

Experimental Analysis of Solar Air Heater Coupled with Solar Water Heating System Augmented with Reflectors

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Abstract

Solar air heaters are renewable, active heating devices that use an absorber plate, a collector and an air blower to heat a space under consideration. They are meant to aid the existing heating devices and not replace it. In conventional solar air heaters, there is absorption of solar radiation by the black absorber plate and used to heat the air beneath it which is made to flow using a blower and heat is used to warm the space. In this study, the conventional solar air heater is modified with the help solar water heating system with a reflector which aids in extra heat gain by the absorber plate of Solar air heater which in turn heats the air to a higher temperature. Study was conducted over a three-day period between 10:00 to 18:00 hours and average meteorological and input values were taken. There was 48% increase in amount of heat gain by the solar air heater while the increased in efficiency of the solar air heater is nearly one and a half times than the conventional solar air heater which was the aim of the study. This modified solar air heaters could be useful in industrial as well as domestic applications as it is more efficient.

Keywords

Solar air heater (SAH), Solar water heating system (SWHS), Modified solar air heater (MSAH), Renewable Energy System, Reflectors

1. Introduction

The world's total annual energy consumption is approximately 5.67×10^{20} J. If we compare the amount of solar energy accessible on Earth 5×10^{20} J per hour, demonstrating that solar energy can provide the world's energy needs without harming the environment (Van De Graaf, 2014). Electricity is now produced by extracting energy from fossil like crude oil, natural gas and coal. Global civilization must break free from the shackles of fossil fuels, and a commitment must be made to switch to renewable and environmentally friendly sustainable resources and phase out fossil fuels. Furthermore, conventional energy resources are scarce. As a result, the world's energy demand must be met via alternative energy sources (Shukla & Modi, 2017). To save our future, we must also plan to take revolutionary step to shift toward cheap solar energy based sources (Silveira, 2003).

Solar air heater collect heat from sunlight and use it to heat air (*Solar Air Heating Systems*, n.d.). A solar air heater catches solar energy in the form of thermal energy and can be used as a thermal collector due to its simple design, low construction cost, and easy maintenance. The kind, dimensions, and design of the absorber plate, the insulating materials, and the quantity of glass covers all influence the solar air heater's effectiveness (Hassan & Abo-Elfadl, 2018). Due to the less heat transfer rate to air from the absorbing surface and the considerable heat loss into the surroundings, solar air heaters function poorly (Alam & Kim, 2017). The usage of expanded surfaces can increase the rate of heat transmission (Daliran & Ajabshirchi, 2018; Mohammadi & Sabzpooshani, 2013), artificial roughness applied to absorbent surfaces (Behura et al., 2017; Kabeel et al., 2017; Sahu & Prasad, 2017) etc. There are also several strategies for reducing solar air heater losses. Multi-pass flow, selective coating on the absorber plate, porous media, and other techniques are among them.

2. Literature Review

Many researchers worked of solar air heater and continually enhancing its performance:

Abdullah et al. (2020) investigated the effect of reflector on newly single pass solar air heater and concluded that there was improvement in thermal efficiency by 10 percent in solar air heater by using of reflectors. Also the mass flow rate of the SAH was proportional to the efficiency. Mandal & Ghosh (2020) performed an experiment on solar air heater with a reflecting source and found the mass flow rate of air is proportional to the efficiency. In an experimental study of (Karoua et al., 2017) with Linear Fresnel reflector of solar air heater, the outlet temperature of air can be achieved to 150°C. In an analysis Bhushan & Singh (2011) proved that due to reduced thermal conductivity of air, the solar air heater's thermal efficiency would low.

Bhowmik & Amin (2017) proposed a technique to enhance the solar collector's performance. He used reflecting element with the solar collector to heat up the water. The collectors capture solar radiation, convert it to heat, and then transmit that heat into a fluid, such as water or air. In the experiment the maximum efficiency obtained without reflector was 51% but this efficiency was improved to 61% by using the reflecting source. Qiu et al. (2021) used reflectors in their experiment and found 19.8% increased radiation on flat plate collector. In a performance analysis of reflectors (Prasanna Kumar & Reddy Sheeba Khan, 2017) the maximum efficiency of collector was obtained at 12:00 to 13:00 because the sun intensity was maximum at this time period. Dinesh et al. (2021) had done an experimental evaluation of two types of diffuse reflectors that are of wavy diffuse and flat diffuse reflector in solar water heater. The water temperature was increased by 4 °C when flat diffuse reflector was used under the evacuated tubes and the water temperature was increased by 6 °C when wavy diffuse reflector was used under the evacuated tubes.

