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PERFORMANCE EVALUATION OF SOLAR AIR HEATER USING INCLINE BAFFLES

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ABSTRACT

To investigate the solar air heater's (SAH) effectiveness, experiments are conducted using flat plates and artificially roughened plate in terms of Inclined and Winglet baffles over the collector surface. This proposed system collector plate comprises Inclined and Winglet ribs and serves as an artificial roughness generator. Airflow rates of 0.01, 0.02, & 0.03kg/s are used in the experiment. To determine the improvement in the proposed work, the experimental results are compared with flat plate SAH. This proposed work offers greater efficiency, useful energy gain, and lower top heat loss than a conventional SAH. The airflow rate of 0.03kg/s gives the topmost efficiency and useful energy gain. The experimental day's average efficiency of a SAH with Incline baffles is 32.6 %, 53.6 %, and 61.9 %, respectively, for the flow rates examined. For the same flow rates, it is 37.4 %, 29.6 %, and 24.39 % more effective than a flat surface SAH. For the same investigated air flow rates, the proposed system gains 37.7 %, 27.63 %, and 23.63 % more energy than flat plate SAH. Substantial reductions in Top losses of up to 8.20 %, 6.55 %, & 7.65 % have been reported at the specified flow rates. Energy metrics and economic study performed shows the payback time, Production factor, Life cycle conversion efficiency and economic values of the proposed SAH is optimum.

Keywords: *Baffles, Artificial Roughness, Solar Air Heater, Efficiency, Useful Energy Gain, Top Heat loss.*

1. Introduction

The use of renewable energy resources is increasing daily. The depletion of fossil fuels and their high polluting nature drives the energy society toward solar energy. In recent years, solar energy has significantly contributed to meeting global energy demands. A solar air heater is essential in converting the solar energy received from the sun into usable heat. SAH converts waste heat into proper heat used in various applications, including agricultural food production, commercial garment industries, fabric and food drying industries, marine product drying, HVAC, and solar desalination.

A novel hybrid duct arrangement was developed to investigate the thermal behaviour of SAH (Sivakandhan et al., 2020). This innovative design improves effective and thermal efficiency by 18.1 % and effective efficiency by 22.4 % when compared to conventional types. The heat transfer characteristics and efficiency of a recycled aluminium solar cane Air Heater were investigated (Murali et al. 2020). This system achieves 69.47 % collector efficiency with fins and 65.98% collector efficiency without fins.

The parameter indicates the maximum hydro thermal performance is about 2.33, which is higher than the other equivalent rib roughness designs used on the solar air heater for their experimental investigation (Gill et al. 2021). The hydraulic and thermal performance of a Double Flow Solar Air Heater with a C-shape rib is investigated experimentally (Gabhane and Kanase-Patil 2017). As a result, the hydro thermal performance parameter in this proposed design is 3.48, and the friction factor is 0.031. SAH's thermo hydraulic performance and heat transfer were investigated using a V-geometry gap pattern with identical gap spacing and arranged in a zigzag pattern (Patel and Lanjewar 2021a). According to the experimental results, the thermal hydraulic performance value is 1.85, and when compared to SAH with smooth plate nusselt number is enhanced by 2.51 times, and friction factor is improved by 2.70 times. The effect of perforation on the thermal hydraulic performance of the SAH was examined using C-shape fins (Saravanan et al. 2021). In terms of heat performance, the perforated fins exceed the smooth absorber plate by 2.67 times and friction factor by 5.34 times, respectively. An arc rib fin was inserted above the absorber plate to create a thermal model for analysing SAH heat transfer (Sureandhar et al. 2021). As a result, compared to smooth plates, arching fins

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provide more excellent thermo-hydraulic performance and heat transport.

A dual-pass SAH research was conducted using absorber plates with conductive aluminium tubes, yielding an efficiency of 40.3 percent, 21%, and 19.4 percent at mass flow rates of 0.025 kilogramme / s, 0.05 kg / s, and 0.075 kg / s, respectively (Abo-Elfadl et al. 2020). Experimental and numerical approaches were used to assess the design and efficiency of SAH with serpentine wavy channels (Singh et al., 2019). Flow rates ranging from 0.01 kg/s to 0.04 kg/s were used in the experiments. It demonstrates that the better results were 66 percent efficiency and 3Pa pressure drop, corresponding to an airflow rate of 0.04 kg / s. Abuşka (2018) developed and tested a unique solar air heater with a conical absorber plate. Three different airflows are used in the experiment. This innovative design has average thermal efficiency of 63.2 percent, 71.5 percent, and 74.6 percent for mass flow rates of 0.04, 0.08, and 0.10 kg/s, respectively. The researchers looked into a hybrid PV/T double-pass SAH with a finned plate (Hegazy et al. 2020). PV modules are mounted on the absorber plate, adjacent to the glass covers, and completely separate from the solar collector for this investigation. They attained daily thermal efficiencies of 53 percent, 27 percent, and 64 percent for the suggested hybrid system, respectively, at a mass flow rate of 0.02 kg/s. Experiments were performed using a SAH with V-shaped baffles over the collector plate (Rajendran et al. 2021). In conclusion, they determined that the suggested system has a thermal efficiency of 13 percent, 11.97 percent, and 3.06 percent higher than the flat surface SAH for the analysed air flow rates.

