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ORIGINAL ARTICLE

Experimental Investigation of Thermal Performance Enhancement in Vertical Absorber Solar Air Heaters Using Fins

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Abstract

Objectives: To compare the thermal performance of vertical absorber solar air heaters (SAHs) designed with and without finned extensions for different air flow rates (AFRs)**. Methods:** Experimental studies were conducted between 09:00 and 16:00 in October 2024 in the Vile Parle, Mumbai, Maharashtra (19.0968°N, 72.8517°E) with four AFRs (0.0383-0.06 kg/s). Change in the temperatures, thermal efficiency and useful energy gain were measured during the experimentation. **Findings:** Vertical absorber with fins consistently outperformed unfinned design. Finned solar air heater achieved peak thermal efficiency of 62 % at 0.045-0.05 kg/s as compared to 50 % for unfinned SAH at 0.06 kg/s. The daily average useful power was raised to 154' W/unit of unfinned to 222 W/unit of finned. Finned designs provided high peak efficiencies throughout the midday and also provided high performance well in the late afternoon, especially in high flow rate. These results support the hypothesis that the geometry of absorbers has a significant impact on the heat transfer performance and energy gained. The findings are in line with literature available and shed light on the best adjustments in the flow rate and efficiency of vertical absorber systems. **Novelty:** The introduction of vertical absorber along with reflective glazing shows that it is possible to improve the efficiency of solar air heaters and increase the amount of energy gained by the thermal system that operate on a sustainable basis with the help of pragmatic use of fins.

Keywords: Vertical absorber solar air heater; thermal enhancement; renewable energy; heat transfer enhancement

1 Introduction

The need to decarbonize thermal processes has prompted a renewed attention in the sphere of solar air heaters (SAHs), in which subtle design criterion related to the geometry of absorber and contrived surface roughness can provide significant performance improvements. However, the effectiveness of such changes in vertical structures has not been explored well. Solar air heaters (SAHs) are cheap, durable and low-cost devices that utilize solar radiation to warm occupied areas, dry farm products and aid supplementary industrial operations [1]. Solar energy can be taken as an alternative to traditional thermal uses in view of the current trends of excessively using fossil fuel reserves and the escalation of environmental problems; climate change, air pollution, and greenhouse gas emissions [2]. Considering the high solar irradiance on the ground, SAHs are an attractive technology toward heating of clean air [3].

This amount of solar energy can be utilized for air conditioning and electricity generation [4]. Heating the air with the help of solar radiation using solar air heaters (SAHs) for space conditioning or drying is one of the most promising applications of solar energy [5]. A solar air heater is a mechanical device which transform solar radiations into thermal energy [6]. A solar air heater (SAH) consists of a black absorber plate, an air passage, a glass cover, an insulated frame, and a blower/fan to drive air flow inside the passage. The absorber absorbs solar radiation, and convective heat transfer heats the air in contact with it. Insulation limits the heat losses to the surroundings [7]. The components of a solar air heater define its effectiveness. Among them, the absorber is the most important component in thermal conversion; it regulates radiation absorption, heat conduction to the air stream passing through, and total heat losses [8]. Therefore, studies have focused on surface augmentation methods, including incorporating ribs, baffles, fins, turbulators and other artificial roughness features to perturb the thermal boundary layer to increase turbulence and increase the effective heat transfer area [9]. Although these techniques can always enhance convective heat transfer (so that large increases in the Nusselt number are obtained in comparison with simple absorbers), they also cause pressure losses that can be attributed to high flow resistance [10]. 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 [11].

In addition to the above benefit of using artificial roughness to augment convective heat transfer, utilizing fin arrays as artificial roughness can increase the heat transfer area and thereby improve the heat transfer rate [9]. 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 [12]. Vengadesan *et al.* [13] 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% greater, respectively, 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 those of the plain absorbers. Various rib roughness parameters also affect the heat transfer and fluid flow process [14]. Changes in the absorber plate design and modification also affect the economic analysis of SAHs [15]. Thermal performance of wavy finned solar air heater can be enhanced by using different fins spacings [16].

