the condenser outlet using type 1 and type 2 thermocouples. Table 1 shows the measuring devices with their measurement and uncertainty ranges.

Table 1. Measuring devices with measurement range and uncertainty data.

Sr.	Measuring Instrument	Measuring Range	Uncertainty
1.	Type 1 thermocouple	-50-99°C	± 0.1°C
2.	Type 2 thermocouple	-100-200°C	± 0.1°C
3.	Pressure gauge (bourdon type)	600-4000 mbar	±1%
4.	Pyranometer TBQ-2	0-2000 Wm^{-2}	7-14 μV-W^{-1}m^2
5.	Anemometer	0.9-0.35 m/s	0.2-0.6%

IV. RESULTS AND DISCUSSION

Experiments with different sheet and tube arrangements in the flat plate collector of the solar-assisted heat pump system for water heating (SAHPSWH) with single-glazed and double-glazed evaporators were conducted under different conditions. The effects of the tank temperature and evaporation temperature on the COP of the hybrid system, of the heat transfer rate across the condenser, of solar radiation on the tank temperature, and of the various parameters of the solar flat plate collector were investigated.

4.1. Effects of Different Tube Configurations

The nomenclature for the absorber plate and tube used for the experimental study is shown in Figure 3, where Di is the internal diameter of the tube, Do is the external diameter of the tube, b represents the bond width between the serpentine tube and the absorber plate with thickness δ, and δt is the thickness of the serpentine tube used.
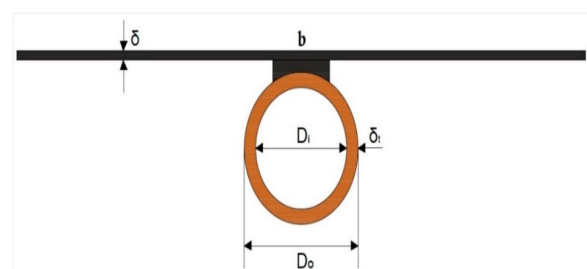

Figure 3. Nomenclature used for absorber plate and tube configuration.

Geometrical and physical data for the tubes obtained from the mathematical modelling for the optimization of the SAHPWHS are represented in Table 2.

Table 2. Geometrical and Physical data for evaporator tubes.

Geometrical Data		Physical Data	
W (m)	0.1	I_T (Wm^{-2})	284-705
D_i (m)	0.0078	U_L (Wm^{-2}K^{-1})	5.26-6.08
D_0 (m)	0.0085	h_{fi} (Wm^{-2}K^{-1})	1000
δ (m)	0.0003	k (Wm^{-1}K^{-1})	387
A_C (m^2)	2.23	tα	0.8

The following two cases were considered to evaluate the effects of different tube configurations on the solar plate collector.

Case 1: In this case, the evaporator tubes were soldered above the absorber plate, with the cross-section area of the serpentine tubes shown in Figure 4a.

Case 2: In this case, the evaporator tubes were soldered beneath the absorber plate SAHPSWH, with the cross-section area of the serpentine tubes shown in Figure 4b.
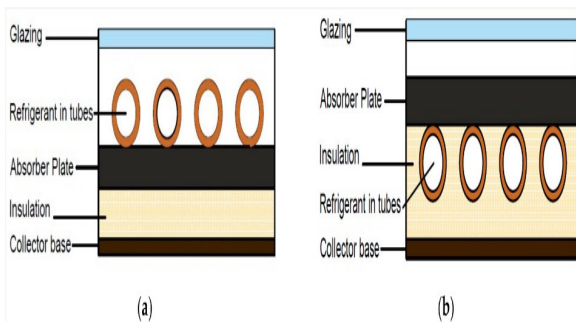

Figure 4. Cross-sections of the serpentine tubes: (a) above the absorber plate; (b) below the absorber plate.

