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ENERGY, EXERGY, AND SUSTAINABILITY ASSESSMENT OF MODIFIED SOLAR AIR HEATER CONFIGURATIONS

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ABSTRACT

This study is an experimental study that compares the thermo-hydraulic, energetic and sustainability efficiency of finned and unfinned solar air heaters which work under the same climatic conditions. Both configurations were also experimented concurrently during a typical sun day (09:00-16:00) encountering four mass flow rates of 0.0383 to 0.06 kg/s⁻¹. The finned heater reached its highest temperature gain of 10 °C, which is a 67-percentage point higher compared to the unfinned system, and reached a thermal efficiency of 56 percent. On the other hand, the unfinned design had a greater exergy efficiency (0.99>5%) and a sustainability index of 5.8 at high flow rates. Together, the findings suggest finned designs have a better performance at lower flow rates, and unfinned systems can be used to implement high-output, applications focused on sustainability.



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I. INTRODUCTION

With growing global emphasis on renewable energy, solar air heaters (SAHs) are gaining popularity as simple, sustainable devices used to harness solar radiation for air heating applications. These systems are widely used in space heating, crop drying, and industrial processes due to their low operational cost and eco-friendliness[1]. World is using fossil fuels as a major energy source for a long period of time[2]. The depletion of fossil fuel along with the environmental issues, climate change, global warming, air pollution and greenhouse gasses have highlighted the need to switch to renewable energy sources in the future[3], [4]. Particularly, Solar energy can be considered as a viable option due to its availability to replace the traditional sources[5], [6]. Solar radiations of 174,000 TW from the sun, makes solar energy as the most important renewable energy source[7]. This amount of solar energy can be utilized to for air conditioning and electrical power generation[8]. Heating the air with help of solar radiations using solar air heaters(SAHs) for space conditioning or drying is one of the most promising application of solar energy[9].

A solar air heater is a mechanical device which transform solar radiations into thermal energy[10]. A solar air heater (SAH) consists of a black absorber plate, air passage, glass cover, insulated frame and a blower/fan to drive air flow inside the passage. The solar radiations are absorbed by the absorber and a convective heat transfer heats the air in contact with the absorber. Insulation limits the heat losses to the surrounding[11], [12]. The components of solar air heater define the its effectiveness. Among them, the design of absorber plate is crucial for the energy conversion process[13]. Different studies have been conducted for enhancing SAHs performance by changing design of the absorber plate[14], [15]. Using an artificial roughness on the absorber plate can offer the better performance as compared to the plain plate absorbers.

Many researchers have reported the enhancement in the overall performance of solar air heater by implementing various type of artificial roughness, baffles, fins, ribs, turbulators etc. The roughness of surfaces on the plate absorber has the potential to enhance convective heat transfer between the absorber and the incoming air. This is as a result of the fact that the convective resistance to heat transfer is proportional to the thickness of the thermal boundary layer[16]. Roughened surfaces act as a flow breaker, to reduce the resistance of the convective heat transfer; they also enhance turbulence and extend the residence time of the air in the SAH, and thus the amount of heat collected by the air increases. But such phenomenon also causes one more drop in pressure[17]. Shayan et. al. studied the effect of using s-shaped ribs on solar heater absorber. The result suggested that Nusselt number can be increased by 4.2 times as compared to plan surface[18].

In addition to the above benefit of using artificial roughness in augmentation of the convective heat transfer, using the fin arrays as an artificial roughness can offer an increase in the heat transfer area and hence improve the heat transfer rate[15]. Solar air heater performance can be enhanced by the fins' proportions, shape, and arrangement. Wavy fins, spherical fins, herringbone corrugated fins, longitudinal fins, louvred fins, pin fins, and other forms of fins have all been studied in an effort to enhance SAH performance[19]. Vengadesan et al.[20] evaluated the effectiveness of SAH coupled with a unique fin combination on its absorber. Together with V-corrugated fins, the fins were continuous, distinct rectangular tubes. The continuous finned absorber's Nusselt number and friction factor were found to be 44.6% and 15.3%, respectively, greater than those of the plain absorber. In addition, the discrete finned absorber's Nusselt number and friction factor were 100% and 28.2% greater, respectively, than the plain absorbers. Various rib roughness parameters also affect the heat transfer and fluid flow process[21]. Changes in the absorber plate design and modification also affect the economic analysis of SAHs[22].

Thermal performance of wavy finned solar air heater can be enhanced by using different fins spacings[23], [24]. The literature review indicates the effectiveness of the use of fins, baffles, ribs and additional elements of artificial roughness in solar air heaters (SAHs) to enhance the thermal performance due to an increase in the heat transfer surface, disruption of the thermal boundary layer, and the development of turbulence in the air channels. It also demonstrates that the size of performance enhancement highly depends on the geometry, orientation and configuration of such augmentative features. However, there is a lack of researches on vertical absorber designs, and the relative effectiveness of finned and unfinned designs is a topic that is not properly explored. The major questions of this experimental study are therefore: (i) to test and determine the thermal efficiencies of vertical absorber SAHs against fins and unfinned at different air flow rates; (ii) to test the effect of including fins in the design on the rise in temperature, useful energy output, and thermal efficiency during the diurnal cycle; and (iii) to provide a complete performance analysis that outlines the practical benefits of using fins in design as compared to unfinned designs

II. MATERIALS AND METHODS

II.1 METHODS

The experimental setup as shown in figure 1 consists of an aluminium tube with aluminium fins inside and without fins to improve heat transfer. A blower is kept at the bottom of the apparatus to enable airflow through the system. Reflective panels are placed around the aluminium apparatus to focus solar radiation onto the apparatus, improving heat absorption. The blower forces air into the base of the setup, where it is periodically heated by the solar radiation. The temperature change of the air at the top is measured to determine the system's effectiveness. To understand precise thermal differences, thermocouples are attached to various points on the setup to record temperatures. The apparatus is exposed to direct sunlight for a period of one to two days to ensure steady heating conditions. The experiment is conducted both with and without the presence of chips inside the system to analyze differences in thermal performance. To promote optimize heat absorption, the entire apparatus is painted black, minimizing reflectivity and enhancing thermal efficiency.