Despite these developments, the existing literature is overwhelmingly concerned with standard (mostly horizontal) absorber designs, and the relative effectiveness of vertical absorber designs and finned and unfinned designs in different operating regimes is not well explored. The current experimental research is aimed at filling this research gap by (i) comparing the thermal efficiency of vertical absorber SAHs with and without fins over a range of airflow rates; (ii) determining the effect of fins on the increase in temperature, useful energy output, and efficiency during a diurnal cycle; and (iii) giving a comparative performance analysis that explains practical trade-offs and aids design choices on vertical SAHs.

2 Methodology

The experimental setup, as shown in Figure 1, consists of an aluminum tube with aluminum 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 aluminum apparatus to focus solar radiation onto it, improving heat absorption. The reflective mirrors introduced an effective concentration ratio in the range of 1.12-1.18, increasing the net irradiance on the absorber surface. Although the mirrors enhance the overall solar input, they may also create localised non-uniform hearing zones. This effect was considered in interpreting absorber temperature distribution and the resulting heat transfer characteristics. The blower forces air into the base of the setup, where the solar radiation periodically heats it. 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 one to two days to ensure steady heating conditions. The experiment is conducted both with and without chips inside the system to analyze the differences in thermal performance. To promote optimal heat absorption, the entire apparatus is painted black, minimizing reflectivity and enhancing thermal efficiency.

To ensure a comprehensive understanding of the vertical solar air heater's performance, a series of experiments is conducted under varying conditions. The influence of ambient temperature, solar intensity, and airflow rate on the system's efficiency is thoroughly examined. Depending on the air velocities measured and the internal diameter of the vertical cylindrical absorber, the flow of air flowing in the tube is within the transitional-turbulent flow regime. Reynolds number of the four mass flow rates (0.0383-0.06 kg/s) that were investigated was observed to fall within the range of Re= 9200-14500. The described clear

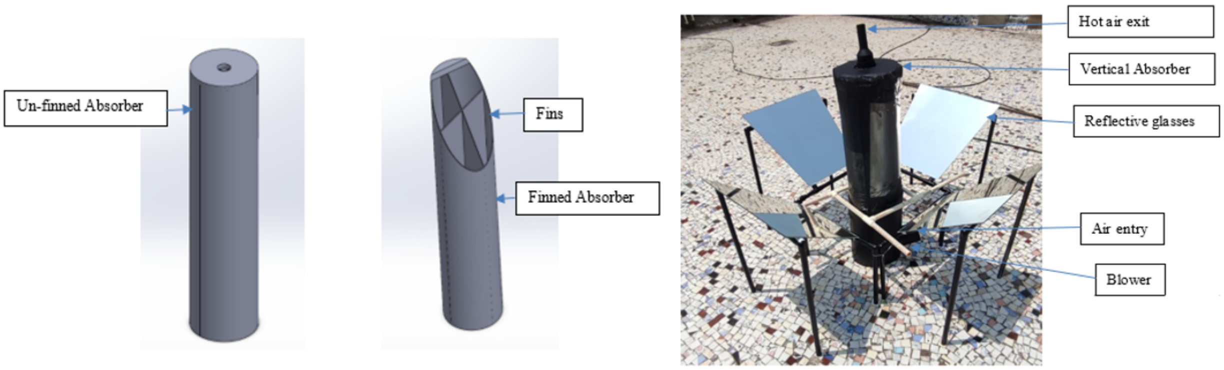

Fig 1. Schematic of the test setup (Unfinned and finned absorber) used in this study.

Table 1. Characteristics of solar air and Measuring instruments

(a) 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

(b) Characteristics of Measuring instruments

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

definition of the flow regime is essential to understand the increase of heat-transfer provided by the finned configuration. The thermocouples are strategically located at the inlet, outlet, and along the aluminum tube to deliver precise temperature readings. These data points permit for the determination of heat gain, efficiency, and thermal losses in the system. Table 1(b) provides details of the measuring instruments used in the experimentation. The blower speed is attuned in increments to analyze the effect of airflow rate on heat transfer effectiveness. By comparing the results obtained with and without aluminium chips, the study aims to assess their role in enhancing thermal performance by increasing the available surface area for heat exchange. The use of reflective mirrors in the setup is significant, as it enables the system to collect more solar radiation than it would otherwise. By directing sunlight onto the absorber, the mirrors help increase the amount of thermal energy collected by the system, thereby improving its efficiency. Table 1 presents detailed information about the characteristics of two solar air heater setups.