A hemispherical dimple-cavity was installed over the collector plate (Goel et al. 2021). Because of the increased heat transfer over friction factor, they find that the best thermohydraulic performance parameter of 3.48 is preferred to the other conceivable roughness geometries. Heat transfer in square duct SAH was investigated due to discontinuous cylindrical shape roughness (Azadani and Gharouni 2021); for a Reynolds number of 8,000, the maximum thermal-hydraulic performance parameter value was calculated was found to be 1.05. A SAH with quarter-circular ribs above the absorber plate was numerically analyzed (Mahanand and Senapati 2021). As a result, SAH with quarter-circular ribs obtains the highest thermal enhancement ratio of 1.88 for a relative roughness pitch of 7.14 and a relative roughness height of 0.042 at a Reynolds number of 15,000, with a relative roughness pitch of 7.14 and a relative roughness height of 0.042. (Kumar et al. 2013) employed numerous V-shaped fins to conduct an experimental study on heat transfer and friction caused by SAH. Under the observed conditions, the proposed numerous V-shaped fins with a gap increase the Nusselt number by 6.74 times while increasing the friction factor by 6.37 times. SAH friction factor and heat transmission were investigated using arc form wire in a S shape (Kumar et al. 2016). As a result, the Nusselt number of SAH rises as the Reynolds number rises, but the friction factor falls. SAH's heat transmission performance was examined (Kumar et al. 2019). As a result, when compared to standard plate SAH, the nusselt number of the proposed system increases 4.83 times. W-shaped ribs were used to examine SAH's thermal performance and heat transfer (Kumar et al. 2020). They've also used the booster mirror to evaluate SAH's abilities. As a result, the Nusselt number of W-shaped ribs with booster mirrors is 29 to 38 percent higher than that of ribs without mirrors. Researchers employed multiple-arc created with gaps to test the heat transfer and friction factor efficiency of SAH (Pandey et al. 2016). They were able to enhance the Nusselt Number and friction factor to 5.85 and 4.96, respectively, by using this form. Several separate V-shaped patterns mixed with staggered fins were used in SAH experiment (Patel and Lanjewar 2021). As a result, they discovered that when compared to typical plate SAH, the nusselt number and friction factor rise by 2.27 and 4.28 times, respectively. The research was conducted by altering the relative roughness height using a solar air heater with multiple V-shaped fins (Bansal et al. 2019). They discovered an increase in heat input gain and mechanical pumping power while adjusting RRH value systems from 0.019 to 0.043.

The initial survey reveals that using baffles, ribs, or other artificial roughness improves solar air heater efficiency compared to using a normal plate air heater. This also shows that many experiments on solar air heaters with various artificial roughness forms have been carried out to improve SAH results (Rajendran et al. 2022). It also demonstrates that baffles have a higher roughness in addition to the air heat discharge rate. As a result, the performance of the solar air heater has substantially improved. However, no research has been done to determine whether inclination baffles paired with a winglet shape above the absorber plate can increase SAH performance. This work combines inclined baffles with a winglet form in the collector plate as an artificial roughness element to improve SAH thermal efficiency.

2. Materials and Methods

The SAH configuration is modelled in SOLID WORKS software utilising an ASHRAE standard 93 SAH with Inclined and winglet baffles over the absorber plate. In this proposed device, an inclined baffle paired with a winglet arrangement is used to create artificial roughness. Figure 1 depicts the proposed system in three dimensions. The system is built of mild steel and has 40mm diameter input and exit tubes. A 1.5 m2 absorber panel coated in black is used for more excellent absorption. The inclined and winglet baffles length is 100mm, and the height is 80mm. The SAH is protected by a 5mm thick transparent glass cover. Because of 5mm thermocole insulation, the system's heat loss is minimised. Solar radiation data from the last five years is collected to determine the location's potential for conducting SAH experiments.

The experiments are going done at National Engineering College's Energy Park (9.1483° N, 77.8321° E). A sun metre is used to quantify sun irradiance during the studies. In November 2021, air will be supplied to the SAH by a blower, and research will be done from morning to evening. The experiment's input parameters are solar radiation, atmospheric temperature, and various airflow speeds. The experiment used airflow rates of 0.01, 0.02, and 0.03 kg/s. During the experiment, a K-type digital thermocouple is used to measure the input, output, absorber plate, and glass temperatures. These temperatures are used to compute the thermal efficiency, useful energy derived from the system, and top heat loss of the SAH system. Furthermore, the study's findings are compared to standard SAH. Figure 2 depicts a SAH with inclined and winglet baffles.