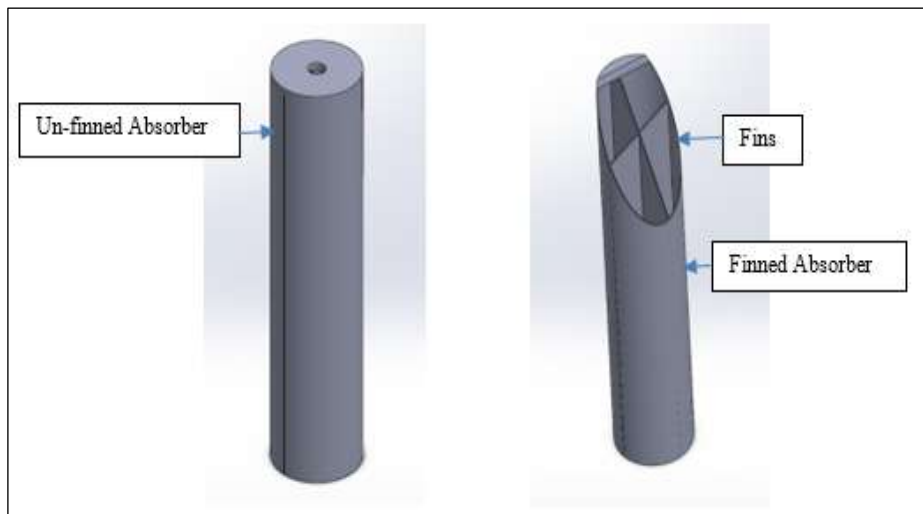


Figure 1: Schematic of the test setup used in this study.
Source: Authors, (2026).

Table 1: Characteristics of solar air.

Components of VSAH	Type Of Material	Material requirement size (mm)			Quantity	Final Size (mm)
		W/D	L	T		
Vertical cylindrical absorber	Aluminum (Coated with black paint)	250	1180	2	1	ø250 x 1180
Fins	Aluminum	123	1180	2	4	123 x 1180
Cap	Aluminum	250	20	2	1	250 x 20
Mirrors	Glass, Transmittivity (0.9), Emissivity (0.85)	500	500	4	4	500x500

Source: Authors, (2026).

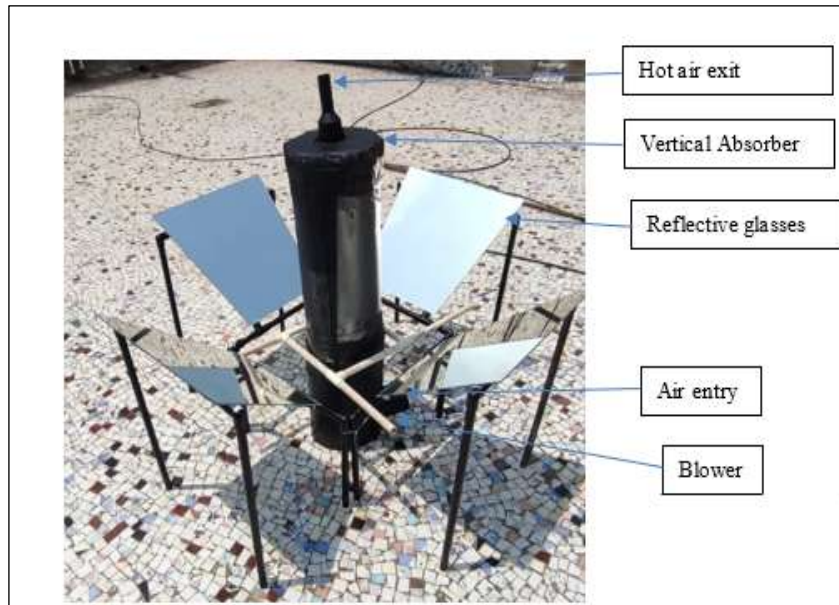


Figure 2: Experimental set up
Source: Authors, (2026).

To guarantee a comprehensive understanding of the performance of the vertical solar air heater, a series of measured experiments are conducted under varying conditions. The influence of ambient temperature, solar intensity, and airflow rate on the efficiency of the system is learnt in detail. The thermocouples are tactically located at the inlet, outlet, and along the aluminium tube to deliver precise temperature interpretations. These data points permit for the determination of heat gain, efficiency, and thermal losses in the system. Table 2 indicate the details of measuring instruments used for the experimentation. The blower speed is attuned in increases to analyze the effect of airflow rate on heat transfer effectiveness. By comparing results attained with and without aluminium chips, the study aims to gauge their role in boosting thermal performance by increasing the applicable surface area for heat exchange. The use of reflective mirrors in the setup is particularly important, as it enables the system to collect more solar radiation than it would otherwise. By directing sunlight onto the absorber, the mirrors help to increase the amount of thermal energy collected by the system, and thus improve its efficiency. Table 1 shows detailed information about the characteristics of two solar air heater set up.