2.1 Experimental Procedure

1. Throughout the study, data were 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 of the air temperature inside the SAH and the absorber cylinder at multiple selected locations.
2. Copper–constantan thermocouples are used to measure the temperature of the 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 measure the temperature of the incoming air accurately. This meticulous approach ensures accurate and reliable temperature data, enabling effective monitoring and optimization of the SAH system's performance.

2.2 Uncertainty analysis

The uncertainties in thermal efficiency (η) and useful heat gain (Qu) were estimated using the Root-Sum-Square (RSS) method[17], combining independent measurement errors from temperature (± 1 °C), mass-flow rate ($\pm$0.3%), and solar irradiance ($\pm$0.5 W/m^2). The resulting combined uncertainties were $\pm$4.2% for η and $\pm$5.1% for Qu, indicating that the experimental results remain reliable within acceptable measurement limits.

3 Results and Discussion

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).

3.1 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** and Blasius correlation **Eq. 2**[18]. Figure 2 presents 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. To validate the experimental value of Nusselt number and friction factor, the hydraulic diameter of the absorber used was considered as 0.25 m i.e., the inner cylindrical diameter of the vertical passage. This was a constant in the Dittus Boelter (to the Nusselt number) and Blasius (to the friction factor) correlations so that a correct and reproducible comparison would be possible with existing literature. Those deviations are well agreed with the validations reported in other studies[13]. This confirms the accuracy and validation of the experimental set up used to carry out the investigation.

$$N_u = 0.023Re^{0.8} \times \mathrm{Pr}^{0.4} \tag{1}$$

$$f = 0.023Re^{-0.25} \tag{2}$$

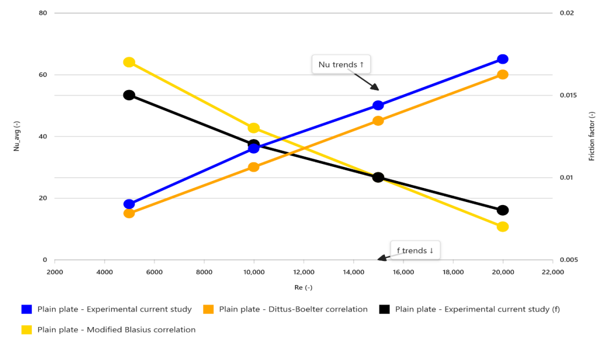

Fig 2. Validation of experimental data with results calculated from correlations

3.2 Solar Radiation and Temperature Difference

The thermal performance of solar air heaters (SAHs) is greatly influenced by the intensity of solar radiations and the temperature difference between the outlet and inlet air streams. experimental data shows that hourly radiation follows a typical daily pattern. It starts at around 320 W/m^2 in the early morning, steadily rises to a peak near 750 W/m^2 around noon, and then gradually decreases towards sunset. This consistent pattern helps in making reliable performance comparisons at different airflow rates (AFRs). The temperature difference which is the difference between outlet and inlet air temperatures, shows a similar trend to solar radiations. Figure 3, shows for a set up with fins, for mass flow rates of 0.0383 kg/s minimum temperature difference is 3°C and maximum 7 °C. For 0.045 kg/s minimum temperature difference is 4°C and maximum 7 °C. For 0.05 kg/s minimum temperature difference is 2°C and maximum 8 °C and for 0.06 kg/s ΔT ranged from 4°C and 8°C. Figure 4, for an un finned SAH for mass flow rates of 0.0383 kg/s minimum temperature difference is 1°C and maximum 6°C. For 0.045 kg/s minimum temperature difference is 2°C and maximum 7°C. For 0.05 kg/s minimum temperature difference is 1°C and maximum 6°C and for 0.06 kg/s ΔT ranged from 1°C and 4°C.

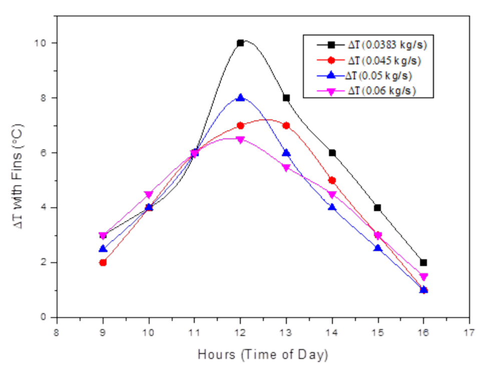

Fig 3. Hourly variations of the temperature difference for the finned SAHs at various AFRs

The analysis shows that solar radiation and temperature difference affect SAH thermal behaviour. Fins greatly increase temperature rise, improving thermal efficiency. These results demonstrate the importance of absorber design in optimising SAH performance across operating conditions.