When combined with a solar air heater, thermal energy storage is one of the most effective ways to store solar energy for heating the air. Solar air heaters use thermal storage materials to heat air both before and after sunset. In an experiment Ghiami & Ghiami (2018) investigated the thermal performance of a single-pass SAH (solar air heater) in which PCM (paraffin wax) was filled in the absorbent plate and there is use of staggered baffles which was embedded on it. There he got nearly 50% differences in efficiency of both the SAH's. A 1.5 mm layer of granular carbon and dessert sand by (Saxena et al., 2015) in ratio of 4:6 was placed on the SAH as a storage of energy at absorber plate, and 1.25 mm glass which is thick and toughened is used to seal it. The best thermal efficiency was attained in forced convection mode was 80.05 percent and in natural convection mode was 20.78 percent. A Thermino-55 filled copper tubes with integrated fins was soldered by (Ghiami & Ghiami, 2018) on absorber plate at its both sides, the functions was both a storage medium and an absorber surface, in the longitudinal direction. An improvement of 89.64 percent in the maximum exergy efficiency and 84.04 percent in energy efficiency was observed in enhanced SAH. Lakshmi et al. (2017) employed gavels under absorber plate which was trapezoidal in shape as a sensible energy storage medium. As a result he got 12.56 percent a maximum exergy efficiency and 36.6 percent as an average daily thermal efficiency.

3. Experimental Setup and Methodology

3.1 Experimental Setup

The experiment was performed to compare the thermal performance of two identical solar air heaters. The first SAH (solar air heater) was a conventional SAH whose performance was compared with the other MSAH (modified solar air heater). The MSAH was coupled with a solar thermal system with pipes. A pump was used for the circulation of water which was placed in a bucket. The experiment was done with the help of flat reflectors reflecting mirror that was faced on the SWHS (solar water heating system) as shown in Figure 1.

3.2 Experimental Model for Conventional and Modified solar air heater

Two identical single pass solar air heaters were used in the experiment. The first was a conventional solar air heater while other was a solar air heater with some modification. There was integration of solar water heating system with the modified solar air heater (MSAH). There was attached a PVC pipe with some tiny holes at the upper part of MSAH for hot water to be spread on absorber plate and an exhaust pipe at the bottom which collect the used water and exhaust it to the bucket. This hot water was used as a heat capturing element. The inlet air enters from the tiny holes from bottom and took heat from this sprinkled hot water and absorber plate and went outside through the exhaust fan. The solid diagram of MSAH was shown in Figure 2. Both conventional and modified SAH made of flat plate collector, insulation on the edges and flat transparent sheet at the top. This assembly was packed in a wooden

box. Air was used as a working fluid. To improve efficiency of collection we use selective coating on absorbent sheet.

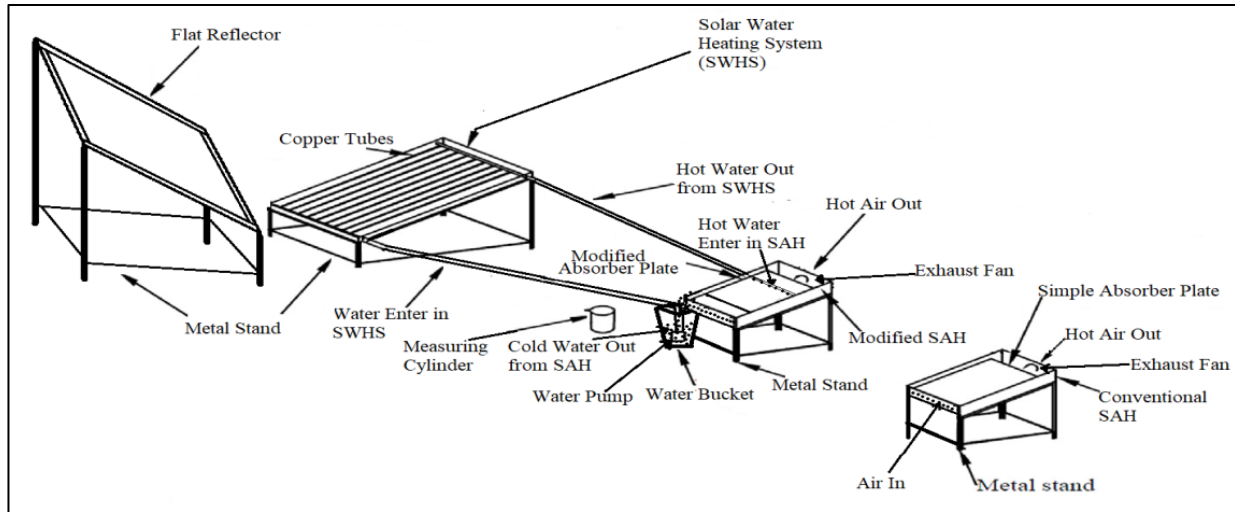


Figure 1. Schematic layout of the experimental setup.

These materials are similar to one used in liquid solar collector. There is some solar radiation transmission from the glass and these radiations are absorbed on the black absorber similar to those of solar water collector. The solid diagram of conventional SAH is shown in the Figure 2. The specification for conventional SAH and MSAH is shown in Table 1.