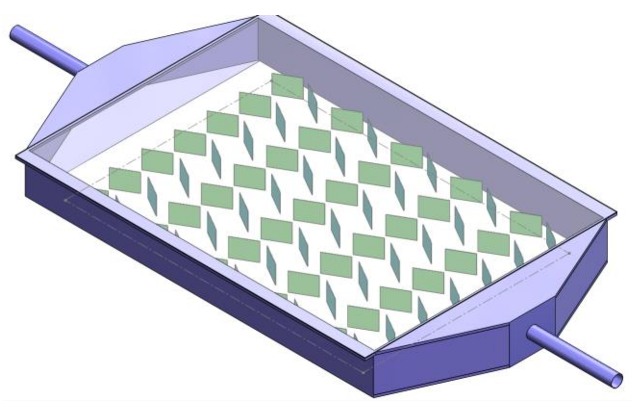

Fig. 1 Design of the proposed SAH

Fig. 2 Fabricated SAH with Incline Baffles

3. Theoretical Analysis

Different parameters are used to determine the system's thermal performance. Mainly input temperature, output temperature, solar radiation, air mass flow rates, and environmental circumstances play a crucial part in the SAH performance. (Rajendran et al. 2022).

Air mass flow rate is evaluated by

$$\dot{m} = \rho A V \quad (1)$$

Where $\dot{m}$-Air flow rate in kg/s, ρ–air density kg/m^3, A- area of inlet pipe in m^2 and V –Air velocity at inlet m/s.

SAH system efficiency is evaluated by

$$\eta = \frac{Q_{out}}{Q_{in}} \quad (2)$$

Q_{out}- useful energy obtained from SAH in Watt, and it is evaluated by

$$Q_{out} = mC_P(T_2 - T_1) \quad (3)$$

Q_{in} - energy input for SAH in Watt, and it is calculated by

$$Q_{in} = IA \quad (4)$$

Heat loss that occurred in the SAH top surface is evaluated by

$$Q_t = \frac{T_g - T_a}{\frac{1}{Ah_r + Ah_w}} \quad (5)$$

Qt - heat losses in top surface in W, Tg - temperature of glass, and Ta - ambient temperature of the local area in K, hr - radiation heat transfer coefficient of SAH in W/m2K, hw -convection heat transfer Coefficient of SAH in W/m^2K.

Convection heat transfer coefficient over the top surface (h_w) is evaluated with the help of wind velocity

$$h_w = 5.67 + 3.86\, V_w \quad (6)$$

V_w- velocity of wind in m/s.

The radiation heat transfer coefficient h_r is calculated by

$$h_r = \frac{\sigma \varepsilon_g (T_g+T_s)(T_g^2+T_s^2)(T_g+T_s)}{(T_g-T_a)} \quad (7)$$

Where σ - Stefan Boltzmann constant (5.667×10^{-8} $W/m^2.K^4$), ε - emissivity of the transparent glass, T_s- temperature of the sky in K.

4. Error Analysis

The faults and errors of the system used for measurement are taken into account for the parameters measured from the devices in this experimental investigation, as specified in Table 1. To decrease measurement errors, procedures such as wrapping the thermocouple's connection by insulation adhered to the continuous measurement are taken. Random and systematic errors are the two sorts of errors. Their ambiguity is of type B (the accuracy and measurement characteristics of the instrument are employed to calculate uncertainty). In the research provided here, collector surface temperatures, airflow rate, and solar radiation are examined separately. Table 1 shows the Uncertainty value produced from the calculation.

$$u = \frac{a}{\sqrt{3}} \quad (8)$$

Table 1 Uncertainty Values

Components	Accuracy	Uncertainty
Sun meter	±1W/m^2	0.5%
Thermocouple	±1^{0}C	0.5%
Data Logger	±1^{0}C	0.5%
Anemometer	±0.05 m/s	0.02%

5. Results & Discussion

Solar radiation has a huge impact on the working of all solar thermal systems. It's an important part of the SAH system to evaluate the system performance. The temperature of SAH's output is improved due to the collection of solar radiation in absorber plate and transparent cover. The solar radiation of the Kovilpatti area, tamilnadu and India (9.1483° N, 77.8321° E) has been analysed for the past five years. It demonstrates that the kovilpatti location is more suited to conduct an experiment on solar thermal system. The experiment is conducted over three days, from November 10 to 12, 2021.During the experiment, the solar radiation is measured using a solar metre. Radiation is measured for regular intervals from morning 9.00 to evening 5.00p.m. Measured solar radiations with time for the experimental days are depicted in the fig 3. Graph shows that similar level of radiation is recorded during the experimental days. The lowest sun radiation value is recorded on the 1st day of the experiment, and the highest value is noted on the 1st day. Radiation values ranged from 289W/m2 to 780W/m2, with a minimum of 289W/m^2 and a maximum of 780W/m^2