As shown in Figure 2 and 3, the temperature difference inversely correlated with the AFR, regardless of absorber type. This is because more air received the same heat energy, reducing the temperature difference from the absorber. For example, average temperature difference for Finned SAH with MFR 0.0353, 0.045, 0.05 and 0.06 kg/sec were found to be 5.4, 4.4, 4.3 and 4.2 °C respectively. For unfinned SAH with MFR 0.0353, 0.045, 0.05 and 0.06 kg/sec were found to be 3.1,3,3.1 and 3.3°C respectively.

At all AFRs, absorber finned SAH had the highest temperature difference as its fins acted as vortex generators and delayed flow, giving that flow more time to exchange heat with the absorber.

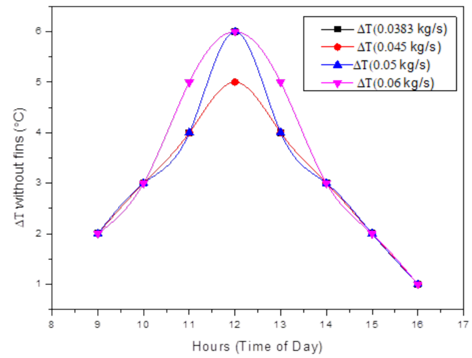

Fig 4. Hourly variations of the temperature difference for the unfinned SAHs at various AFRs

3.3 Energy Analysis

The energy performance of solar air heaters (SAHs) is mainly assessed through the useful energy gain (Qu), which shows the thermal energy absorbed by the air stream. Based on the experimental data, Qu was calculated using Eq. (Number):

$$\mathrm{Qu} = \mathrm{AFR} \times \mathrm{Cp} \times \Delta\mathrm{T} \tag{3}$$

Here AFR is the air flow rate, Cp is the specific heat of air ($\approx$1005 J/kgK) and ΔT represents temperature difference between outlet and inlet air. Thermophysical properties of air including density and specific heat capacity were assumed constant. Qu varied with the hour of the day, following solar radiation. It built through the morning, peaked at midday and declined towards sunset. For unfinned absorbers figure 5, the Qu values were between approximately 39W and 362 W with a mean of 154W, while for a finned absorber figure 6, Qu values were between approximately 45W and 402W with a mean of 222W. Clearly suggesting the better performance by finned arrangement as the heat transfer area increases.

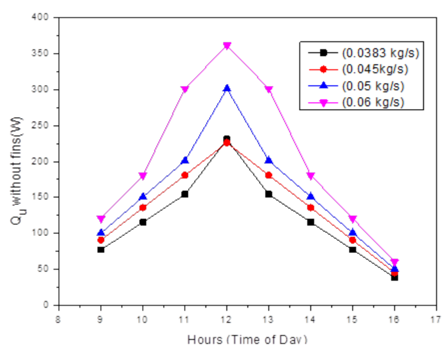

Fig 5. Variation of the daily useful power for the unfinned SAH versus Time of the day

In addition to air flow rate, temperature difference is also main contributor to the useful power gained (**Eq. 6**). The useful power can be greatly affected by the temperature difference at the same AFR. As AFR is were kept constant for each operating day, temperature difference and useful gain follows almost similar trend (Figure 3 and 4). Finned configuration of SAH examined the maximum gained of useful power as 402, 392 and 385 W at mass flow rate of 0.05, 0.06 and 0.0383 kg/s, respectively.