Table 1. Specifications of Conventional and Modified Solar Air Heater

Details of Components of SAH	Specifications
Material of absorber plate	Thin aluminium sheet
Dimensions of absorber plate	998 mm × 698 mm
Thickness of absorbent sheet	1.5 mm
Thermal properties of absorber sheet	Emissivity ≈ 0.09, Absorptivity ≈ 0.93 Thermal conductivity ≈ 236 W/m.K
Box material	Wood
Dimensions of box	Thickness = 12 mm 1048 mm × 748 mm × 190 mm
Wood's thermal conductivity	≈ 0.23 W/m.K
Cover material	Acrylic Sheet
Dimensions of acrylic sheet	Thickness = 2 mm 1048 mm × 748 mm,
Emissivity of acrylic sheet	0.90
Gap between glass cover and absorber plate	177 mm
Tilt angle of SAH	30°
Sealing adhesive	Silicone
Inlet area and outlet area of air	1045 mm ² & 7854 mm ²
Material of inlet water pipe	PVC
Dimensions of inlet water pipe	∅8mm, Length = 678 mm
Number of Sprinkling holes in pipe	12
Outlet pipe material	PVC

Outlet pipe dimensions	∅ 100 mm, Length = 680 mm
Area cover by water of absorber plate	502 mm × 650 mm

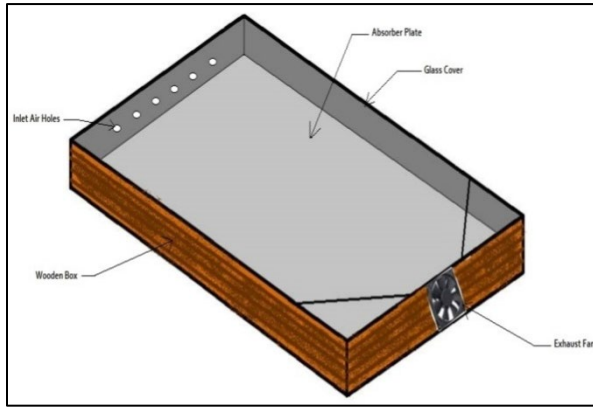


Figure 2. 3-D picture of conventional solar air heater

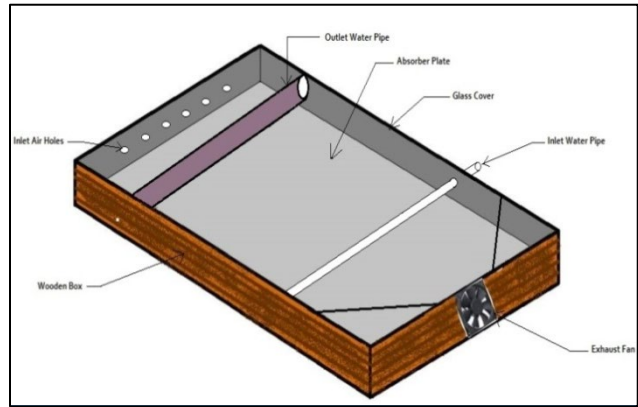


Figure 3. 3-D picture of modified solar air heater

3.3 Experimental Model for Solar Water Heating System

A SWHS (solar water heating system) is a device to which cold water is heated by solar energy. A SWHS consists of a storage tank, flat plate solar collector, and connected pipes. Copper sheets were welded to copper tubes with a black coating of highly absorbent material with acrylic glass sheet on top and insulation at the edges. The whole thing was packed inside a wooden box. The collector is normally facing the sun and connected to a continuous water supply, and the system is frequently located on a roof or in the open ground (*Solar Water Heating System* — *Vikaspedia*, n.d.). The flow of water took place between copper tubes which absorbed heat from the sun.

The 3-Dimensional model of solar water heating system which was used in the experiment is shown in Figure 3. The SWHS specifications are listed in Table 2. The modified solar air heater uses SWHS to heat up the air, which acts as a sensible heat storage medium. Water has approximately double the specific heat of most other materials in a narrow temperature range of temperature from 5 °C to 90 °C (Sarbu & Sebarchievici, 2018). The hot water pipe connecting to the top plate of the modified SAH carried hot water from the SWHS. The air moving from the channel between the absorber plate and cover receives extra heat from the hot water.

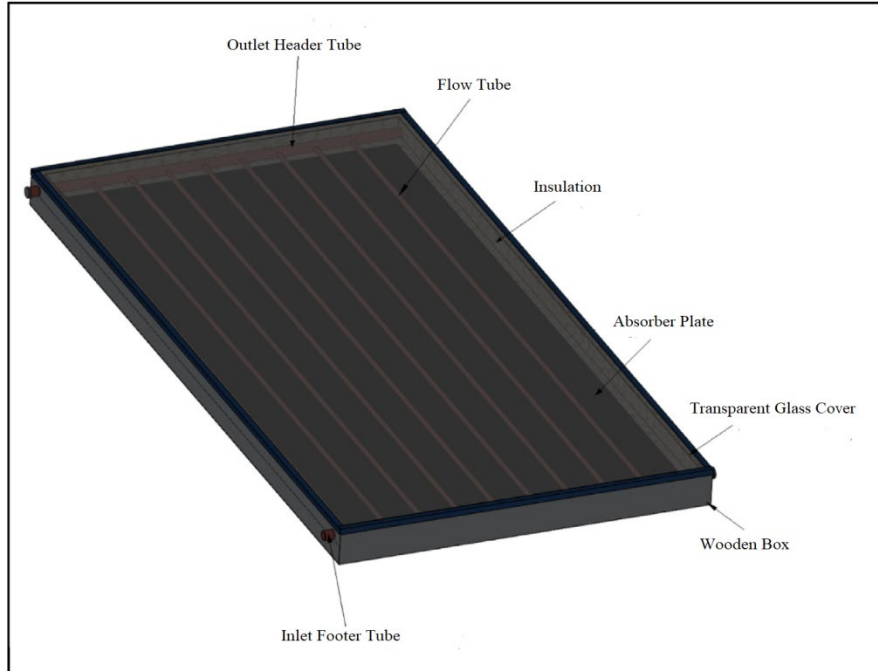


Figure 4. Solid model of solar water heating system

Table 2. Specifications of Conventional and Solar water heating system:

Details of Components of SWHS	Specifications
Material of absorber plate	Thin sheet of Aluminium
Dimensions of absorber plate	99cm × 80 cm
Thickness of absorber plate	0.3 cm
Thermal properties of absorber plate	Emissivity ≈ 0.09; Absorptivity ≈ 0.93 Thermal conductivity ≈ 236 W/m.K
Box material	Wood
Box dimensions	122 cm × 88 cm
Wood's thermal conductivity	≈ 0.09 W/m.K
Cover material	Acrylic Sheet
Cover dimensions	122 cm × 88 cm
Cover emissivity	0.90
Gap between sheet and absorber plate	62.5 mm
Tilt angle of SWHS	30°
Sealing	Silicone
Material of Inlet and outlet water pipe	Copper
Pipe dimensions	∅ 12.5 mm, Length = 90 cm
No. of pipes	6
Distance among two consecutive pipes	80 mm
Pipe properties	Emissivity ≈ 0.03, Thermal conductivity ≈ 385 W/m.K

3.4 Methodology

The experiments were carried in such a way that reflecting mirror face on SWHS (solar water heating system) and investigate the effect of hot water on MSAH (modified solar air heater) and the comparison was done with the conventional solar air heater (SAH). In this case, the reflecting mirror was faced on SWHS to heat up the water. The experiment was conducted on the terrace of the AB-Block, of NIT, Kurukshetra, Haryana, India, (29.95N, 76.82E)

from 10:00 AM to 06:00 PM in three consecutive days from April 30th to May 2nd. Figure 1 shows the schematic arrangement of the experimental setup also photograph of experimental setup is shown in Figure 4.

In this experiment nearly constant velocity (approx. 2.1 m/s) of outlet air from SAH was obtained because of DC exhaust fan used in both the air heaters. The outlet velocity of the air was measured by anemometer. Similarly to the fan, a DC pump was used to maintain a constant flow rate (i.e. 0.1053 kg/s) of water in the SWHS. For checking the mass flow rate of water, jar method was used on hourly bases to check whether the flow rate is same or some variation. Due to same quantity of water was circulated from the bucket; we got a constant flow rate. At regular intervals of 1 hour the temperature of several components of MSAH such as temperature of absorber plate, temperature of air at inlet and outlet, temperature of inlet and outlet water flow was monitored. The temperature of absorber plate, inlet and outlet air was also measured for the same time interval in conventional SAH. Absorber plate temperature of SWHS with the temperature of copper tubes and the temperature of water at inlet and outlet was also measured at a constant time interval of one hour. The absorber plate temperature in both SAHs and SWHS, and temperature of copper tubes was recorded at three different locations and averages are taken. Metrological parameters such as solar radiation, wind velocity and ambient temperature were captured from (*Historical Weather Data for Any Location | Visual Crossing*, n.d.) on hourly bases for Kurukshetra.

4. Performance parameters

4.1 Useful heat gain (Q_u)

Eq. (1) has been used to calculate the useful heat gain (Q_u) received by air in W.

$$Q_u = \dot{m}_a \times C_{p,a} \times (T_{o,a} - T_{i,a}) \quad (1)$$

Where, \dot{m}_a = mass flow rate of air in kg/s
 $C_{p,a}$ = specific heat of air in J/kg.K
 $T_{o,a}$ = Temperature of outlet air in °C
 $T_{i,a}$ = Temperature of inlet air in °C

$$\text{Also, } \dot{m}_a = \rho_a \times A_{c/s \text{ pipe}} \times v_a \quad (2)$$

ρ_a = density of air
 $A_{c/s \text{ pipe}}$ = area of cross-section of pipe in m²
 v_a = velocity of air from solar air heater in m/s

4.2 Experimental Instantaneous Efficiency (η_{exp})

The thermal efficiency of solar collectors is defined by (Arunachalam & Edwin, 2017) as the ratio of energy gain to solar radiation incident on the collector plane, represented in equation (3),

$$\eta_{exp} = Q_u / (IA_{pm}) \quad (3)$$

Where, I = solar irradiation on solar air heater (W/m²)
 A_{pm} = area of absorber plate in (m²)



Figure 5. Complete photograph of experimental setup

5. Results and Discussion

The test was conducted for a three-day period. The parametric results as provided in the paper are hourly values on average bases for both SAH's and SWHS across the three days of the experiment. The average value of observations is used to calculate the values of parameters in tables. The mass flow rate of outlet air from SAH's was 0.015 kg/s. The velocity of air was kept constant at 3.9 m/s. Despite this, there is little variance in the mass flow rate of air according to the time, as this is based on air density of air, which is temperature dependent and change according to time.