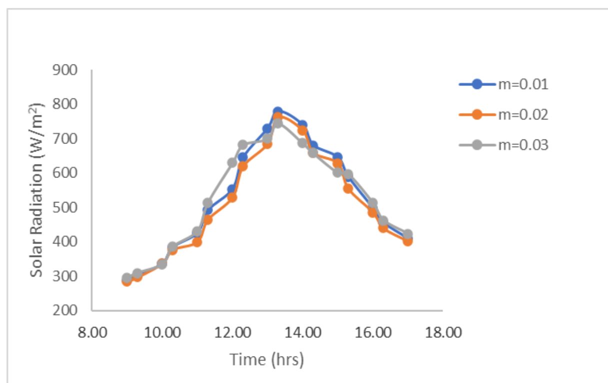

Fig. 3 Solar Radiation vs. Time

The temperature of the solar air heater's input, output, glass, and the plate is measured with the help of thermocouples. Temperatures are correspondingly measured at flow rates of 0.01, 0.02, and 0.03. The temperature rises with solar energy from sunrise until afternoon and then lowers till sunset. The input temperature of a Flat surface solar air heater (FSAH) and a SAH with Incline baffles (ISAH) over time is depicted in Figure 4. In both SAH setups, the ambient temperature of the local area ranges from 29^{0}C to 38^{0}C, and is employed as an input temperature. The collector plate temperature and the glass temperature for both SAH are shown in Figures 5 and 6. The collector plate and glass temperature are higher than the air temperature due to their thermal conductivity, transmissivity ranges, and straight exposure to the sun. As a result of the forced air absorbing high heat from the plate, so the outlet temperature is high. The externally forced air circulates throughout the absorber plate's body, absorbing further heat. In SAH with baffles, the glass and collector surface temperature is maximum than normal SAH. Unlike a typical air heater, SAH with baffles prevents air from flowing freely throughout the system. It maintains the air in the system for an extended period than a conventional SAH. Compared to the traditional system, it gives higher air temperature in the system outlet port.

For the flow rates tested, Figure 7 indicates the temperature of SAHs' exits with time. The findings show that the air heater's output temperature rises as the flow rate is reduced. For 0.01 kg/s and 0.03 kg/s, the maximum and minimum outlet temperature is recorded. The average outlet temperature of an FSAH is 50.8°C, 48.8°C, and 47.4°C, respectively, for 0.01, 0.02, and 0.03 Kg/s flow rates. For the same air flow rate, the average outlet temperature of ISAH is 60.8°C, 54.4°C, and 51.4°C. The baffled air heater's outlet temperature is 16.4 %, 10.2 %, and 7.7 %, superior to the FSAH for the relevant airflow rates.