The experiment was performed in a cold climate after establishing steady-state conditions with varying solar intensities on different days and with variations in ambient temperatures. The data recordings for solar intensity were carried out at 30 min intervals for the two cases, which were almost the same as observed in Figure 5.
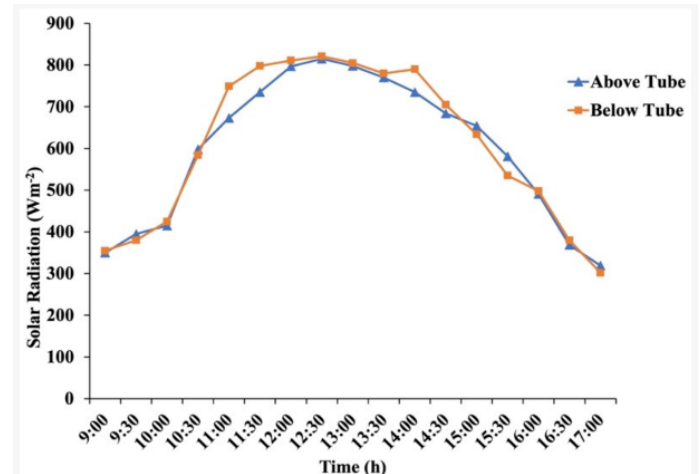

Figure 5. Solar intensity variations with time.

The thickness of the absorber plate and pitch W (center-to-center distance of tubes) were mathematically computed for economical optimization of the experiment, as a low value of W will result in an increased length and a higher δ value will increase the material cost. Additionally, the F′ value was observed to be strongly influenced by W and δ in Figure 6a,b, as F′ increased with an increase in the thickness of the absorber plate and correspondingly decreased with an increase in the W value; therefore, the optimal pitch and thickness for absorber plate for the experiment were 0.1 and 0.003 m, respectively.
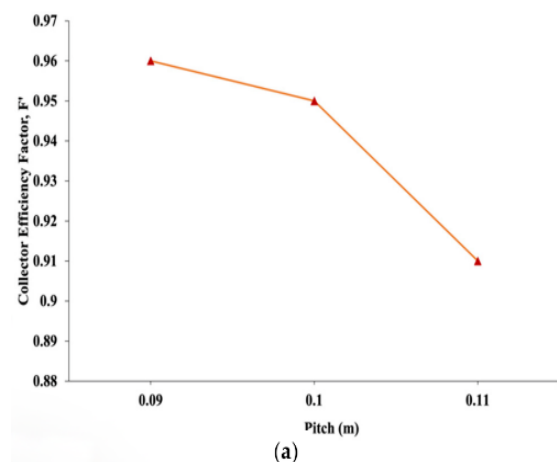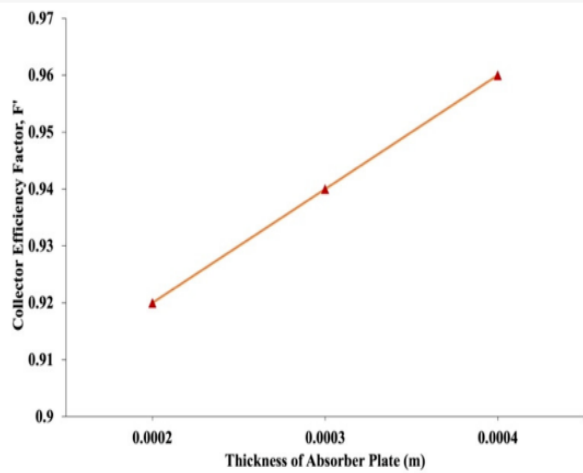
(b)

Figure 6. Collector efficiency factor variations due to different factors: (a) pitch of tubes; (b) absorber plate thickness.