5.1 Meteorological parameters variation

The hourly variation in meteorological like ambient temperature, sun irradiation and wind velocity for the experiment is demonstrated in Figure 5. Table 3 shows the average value of meteorological parameter on daily bases. The performance of conventional SAH (solar air heater), MSAH (modified solar air heater), and SWHS (solar water heating system), are influenced by these parameters because meteorological metrics are dependent on atmospheric conditions, they show random variance.

The daily average value of solar radiation and ambient temperature was 556 W/m² and 37.89°C respectively. If the absorption of solar irradiation is high then it suggests that there is increment in the performance of all three apparatus i.e. conventional SAH, MSAH, and SWHS. There is great temperature difference between the absorber plate and the ambient temperature due to higher solar radiation and it results in greater heat loss; also there is lesser heat loss from SWHS, conventional and modified SAH if wind velocity is less.

Table 3. The average values in meteorological parameters.

Ambient parameter	Average Values
Solar Irradiation (W/m ²)	556
Ambient temperature (°C)	37.89
Wind Velocity (m/s)	3.89

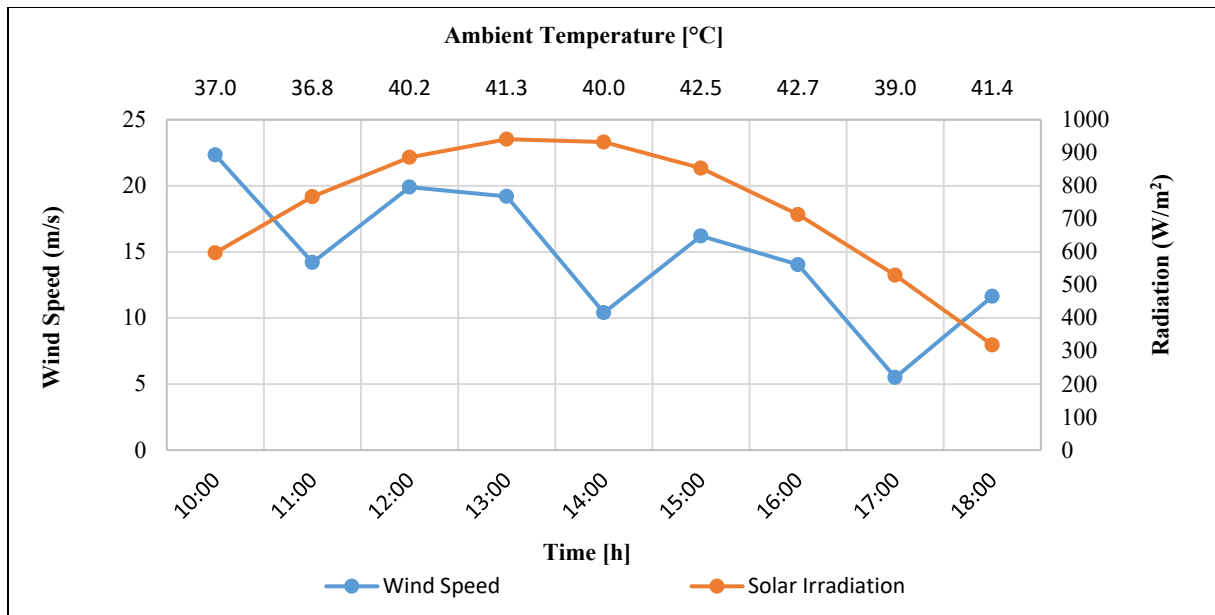


Figure 6. Variations in meteorological parameters.

5.2 Temperature variations in different elements of conventional SAH and modified SAH:

Figure 6 and Figure 7 respectively show the variation in temperature of inlet air, outlet air and the absorber plate on average hourly bases in both SAH's. In addition, Figure 7 also shows the variation in temperature of inlet, and outlet water in MSAH on hourly bases. Table 4 shows the values of different components of conventional and modified SAH on daily average bases. In this experimental work, the modified SAH obtained 7.54% higher output air temperature than the conventional SAH. The heat capturing element, water, circulates with high temperature in MSAH which maintain the temperature of absorber plate after work. This was due to reflecting surface that reflect sun radiation to SWHS (solar water heating system), due to which the temperature of water was increased. This was also the reason for increased absorber plate temperature in MSAH than conventional SAH.

The following factors contributed to the increased air temperature in modified SAH:

- The temperature of absorber plate increased due extra heat gain by water in SWHS by the use of reflecting surface.
- Additional heat received by air from hot water flowing on the plate also with the absorbing plate.

Table 4. Average values of various parameters in conventional and modified SAH.