II.1.1 Experimental Procedure

1. Throughout the study, data was collected on an hourly basis for a range of variables, encompassing air flow rate, solar radiation, ambient temperature, as well as inlet and outlet air temperatures. Additionally, measurements were taken for the temperature of air inside the SAH and the absorber cylinder at multiple selected locations.
2. Copper–constantan thermocouples are utilized to measure the temperatures of air inside the SAH.
3. In the SAH (Solar Air Heater) system, precise temperature measurements are crucial for efficient operation. To achieve this, a thermocouple is strategically positioned at the centre of the inlet section to accurately measure the temperature of the incoming air. This meticulous approach ensures accurate and reliable temperature data, enabling effective monitoring and optimization of the SAH system's performance.

III. RESULTS AND DISCUSSIONS

The results of vertical absorber solar air heater were recorded for various days of October 2024. Experimentations were carried out from 9 am to 4 pm on two examined vertical absorber SAH at various flow rates at Vile Parle, Mumbai Maharashtra (19.0968° N, 72.8517° E).

Table 2: Details of the measuring instruments.

Instrument	Function	Accuracy
Solar power meter	Measures solar radiation	intensity $\pm 0.5 \text{ W/m}^2$
Thermocouples (Type K)	Measures temperature	$\pm 1 \text{ }^\circ\text{C}$
Temperature digital meter	Displays temperature	$\pm (0.05\% \pm 0.3 \text{ }^\circ\text{C})$
Selector switch	Switches instruments	0.05%
Hot-wire anemometer	Measures air velocity	$\pm 0.3\%$

Source: Authors, (2026).

III 1 VALIDATION OF THE EXPERIMENTAL SETUP

The experimental results were validated using the values of the average Nusselt number and friction factor for SAH with plain absorber plate were compared to the results estimated from Dittus-Boelter correlation Eq.1 for and Blasius correlation Eq. 2 [25] for Fig.(1) present the validation, it can be seen that percentage of error of the current experimental results with the results of correlation varied in the range of 8.33% to 20.00% for and 11.76% to 14.29% for . Those deviations are well agreed with the validations reported in other studies[20][25]. This confirms the accuracy and validation of the experimental set up used to carry out the investigation.

$$Nu_u = 0.023Re^{0.8} \times Pr^{0.4} \quad (1)$$

$$f = 0.023Re^{-0.25} \quad (2)$$

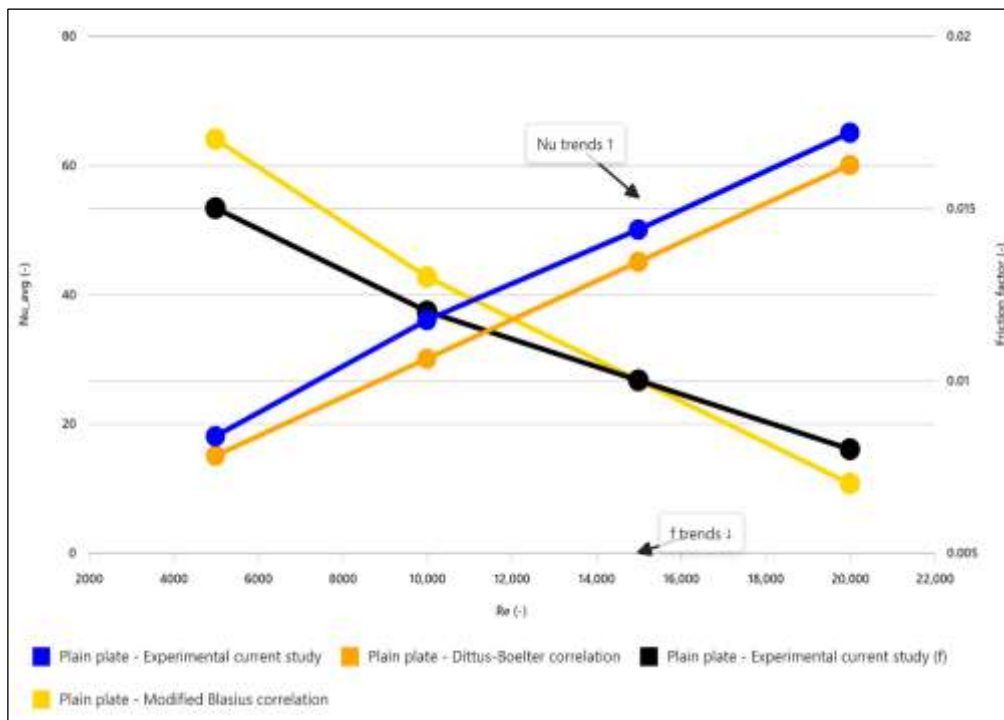


Figure 3: Validation of experimental data with results calculated from correlations.
Source: Authors, (2026).

III. 2 SOLAR RADIATION AND TEMPERATURE DIFFERENCE

As can be seen based on the Figure 1, the temperature difference observed is significantly high compared to the Figure 2 that illustrates unfinned systems at all the mass flow rates considered. The highest ΔT in the finned mode is of the order of 10 degrees Celsius at noon with the lowest flow rate (0.0333 kg s⁻¹) and this is identical to the coincident maximum in the unfinned setup at 6 °C. Such difference implies that finned equipment's enhance heat transfer through the increase in the heat-exchange surface area. Further, the mass flow rate increases causing ΔT to decrease within both setups, a result expected owing to rising flow velocities which reduce the residence time of the fluid hence limiting its thermal absorption potential. However, this reduction is emphasized more strongly in the finned system, which suggests that the most effective fins in the system are realized at low flow rates. Overall, the thermal performances of fins inclusivity are better, especially in the midday sun axis and when the flow is of low magnitude.