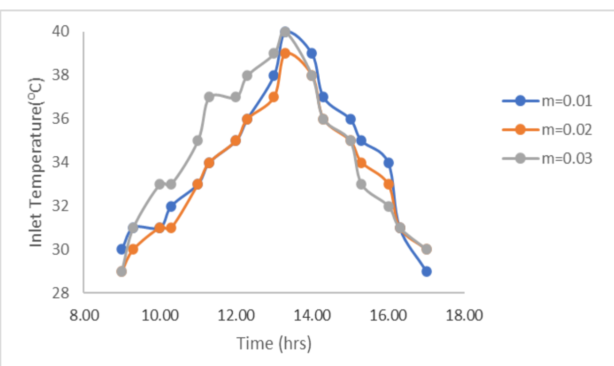

Fig. 4 Air inlet Temperature with time for both setup

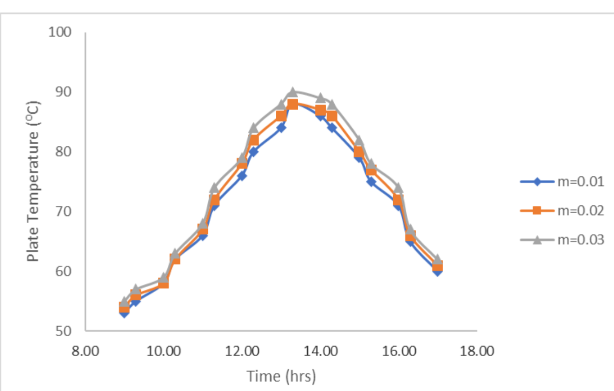

Fig. 5 (a) Plate Temperature vs. time for SAH without baffle

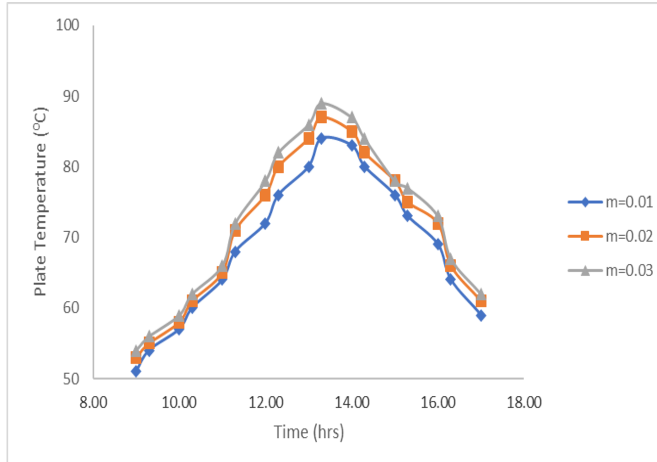

Fig. 5 (b) Plate Temperature vs. time for SAH with baffle

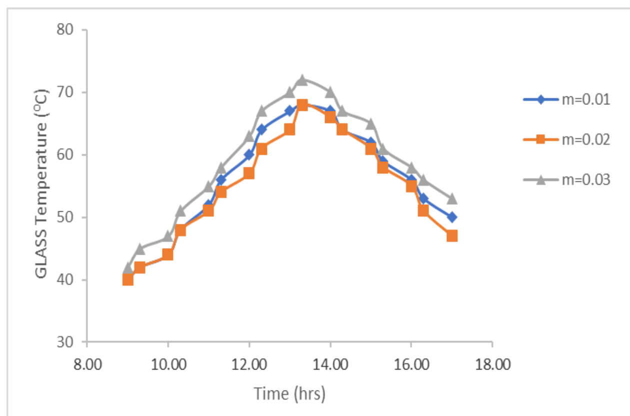

Fig. 6 (a) Glass cover Temperature vs. time for SAH without baffle

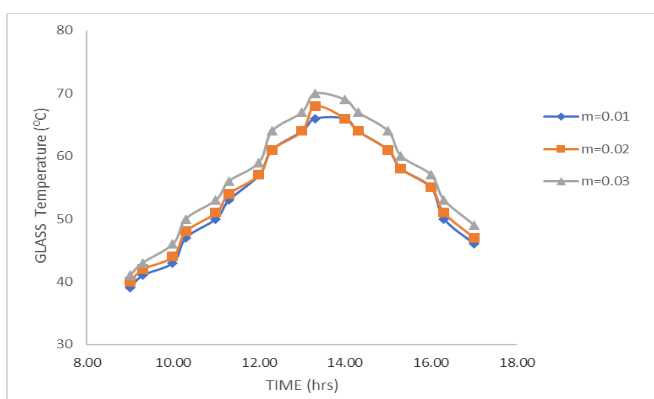

Fig. 6 (b) Glass cover Temperature vs. time for SAH with baffle

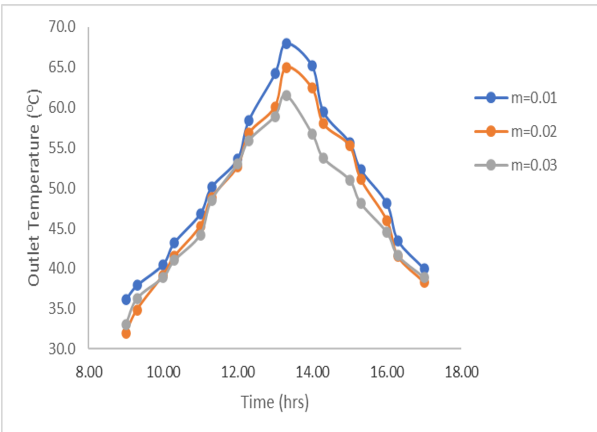

Fig. 7 (a) Air Output Temperature vs. time for SAH without baffle

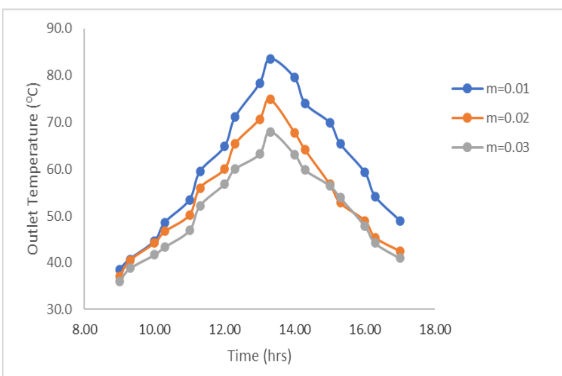

Fig. 7 (b) Air Output Temperature vs. time for SAH with baffle

The amount of energy gained from the system determines the efficiency of a solar air heater. The key factors that decide the amount of energy gains are air flow rate, air density, and temperature differential. As solar radiation increases from morning until 1.30 p.m., the energy gain is also moving in the same way. After that, the energy gain figures start to drop till the completion of the day. Figure 8 depicts the useful energy derived from FSAH and ISAH with mass flow rate over time. The energy gain value increases as the flow rate increases. It also improves the baffled solar air heater's convective heat transfer and efficiency. The system's performance improves as a result. The maximum energy gain is obtained at a mass flow rate of 0.03kg/s, while the lowest is obtained at a mass flow rate of 0.01kg/s. At flow rates of 0.01, 0.02, and 0.03 kg/s, the highest daily energy gain for FSAH is 166.77, 303.74, & 387.87W, respectively. In contrast, the maximum daily energy gain for ISAH is 268.02, 419.73, & 507.93W.