Parameters/Type of SAH	Conventional SAH	Modified SAH
Avg. Temp. of absorber plate (°C)	67	66.5
Temp. of inlet air (°C)	39.6	39.6
Temp. of outlet air (°C)	45.1	48.5
Temp of water at inlet. (°C)		47.1
Temp of water at outlet. (°C)		43.4
Daily avg. value of mass flow rate of air (kg/s)	0.016	0.015

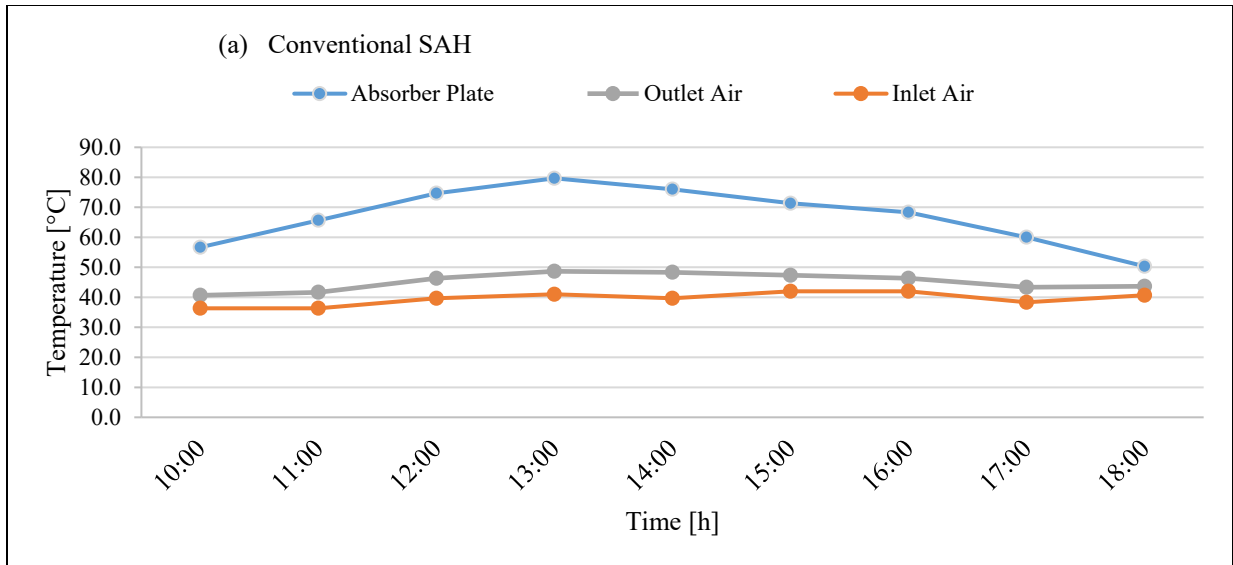


Figure 7. Variation in temperature of different elements in conventional SAH.

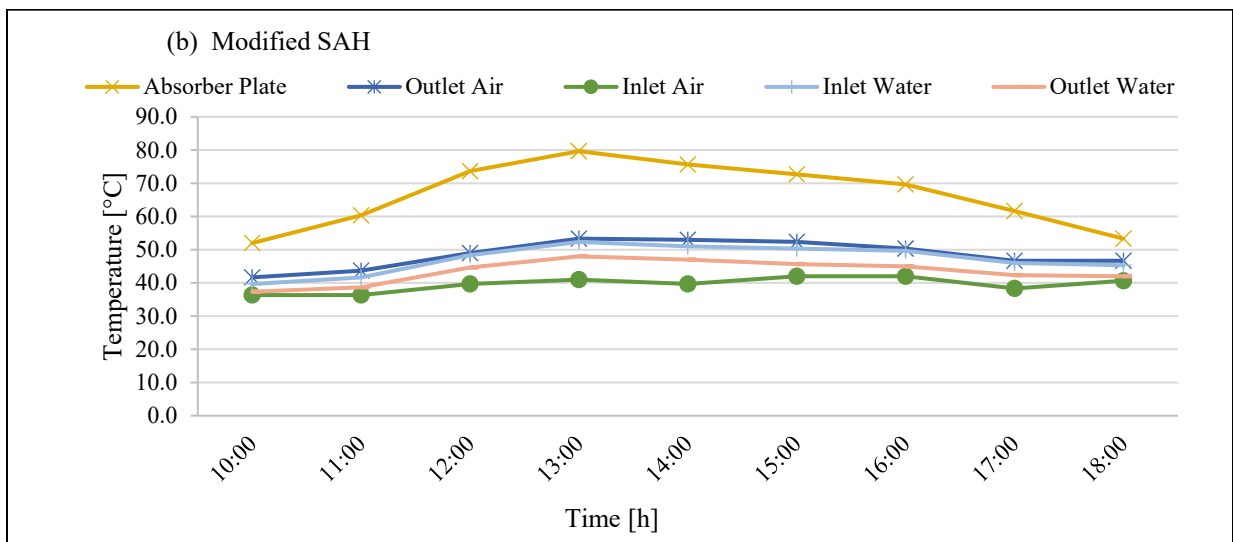


Figure 8. Variation in temperature of different elements in modified SAH

5.3 Temperature variation of different elements of SWHS

Figure 8 illustrate the fluctuation in temperature of the inlet water and outlet water in SWHS (solar water heating system) and the absorber plate on hourly base. The daily average values of various components of SWHS in the experiment are shown in Table 5. The temperature of the water leaving SWHS was found to be greater due to incident solar radiation and increase in temperature of absorber plate. The temperature of water at outlet from the modified SAH was 47.1°, this temperature is reasonable temperature for home uses like laundry, hand washing, bathing also for heating space and which significantly saves energy from household appliances.