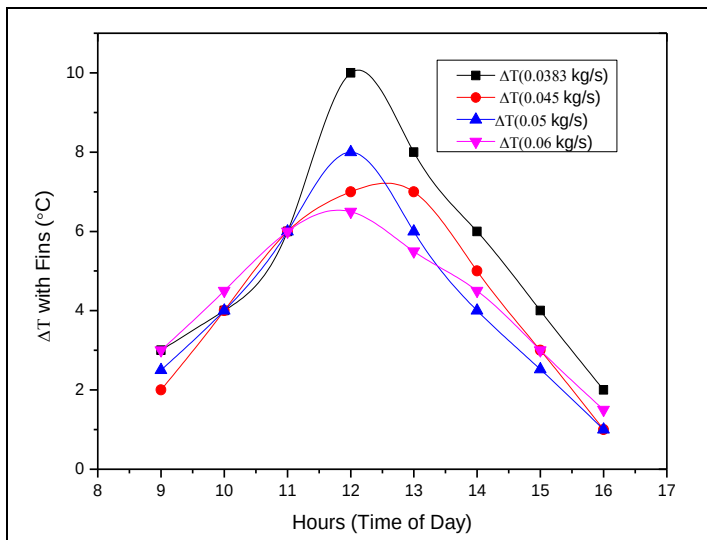


Figure 4: Hourly variations of the temperature difference for the finned SAHs at various AFRs.
Source: Authors, (2026).

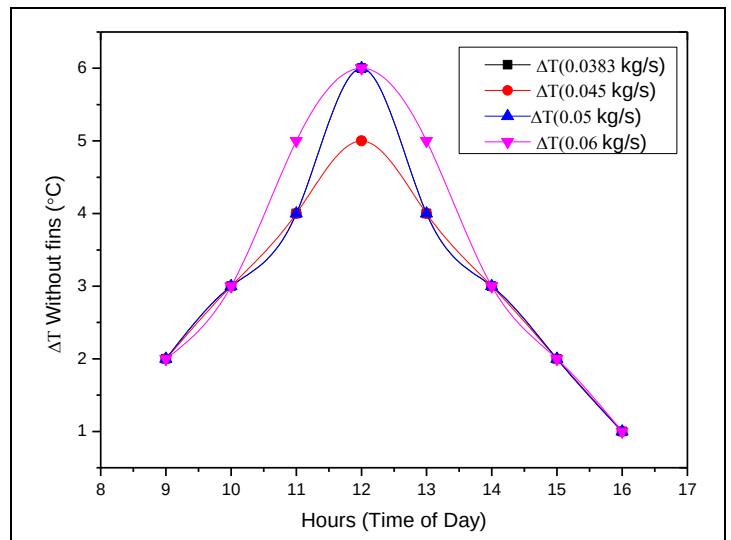


Figure 5: Hourly variations of the temperature difference for the unfinned SAHs at various AFRs.
Source: Authors, (2026).

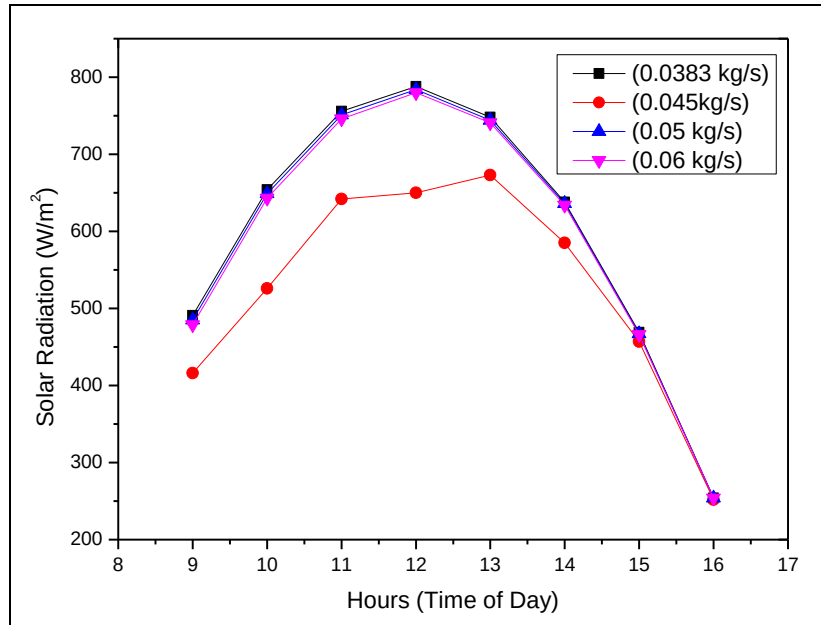


Figure 6: Hourly variations of the solar radiation during the operating hours.
Source: Authors, (2026).

III. 3 ANALYSIS OF SOLAR RADIATION TREND:

Change in solar radiation as shown in Figure 3 through the day shows that the curve is canonical or forms a bell shape, and peaks probably around solar noon. The solar intensity peaks at 09:00 with an intensity of around 420 to 500 W/m^2 and then starts to rise gradually to reach 780-800 W/m^2 at 12:00 and afterwards reducing gradually up to 250-300 W/m^2 at 16:00. The curves of various rates of mass flow overlap nearly completely, thus establishing the fact that the radiation of the sun is basically independent of the mass flow rate rate, and it is mostly determined by the weather conditions and sun location. The effect of this trend on thermal and exergy performance is that all parameters of system efficiency and heat gain follow the same pattern of irradiance. The maximum radiation (11:00 and 13:00) coincided with the maximum thermal efficiency, useful heat gain and sustainability index serving as a guide in the previous figures hence the reason as to why it is necessary to take the machine at these times to have the best performance.