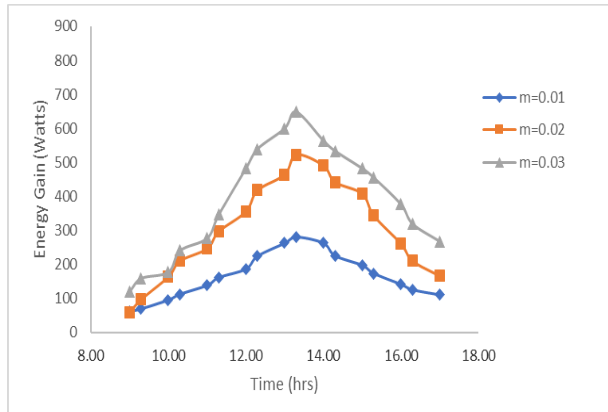

Fig. 8 (a) Useful Energy Gain vs. time for SAH without baffle

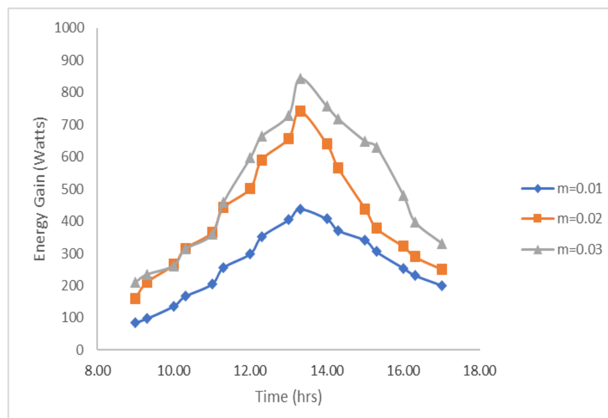

Fig. 8 (b) Useful Energy Gain vs time for SAH with baffle

Figure 9 depicts the average energy gain value for the tested day at various airflow rates. Average useful energy derived from SAH without baffle on a particular day is 166.77, 303.74, and 387.87 W, respectively, at flow rates of 0.01, 0.02, and 0.03 Kg/s, whereas the value for SAH with incline baffle is 268.02, 419.73, and 507.93 W for the same flow rate. It shows that the average useful energy gain value of SAH with baffle is 37.7 %, 27.63 %, and 23.63 % more than SAH without baffle.

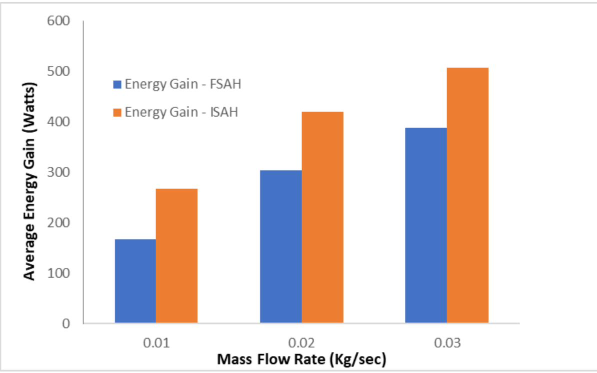

Fig. 9 Average Energy Gain of Both SAH vs. mass flow rate

A solar air heater's top heat loss substantially impacts its performance. As a result, establishing the top heat loss of the recommended solar air heater system is critical. Top heat loss is also used in the same pattern as energy gain. It improves until the afternoon before starting to decline till the end. Figure 10 shows the heat loss over the top surface of SAH without baffle and SAH with baffle over time for different mass flow rates. As shown in the figure, the top heat loss of a flat SAH is higher than the SAH with the baffle. The flat solar air heater's temperature range is narrower than the baffled air heater, resulting in superior losses at the system's top surface. Due to less air outlet temperature of flat SAH than the baffled SAH, air heater without baffle loses more heat from the system. The glass and ambient temperatures play a significant role in determining the top loss value.

At a flow rate of 0.03kg/s, the largest top loss for FSAH is reported during the experiment day. The lowest and maximum top heat loss values for an FSAH are 158.8 and 644.5 W, respectively. Figure 11 depicts the average top heat loss at various airflow rates. For flow rates of 0.01, 0.02, and 0.03kg/s, the average top heat loss of SAH without baffle is 418.65, 431.93, and 461.63W, respectively. For the same assessed flow rates, ISAH drops 384.3, 403.6, and 426.5W across the top surface of the system. SAH with baffle has a higher average top heat loss than the conventional air heater, at 8.20 %, 6.55 %, & 7.65 %, respectively.