Table 5. Average values of several elements in SWHS.

Parameter	Avg. values
Temperature of absorber plate (°C)	74.6

Inlet water temperature (°C)	43.4
Outlet water temperature (°C)	47.1
Mass flow rate of water (kg/s)	0.1053

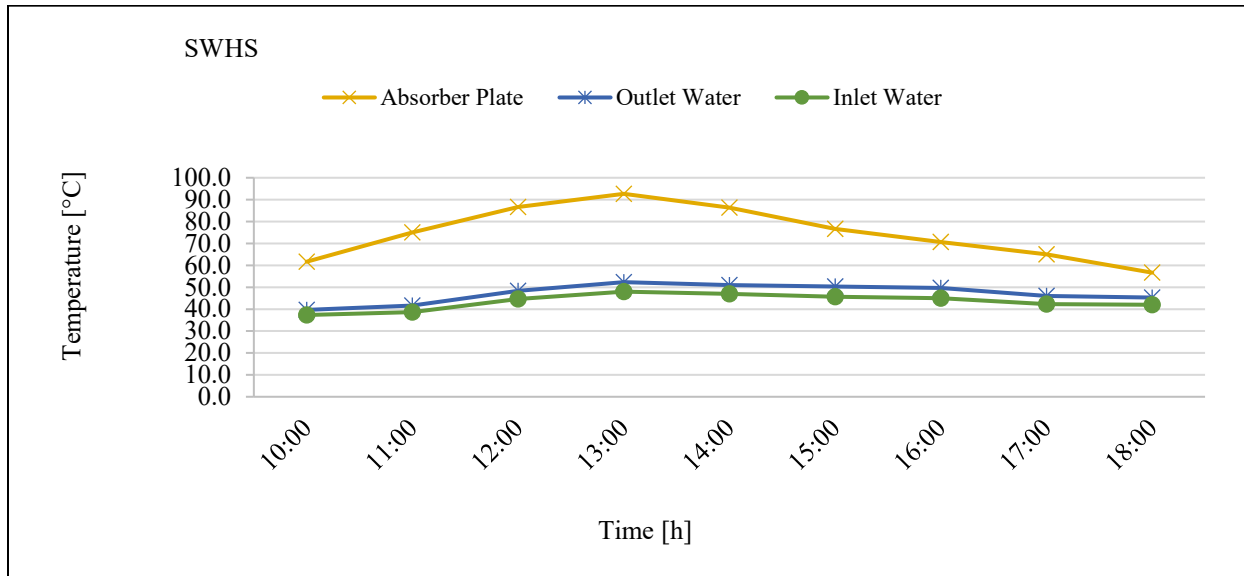


Figure 9. Variation in temperature of different elements of SWHS

5.4 Heat gain received by the air in both conventional and modified SAH

Figure 9 depicts the hourly fluctuation in heat gain received by the air in conventional and modified SAH. The daily average heat gain by conventional SAH and modified SAH was 90.8 W and 134.4 W. The daily average heat gain in modified SAH was nearly 48% more than conventional SAH. This was because the air in MSAH captured heat from both absorbing plate and sprinkling water.