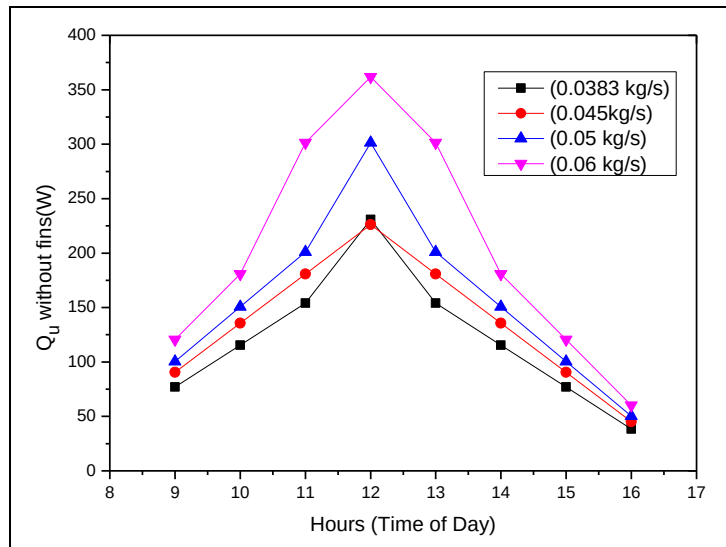


Figure 7: Hourly variation of the daily useful power for the unfinned SAH.
Source: Authors, (2026).

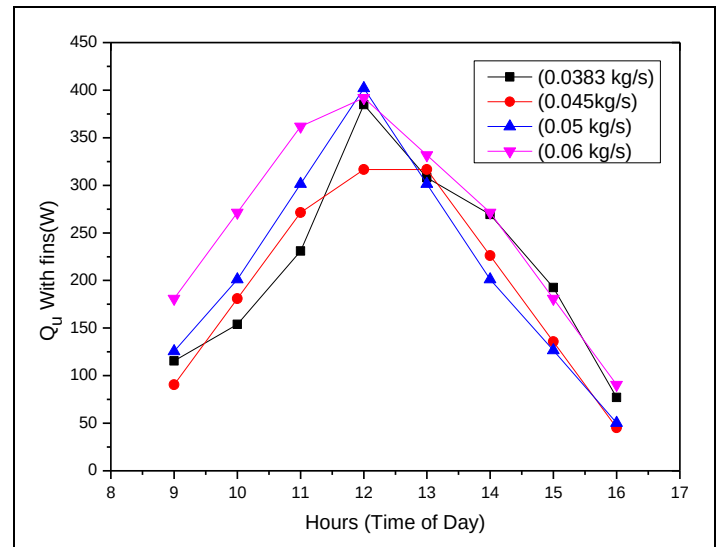


Figure 8: Hourly variation of the daily useful power for the finned SAH.
Source: Authors, (2026).

III.4 COMPARATIVE ANALYSIS OF USEFUL HEAT GAIN (QU):

The two arrangements Figure 4 and Figure 5, exhibit a similar diurnal cycle, with the percent of useful heat gain gradually increasing in the morning, reaching its peak at solar noon, then decreasing in the late-afternoon hours. Nonetheless, the flow-rate rank and the magnitude vary. The optimum Q_u in the unfinned setup will be at 0.06 kg/s -1, which will reach levels of about 360 W at noon, 0.05 W -1 (300 W), 0.0383 W -1 (190 W), etc. However, the finned configuration has a slightly higher peak values of mid-range flow rates with 0.05 kg/s -1 and 0.06 kg/s -1 being more than 400 W by comparison and lower flow rates also increase out of better heat transfer by fins. This implies that the visible advantage of fins is realized at low and moderate levels of flow as they enhance the turbulence and area of heat transfer but the same cannot be said at high flow levels since the advocacy between configurations is reduced. In general,

fins enhance thermal responsiveness and expand the working range of functions and therefore are applicable to applications that require a greater rise in temperature and a steady increase in heat gain at the best solar hours.

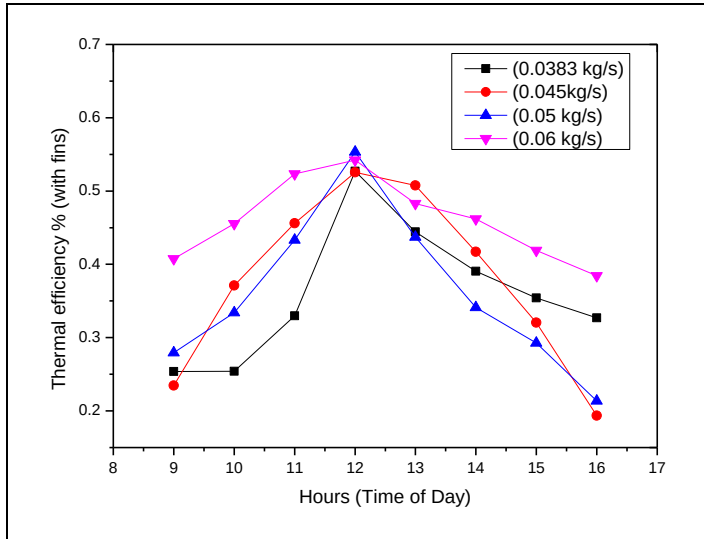


Figure 9: Hourly variations of the thermal efficiency of finned SAH

Source: Authors, (2026).