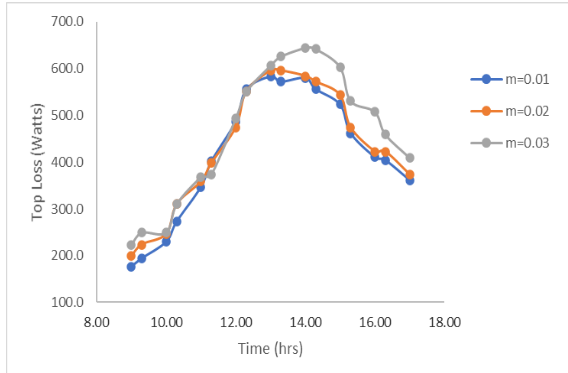

Fig 10. (a) Top heat loss vs time for SAH without baffle

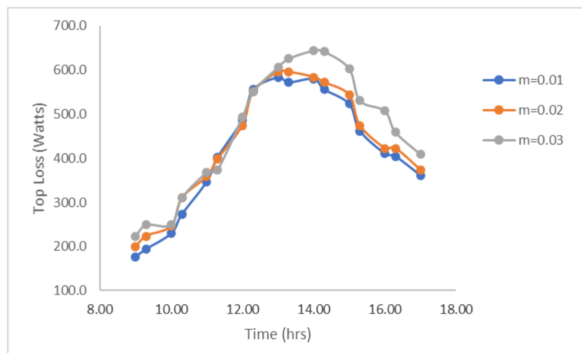

Fig 10. (b) Top heat loss vs time for SAH with baffle

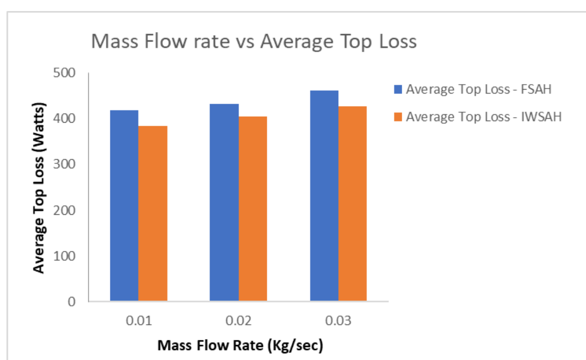

Fig. 11 Average Top heat loss vs mass flow rate

When selecting a system for various applications, the efficiency of that system is a crucial aspect to consider. The amount of energy gained, the amount of solar radiation received, and the size of the system are the key determinants. The change in thermal efficiency over time for varied mass flow rates is depicted in Figure 12. The use of baffles in the system allows the air to be stored for longer. The heat transfer from the solar collector to the working fluid (Air) is improved. Because of this, the FSAH have a lesser efficiency than the ISAH. SAH's thermal efficiency rises during the day, peaking in the afternoon. Collector plates and other devices absorb and recover heat during the experiment due to the mooring effect before supplying it to the air. This method is used to advance the system's efficiency. With higher airflow rates, the efficiency value increases. SAH reaches its maximum and minimum efficiency values for the flow rate of 0.03kg/s and 0.01kg/s, respectively. The highest and least efficiency values for baffled solar air heaters for a day are 85.1 % and 19.8 %, respectively, and 61.4 % and 11.6 % for flat plate solar air heaters. During the afternoon session, FSAH with flow rates of 0.01, 0.02, and 0.03kg/s had peak efficiency of 24.1 %, 45.6 %, and 58.0 %, respectively. For the same flow rate, the highest efficiency of an ISAH is 37.5 %, 64.7 %, and 75.5 % per day.

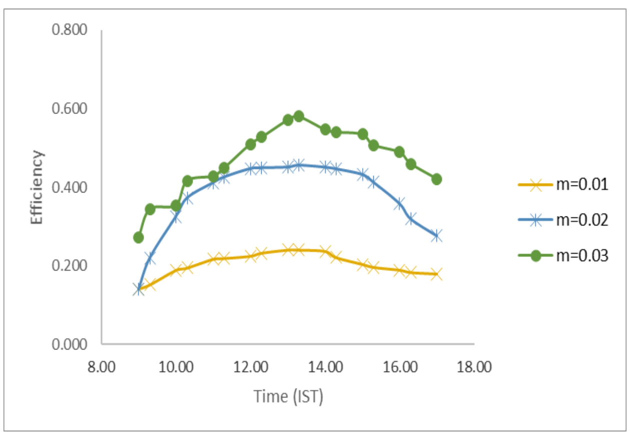

Fig. 12 (a) SAH Efficiency without baffle vs. time

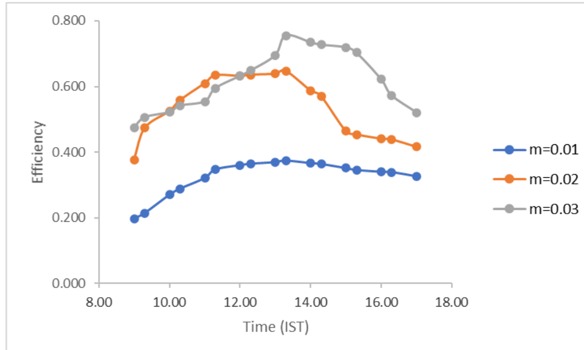

Fig 12. (b) SAH Efficiency with baffle vs. time for SAH

Figure 13 represents the average efficiency attained by SAH for different airflow rates over the experiment's days. For airflow rates of 0.01, 0.02, and 0.03kg/s, respectively, the average thermal efficiency of FSAH is 20.4%, 37.7%, and 46.8 percent. ISAH's average thermal efficiency is 32.6%, 53.6%, and 61.9% for the same airflow rates. This range is higher than the FSAH by 37.4 percent, 29.6 percent, and 24.39 percent. According to the findings, increasing the airflow rate improves the SAH's efficiency and heat transfer rate.