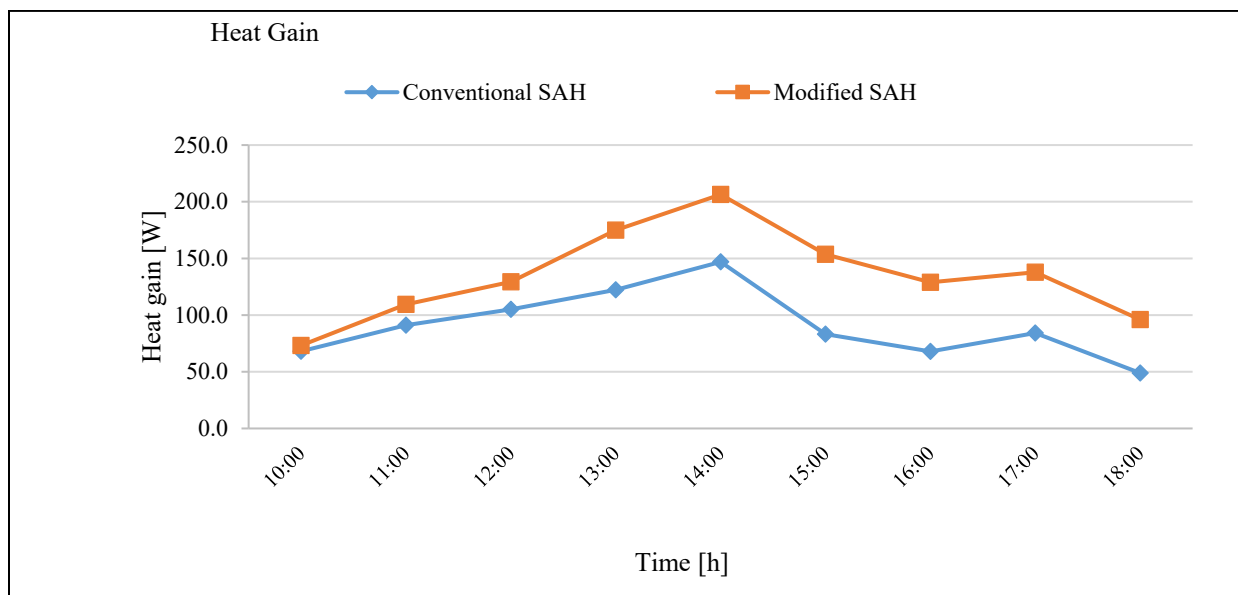


Figure 10. Variation in heat gain received by air in conventional and modified SAH.

5.5 Efficiency variation for conventional and modified SAH's

Figure 10 demonstrates the hourly variation in efficiency of both conventional and modified SAH. The Experimental efficiency of conventional and MSAH was 18.2% and 27.6% respectively. The daily average efficiency of modified SAH was 51 percent higher than conventional one. There are higher losses in conventional and modified SAH if the efficiency is low. Explanation for inferior performance of conventional SAH was due to lower efficiency and higher irreversibility that happened in it (Bayrak et al., 2013).

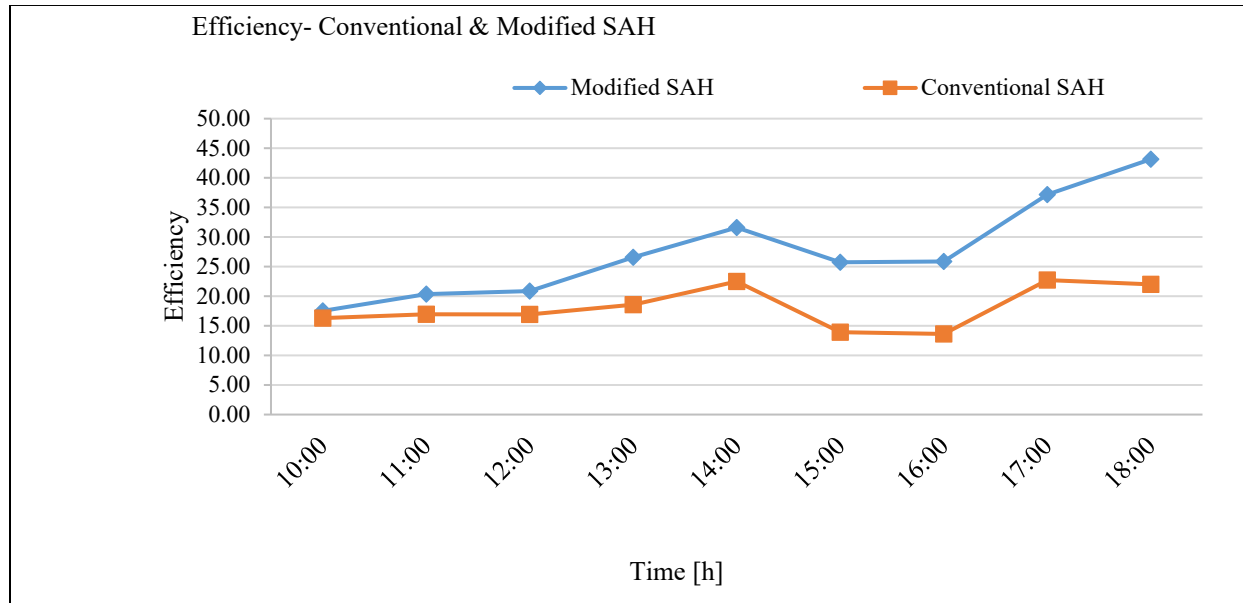


Figure 11. Variation in efficiency of conventional and modified SAH

5.6 Proposed Improvements

In the current experimental investigation, the enhancement in SAH is done with the coupling of SWHS (solar water heating system) and the use of reflectors with the constant mass flow of water in SWHS and constant mass flow of air in SAH's. There are also many issues which can be investigated for further research. Recommended issues studied are as follow:

The flow rate variation of liquid and air in SWHS and SAH's can be done and can optimize the best value for the highest output gain.

Double pass SAH can be used instead of single pass SAH and investigate the same experiment also analyze the output result for both the cases.

6. Conclusions

The thermal performance of modified SAH and conventional SAH has been evaluated. The augmentation in this experiment was of reflectors. The reflector was faced on SWHS for three consecutive days. The comparisons are done in conventional and modified SAH and found that modified SAH is beneficial than conventional SAH.

The following are the main findings for modified solar air heater compared to conventional SAH:

- The modified SAH obtained 7.54 % higher output air temperature than the conventional SAH.
- The daily average heat gain absorbed by the air in modified SAH was 48% greater than conventional SAH.
- The efficiency of the conventional and MSAH was 18 percent and 27 percent respectively.

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