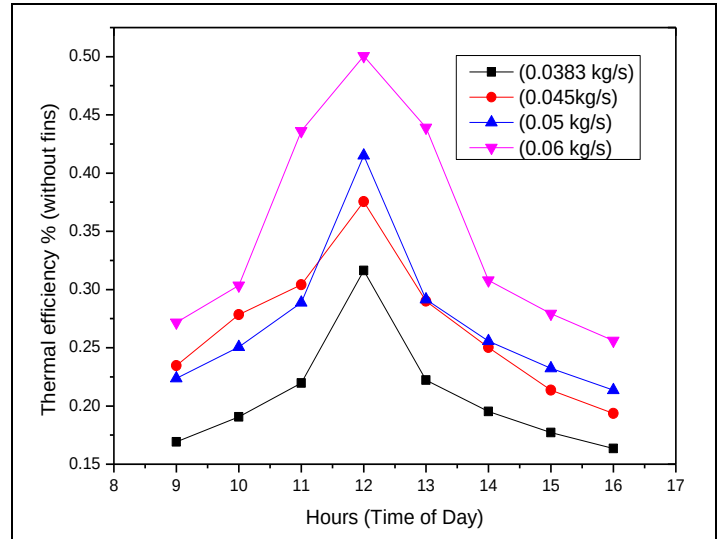


Figure 10: Hourly variations of the thermal efficiency of unfinned SAH

Source: Authors, (2026).

III.5 COMPARATIVE ANALYSIS OF THERMAL EFFICIENCY:

Thermal efficiency as shown in Figure 6 and 7, is increased at the beginning of the mornings, peaks near the solar noon and then reduces later in the afternoons. However, the absolute magnitudes as well as the hierarchy of the flow rates are very different. The apex efficiencies of about 0.56 are achieved at a mass flow rate of approximately 0.05kg s to the minute and then about 0.55 at 0.06kg s to the minute; the other flow rates have intermediate efficiencies of about 0.52 at 0.0383kg s to the minute and 0.53 at 0.045kg s to the minute. In contrast, the unfinned design has a peak efficiency of about 0.50 at 0.06 -1kg/s and the next value, which is about 0.42, at 0.05 -1kg/s. These experimental findings indicate that thermal performance can be significantly improved by the presence of fins, particularly in the mid-range flow rates, by increasing the amount of heat-transfer area and increasing the turbulence. As much as both systems follow the temporal pattern determined by the level of solar irradiance the finned design continues to demonstrate superiority over the unfinned one in all the flow rates that are investigated, making it better suited to any application that demands high thermal efficacies in peak sunlight periods.

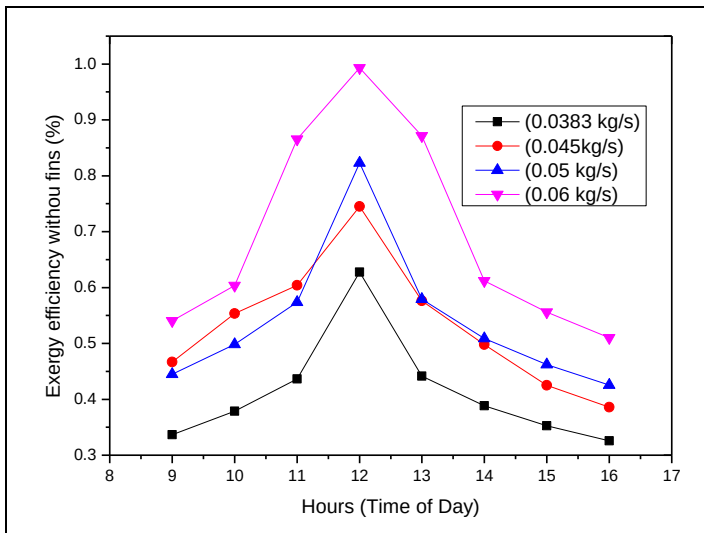


Figure 11: Hourly variation of exergy efficiency during operating hours for unfinned SAH.

Source: Authors, (2026).

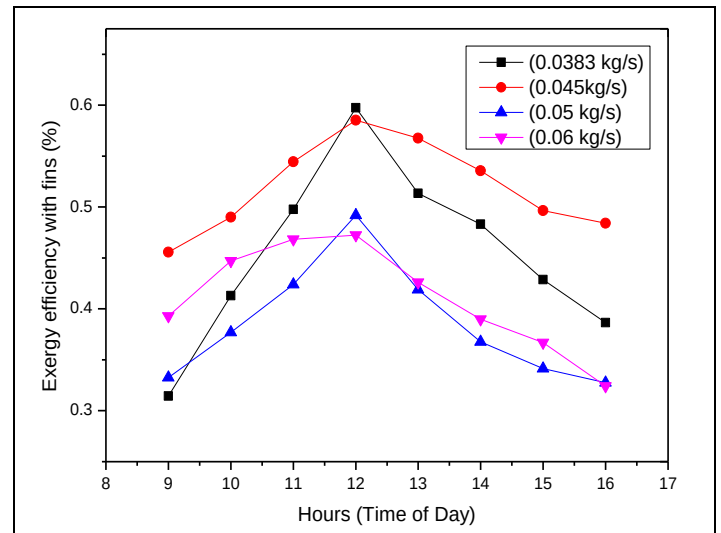


Figure 12: Hourly variation of exergy efficiency during operating hours for finned SAH.

Source: Authors, (2026).

III.6 COMPARATIVE ANALYSIS OF EXERGY EFFICIENCY

Relative change of exergy efficiency of finned and unfinned solar air heaters during a day was also studied at various mass flow rates (0.0383, 0.045, 0.05 and 0.06 kg s⁻¹) as shown in Fig. 8 and 9. The two settings are similar in terms of a diurnal trend, which is characterized by gradual increasing trend in the mornings, a steep rise around solar noon (12:00 -12:00), and a subsequent decay to late afternoons, which are based on the background solar irradiance pattern.