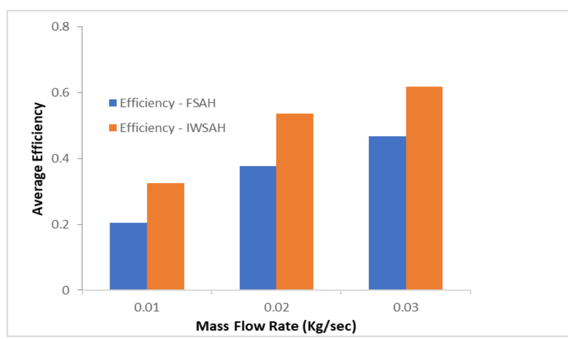

Fig. 13 Average efficiency vs. air mass flow rate

Table 2 presents a comparative study of ISAH results with available designs. It is self-evident that the proposed Baffles considerably increase SAH system efficiency.

Table 2 Comparative study of ISAH with available designs

Author	Baffle types	Results
ISAH	Incline baffles	The highest average thermal efficiency value of ISAH is 61.9%.
(Abo-Elfadl et al. 2020)	Conductive aluminium tubes	The average efficiency of the double pass TSAH -41%
(Singh et al. 2019)	Fully-developed serpentine wavy channel	Maximum thermal efficiency - 66%
(Hegazy et al. 2020)	Hybrid PV/T double-pass finned plate	Highest thermal efficiency - 64%.

6. Conclusions

In this experiment, the performance of a solar air heater without a baffle setup is compared to that of a SAH with Incline baffles. The influence of baffles on the system's top heat loss, energy gain, and efficiency is explored by adjusting mass flow rates. As a result of the research, the following results are reached.

The solar air heater performance is increased by adding Incline baffles over the collector plate. The performance of the SAH system is enhanced as the inlet airflow rates are raised. SAH's useful energy gain and efficiency are maximized by increasing airflow rates while lowering output temperature. Air mass flow rate of 0.03kg/s results in the most significant energy gain and efficiency increase.

The suggested SAH with Incline shape baffles delivers 16.44 %, 10.29 %, and 7.78 % higher output temperature than the air heater without baffle for the investigated flow rates.

Incline shape baffle's maximum average energy gain is 268.02, 419.73, and 507.93 W, respectively. It is 37.7 %, 27.63 %, and 23.63 % more efficient than a solar air heater without baffle arrangement for 0.01, 0.02, and 0.03kg/s air flow rate.

The suggested system has reduced heat losses over the top surface than a SAH without baffles, with system losses of 8.20 %, 6.55 %, & 7.65 % heat over the top surface. The suggested ISAH improves the system's average thermal efficiency by 37.4 %, 29.6%, and 24.39 % for identical airflow rates compared to the SAH without baffle. With an airflow rate of 0.03kg/s, the modified system gives the highest day efficiency of 75.5 % and the maximum average thermal efficiency of 61.9 %.

Nomenclature

SAH Solar Air Heater
ISAH Incline baffles solar air heater
EPT Energy Payback Time
FSAH Solar Air Heater with Flat plate (Smooth surface)
LCCE Life Cycle Conversion Efficiency
E_{out} Energy output (kW h/yr)
E_{in} Total Embodied energy (kW h)
E_{sol} Total solar radiation (KWh)
I Solar radiation [W/m^2]
T Temperature [K]
T_1 Input Air Temperature [K]
T_2 Output Air Temperature [K]
T_g glass surface temperature [K]
T_a Air Atmospheric temperature [K]
T_s Temperature of Sky [K]
m Rate of flow [kg/s]
Q_{out} Heat Energy gain [W]
Q_{in} Heat energy supplied [W]
Q_t Heat loss from Top [W]
h Heat transfer coefficient [W/m^2 K]
h_w Top convection heat transfer Coefficient [W/m^{2}K]
h_r Radiation heat transfer coefficient [W/m^{2}K]
C_p Specific heat of air [J/kg K]
V Average air velocity [m/s]
V_w Wind Velocity [m/s]
A Area of absorber [m^2]
η SAH Efficiency [%]
Nu Nusselt Number
Re Reynolds Number
ρ Density [kg/m^3]
F Friction Factor
ε Emissivity of glass
G Total incident solar radiation [W/m^2]
σ Stefan Boltzmann constant [W/m^{2}K]

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