Figure 7 and 8 present variation of thermal efficiency with respect to time of the day for finned and unfinned vertical absorber solar air heater at various AFR. Trend from the figure shows that regardless of the absorber type and AFR, there is an increase in the thermal efficiency during morning hours due to maximum absorption of net energy with relatively small heat losses from SAH to the room temperature. Then there was decrease in the trend in the afternoon as solar radiations deteriorate. For the unfinned SAH as shown in figure 7, thermal efficiency ranges from 17%- 50%. All curves rise from morning to a sharp peak

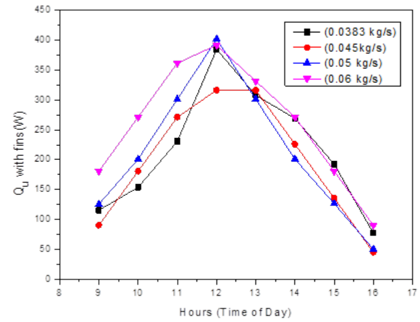

Fig 6. Variation of the daily useful power for the finned SAH versus Time of the day

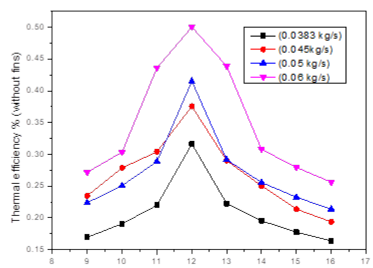

Fig 7. Hourly variations of the thermal efficiency of unfinned SAH

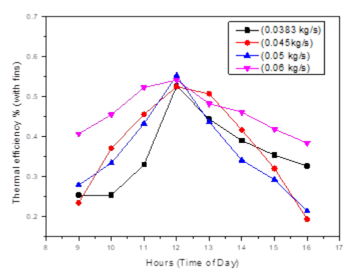

Fig 8. Hourly variations of the thermal efficiency of finned SAH

at 12 pm, then declines. The maximum efficiency 50% was found at 0.06 kg/s AFR at noon. Figure 8 depicts hourly variations of efficiency for SAH with fins for different AFRs. Thermal efficiency ranges from 20% to 62%. The variation in the thermal efficiency is slightly delayed during 12-1 pm, indicating improved heat transfer capacity across wider midday widow. Peak values are 60% - 62% for 0.045-0.05 kg/s at 12 pm, while 0.06 kg/s archives 58% at 12 pm but archives higher performance later in the afternoon. The reported peak efficiencies represent instantaneous values near solar noon, whereas the daily averages are lower due to afternoon decline in irradiance.

Fins produced a uniform increase in the thermal efficiency across whole duration of the day, with peak gain at noon. The magnitude is larger at lower and moderate AFRs (e.g., 20-30 % points at noon for 0.0383-0.05 kg/s) and more modest at the highest flow rates (e.g. 8-10% at noon for 0.06 kg/s). While the incorporation of fins substantially improved heat transfer, it also resulted in the pressure drop across the absorber. The blower power consumption increased by 6-9% relatively to unfinned configuration. The increase in useful energy output (68 W) more than compensated for the slight rise in blower power consumption, showing that finned configuration is still energetically advantageous.

4 Conclusion

The experimental study of vertical absorber solar air heaters (SAHs) with and without fins demonstrates that the absorber's structure plays a significant role in determining its thermal performance. At all the experimented air flow rates (0.0383-0.06 kg/s), the finned design consistently yielded better performance than the unfinned design in terms of temperature increase, useful energy gain, and thermal efficiency. Fins led to an increase in efficiency during the day, with the most significant gains occurring at noon. The finned SAH was able to be maximally efficient (62% at 0.045, 0.05 kg/s), and the unfinned SAH at 0.06 kg/s (50 %). In the case of unfinned SAHs, the optimum flow rate (0.06 kg/s) had the most optimal performance during midday. Conversely, finned SAHs performed best at low flow rates (0.045-0.05 kg/s) at noon, and better performance was maintained in the late afternoon at increased flow rates. The finned design provided a greater daily average useful power (222 W) than the unfinned design (154 W), which validates the value of increasing the heat transfer area. The optimum airflow range of 0.045-0.05 kg/s overserved for the finned absorber directly reflects the balance between convective heat transfer enhancement and residence time reduction in the vertical geometry. At lower AFRs, residence time becomes insufficient. The finned design successfully mitigates this trade off by increasing effective heat transfer area, enabling superior performance across the optimal airflow window. The addition of fins improves heat transfer by reducing turbulence and maximising the coverage of the effective surface area, thus providing a feasible solution to increase the efficiency of the SAH in various operating conditions.

In general, the combination of vertical absorber SAHs with the addition of fins significantly and consistently improves the thermal performance, especially at moderate air flow rates. The suggested design change is expected to have a beneficial impact on the amount of energy captured and operational efficiency, which can justify its use in solar air heating systems as a means of providing sustainable thermal usage.

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