However, the ranking of the performance differs: unfinned systems are favoured to reach higher flow rates, with 0.06kg/s^{-1} reaching the largest peak exergy efficiency ($\sim 0.99\%$), and finned systems being able to make good performance in the lower flow rate ranges, with 0.045kg/s^{-1} and 0.0383kg/s^{-1} getting the largest peak efficiencies near $0.60\text{--}0.62\%$ each. This contradiction can be explained by the fact that the fins allow improving the heat transfer during lower velocities and, therefore, preserve high outlet temperature and support the second-law performance. The average efficiencies of the unfinned and finned devices are approximately 0.41 and 0.71 per cent/day, respectively, which further supports the need to optimize based on the objective of the design, respectively.

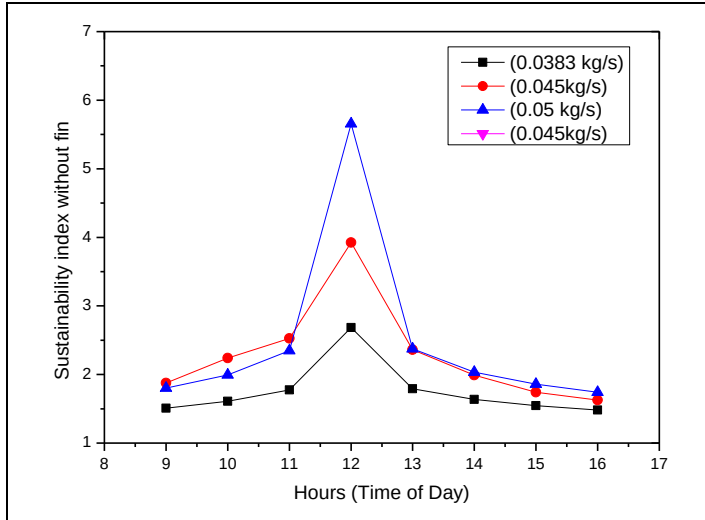


Figure 13: Hourly variation of Sustainability Index (SI) during operating hours for unfinned SAH.
Source: Authors, (2026).

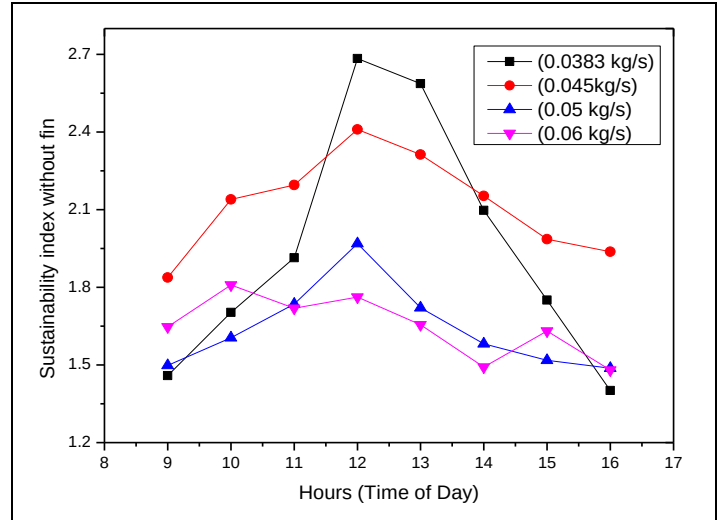


Figure 14: Hourly variation of Sustainability Index (SI) during operating hours for finned SAH.
Source: Authors, (2026).

III.7 COMPARATIVE ANALYSIS OF SUSTAINABILITY INDEX

A comparison of the relative change of the Sustainability Index (SI) between finned and unfinned solar air heating systems at four discrete mass flow rates (0.0383 , 0.045 , 0.050 and 0.060 kg/s^{-1}) over a canonical solar day ($09:00$ to $16:00\text{ h}$) Fig. 10 and 11 indicates that the two systems are consistent in their diurnal patterns: the SI rises in the morning, reaches a strong peak around solar noon (around $12:00\text{ h}$) and decays in the afternoon. The absolute magnitude and the ordinal ranking, however, are very different; the unfinned system has a peak SI of about 5.8 at a mass flow rate of 0.050 kg s^{-1} , which is very high and thus signals a better overall sustainability performance as compared to the finned counterpart that has a peak SI of about 2.7 at 0.0383 kg s^{-1} . It can be explained by the higher value of the disparate peaks due to the extra complications of the material and fabrication that the finned design demands and causes an impact on the calculated sustainability measures. Moreover, the best flow rate choice has a configuration-specific behavior: unfinned systems can achieve the highest SI at moderate flow rates (0.050kg/s^{-1}), but finned systems can also reach their best performance at lower flow rates, in the range of $0.0383\text{--}0.045\text{kg/s}^{-1}$. Such results demonstrate inherent trade-offs between thermal augmentation and the impact on the environment and thus the need to select design techniques that are responsive to application needs.

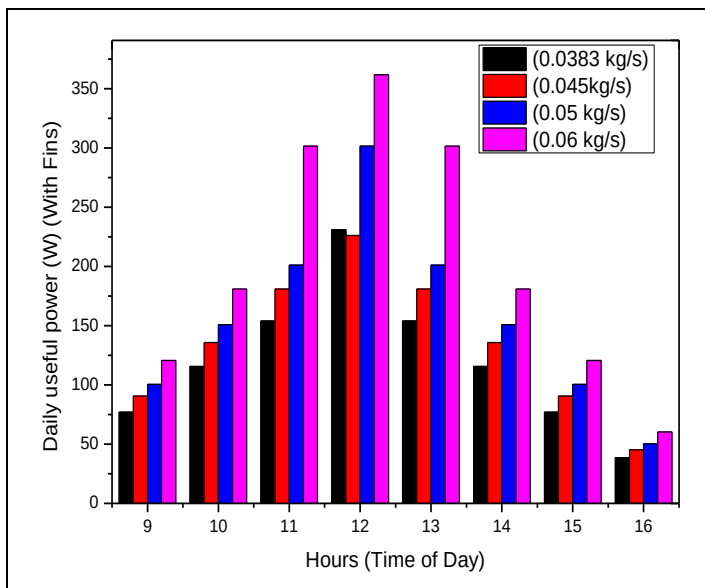


Figure 15: Hourly variations of useful power during operating period for finned SAH
Source: Authors, (2026).