The effect of the efficiency of the collector (η) on the F′ (Figure 7) resembled the prominence of the collector tube arrangement, i.e., when placed below the absorber plate, η values ranged from 46% to 58%, with variations in F′ ranging between 0.75 and 0.83, while η values ranged from 60% to 75% when the tubes were placed above the absorber plate, with varying F′ values ranging from 0.91 to 0.95.
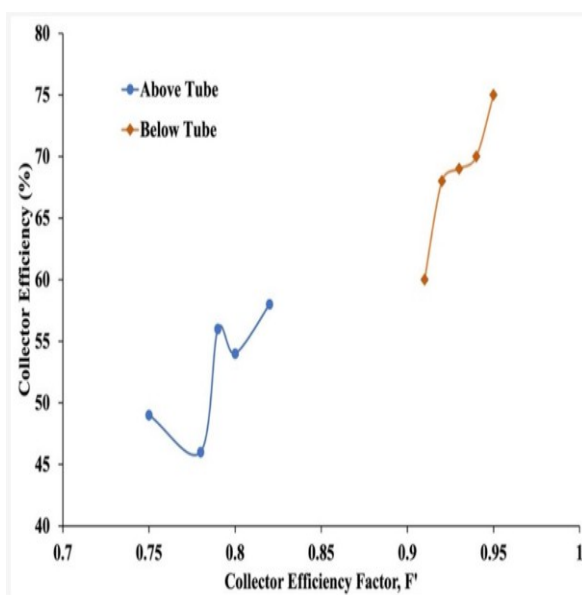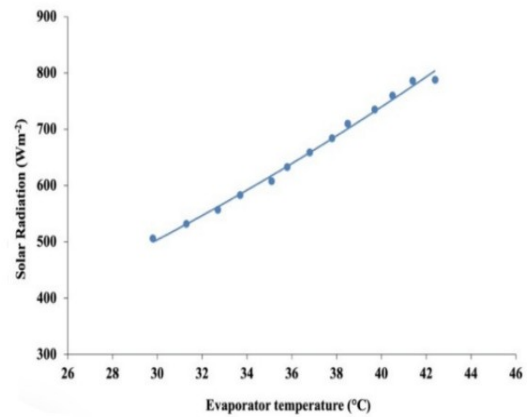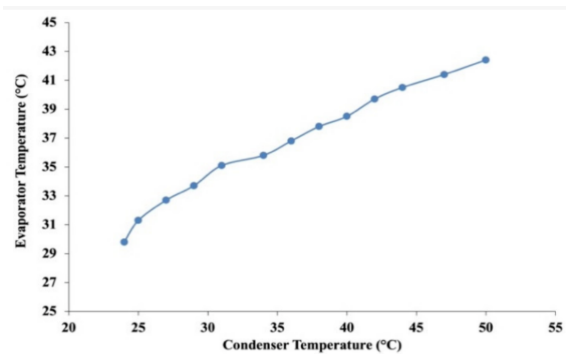

Figure 7. Collector efficiency factor variations.

(a)

Figure 8a depicts the increases in evaporator temperature with increasing solar radiation. Increases in evaporator temperature also increased the performance of the SAHPSWH.

(b)

Figure 8. Effects of various factors on evaporator temperature: (a) solar radiation; (b) condenser temperature.

Figure 8b shows the effects of the evaporator temperature on the condenser temperature, showing that with the increases in evaporator temperature, the working fluid condensing temperature also increased. Nevertheless, the effects of the solar radiation on the evaporator temperature were greater than that of the condenser temperature. When solar radiation started decreasing, the evaporator temperature decreased irrespective of the condensing temperature, showing that at a higher temperature, evaporation takes place in the system, which in turn improves the performance of the system.

The evaporator temperature is not allowed to exceed a certain value, as the compressor may get damaged when pushed beyond its operating limits. In the case of the below tube arrangement, the evaporation temperature may have been equal to ambient temperature; hence, better performance for the SAHPSWH was achieved as compared to the above tube arrangement shown in Figure 9.
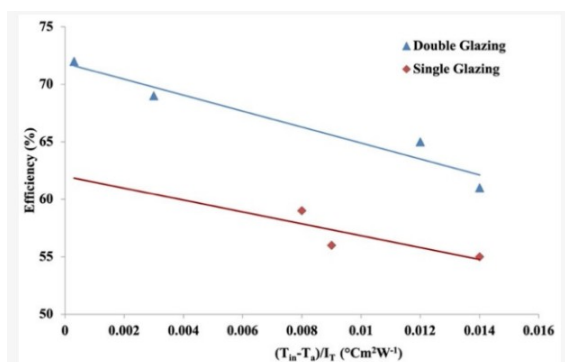