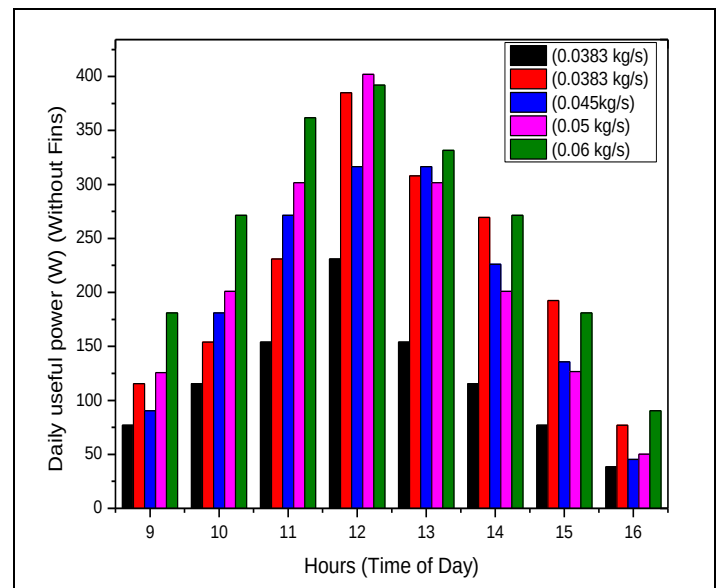


Figure 16: Hourly variations of useful power during operating period for unfinned SAH.
Source: Authors, (2026).

III.8 COMPARATIVE ANALYSIS OF DAILY USEFUL POWER:

Daily useful power output of each of the two configurations as shown in Fig. 12 and 13 follows a diurnal pattern where there is a monotonic increase in the early morning followed by a peaking value in the area around the solar noon and then a decrease towards the end of the afternoons. However, there is a difference in the absolute magnitudes and ranking of the flow rates in finned and unfinned systems. At a mass flow rate of 0.06kg/s -1 the maximum power output is accomplished, and has values of approximately 360 W at noon, 0.05kg/s -1(260 W), 0.0383kg/s -1 (230 W). On the other hand, the unfinned design achieves higher max power outputs, 0.06kg/s-1 and 0.05kg/s-1 respectively being above 400W, and lower flow rates correspond to relatively lower outputs of power. This observation shows that the absolute power production does not significantly increase with the presence of fins at high flow rates but the advantage of fins is instead in terms of thermal efficiency and temperature increase at low flow rates. This means that unfinned systems will produce more useful power given the same operating conditions and thus are more useful in applications where quantity of energy is needed and finned systems is more useful in processes which are temperature sensitive.

IV. CONCLUSIONS

The presented experimental study is a comparative evaluation of finned and unfinned solar air heaters (SAHs) running on the same climatic and operational conditions. It is shown that thermal performance is significantly enhanced with the presence of fins and at reduced mass flow rates. The finned design reached a highest temperature increase of about 10 -1 °C at a mass flow rate of 0.0383 -1 kg -1, in comparison to the highest increase of 6 -1 CO of the unfinned heater. Thermal efficiency also improved with finning to a maximum of 0.56 at 0.05 kg s -1 of flow rate but the non-finned design had a maximum of 0.50. Such advantages can be ascribed to the increased heat-transfer surface and the increased turbulence of the fins. Heat transfer and power generation measures of the two set-ups were in accordance with the incident solar radiation profile, with their maximums achieved around the solar noon. The benefit of finned devices over unfinned devices was highest at low and moderate flow rates because of better heat absorption ability and high absolute useful power output at higher flow rates due to reduced hydraulic resistance and simpler geometry. Trade-offs were found between exergy and sustainability evaluations: the trade-offs were that the unfinned SAHs were more efficient in the second law (maximum 0.99) and sustainability index (6), and the finned systems were advantageous at lower flow rates because of the retained outlet temperature and reduced exergy destruction. Overall, it can be concluded that those finned SAHs are better in the case of the need to achieve high thermal efficiency and temperature lifting at low mass flow rates e.g., in solar drying, preheating and space heating. On the other hand, unfinned SAHs are favourable in uses that place greater emphasis on power output, exergy efficiency and enhanced sustainability performance.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Nilesh Bhojraj Balki

Methodology: Nilesh Bhojraj Balki, Ravi Terkar, Ashish Deshmukh

Investigation: Nilesh Bhojraj Balki, Ravi Terkar, Ashish Deshmukh

Discussion of results: Nilesh Bhojraj Balki, Ravi Terkar, Ashish Deshmukh

Writing – Original Draft: Nilesh Bhojraj Balki

Writing – Review and Editing: Nilesh Bhojraj Balki, Ravi Terkar, Ashish Deshmukh

Resources: Nilesh Bhojraj Balki, Ravi Terkar, Ashish Deshmukh

Supervision: Ravi Terkar, Ashish Deshmukh

Approval of the final text: Nilesh Bhojraj Balki., Ravi Terkar, Ashish Deshmukh

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