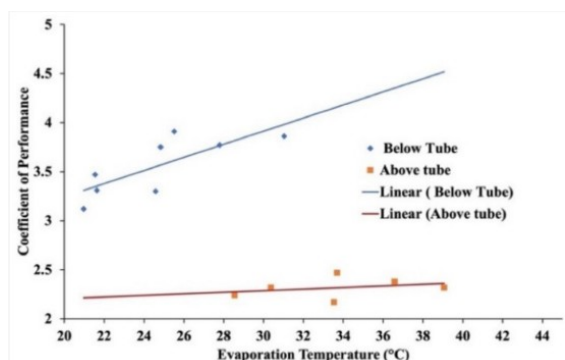*Figure 9. Variations in the temperature difference (Te– Ta) with time.*

Figure 10. COP of the system with varying evaporator temperature

V. CONCLUSIONS

This study was undertaken to examine the performance of the SAHPSWH and to find the best sheet and tube arrangement for flat plate collectors in colder climates of India. The experiment was performed in a composite climate during winter months. The tilt angle of the solar collector was 50° during the experiment. The key conclusions are listed as follows:

The results showed that 30 L of water could be heated from 23 °C to 50 °C in 55 to 75 min when evaporator tubes were soldered above the absorber plate, with energy consumption rates of about 0.30 to 0.39 kWh and with COP values varying between 2.17 and 2.47;

When evaporator tubes were soldered below the absorber plate, water was heated from 23 °C to 50 °C in 55 to 85 min, while the energy consumption ranged from 0.18 to 0.29 kWh and the COP values of the system ranged from 3.12 to 3.91;

It is evident that for both cases, the heat gain was almost same, while the maximum COP was achieved in the second case. This result clearly shows that the performance of the system with the below tube arrangement was better than the above tube arrangement;

The flat plate collector efficiency ranged from 46% to 58% when the tubes were placed below the absorber plate, with F' values ranging between 0.75 to 0.83. The efficiency ranged between 60% and 75% when the tubes were placed above the absorber plate, with F' values ranging from 0.91 to 0.95;

The efficiency factor of the collector (F') directly affects the efficiency of the solar flat plate collector (η), which is influenced by two parameters, namely the center-to-center distance of the absorber tubes W and the absorber plate thickness δ. The tube distance W had a strong influence on F', which resulted in a decrease in F' with an increase in W. Consequently, by increasing the thickness of the absorber plate, a significant increase in F' was observed;

For different glazing arrangements, the results showed that in the SAHPSWH, 30 L of water could be heated from 20 to 50°C in 95–110 min with single glazing and with

energy consumption of about 0.35 to 0.43 kWh and with COP ranging from 2.26 to 2.98. In the second case, the SAHPSWH with the double-glazed flat plate collector heated 30 L of water in the morning session from 20 to 50°C in about 55–90 min, with energy consumption of about 0.25 to 0.34 kWh and with COP values ranging from 2.86 to 3.89. For both cases, the energy gain was almost same. This result clearly shows that the system performance with the double-glazed flat plate collector was better than with the single-glazed flat plate collector in the solar-assisted heat pump system for water heating (SAHPSWH);

The collector efficiency is strongly influenced by the parameter $(T_i–T_a)/I_T$; if this parameter increases then collector efficiency decreases, because the slope of this line – $(F_R\ U_L)$ represents the rate of heat loss from the collector. This slope decreased as the number of glazing layers increased from zero to three.

The solar-assisted heat pump system for water heating (SAHPSWH) model in this study showed the best energy savings and has applicability for variable weather conditions. This is especially important for regions with a composite climate such as India, where space conditioning and water heating are required year-round. The present study has verified that the SAHPSWH is very reliable if it is carefully designed.

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