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Optimal Collector Aspect Ratio for Improving Thermal Efficiency of Louvered Finned Solar Air Heaters Using Nanoparticles

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Abstract

The current study investigated the effect of collector aspect ratio on the thermal performance of a louvered finned solar air heater (LFSAH) using nanoparticles. Analyses are performed on various collector aspect ratios and mass flow rates (MFR) to determine their impact on heat transfer and overall system performance. The findings reveal that changing the collector aspect ratio has significant effects on the thermal efficiency and heat transfer properties of a solar air heater (SAH). It has been observed that increasing the aspect ratio increases heat transmission and improves the thermal efficiency of the system. When an aspect ratio of 4:1 was used, LFSAH and PSAH attained the highest thermal efficiency, with percentages of 81.63% and 68.13%, respectively. The study's findings provide useful information for improving the design and operation of LFSAH while keeping the aspect ratio as a critical variable in consideration. In the context of solar air heaters, optimizing the aspect ratio offers substantial benefits. By enhancing energy efficiency, it reduces reliance on fossil fuels and effectively minimizes air pollution. Additionally, this optimization contributes to water conservation and mitigates the risk of groundwater and surface water pollution. Furthermore, promoting energy-efficient heating systems helps mitigate soil contamination risks. Hence, the study underscores the importance of considering the aspect ratio in the design of louvered finned solar air heaters, providing valuable insights for the development of sustainable heating systems that foster a cleaner environment.

Keywords

Solar air heater, Louvered finned, Aspect ratio, Thermal analysis

Introduction

The SAH is a device that uses solar energy to heated air for agricultural, ventilation, and space heating purposes. Finned SAH are one of the most popular types of SAH due to their effectiveness and compact form. Fins improve heat transfer between the absorber plate and the air by increasing the absorber surface area. A SAH's aspect ratio is critical to its thermal performance and efficiency. The aspect ratio, defined as the ratio of the collector's width to its height, influences heat transfer characteristics, airflow distribution, and overall system efficiency. A significant contribution to studies of absorber surfaces is available in literature. In this context, an analysis of the effectiveness of a complete absorber surface SAH inserted twisted tape was done by [1]. The twist ratio (Y) was adjusted to different values of 2, 4, 6, and 8. The study's findings showed that at a MFR of 0.025 kg/s, the thermal efficiency of the collector with a twisted ratio of

2 increased by 8.3 percent when the insolation was raised from 500 to 1000 W/m^2. The results also showed that a considerable improvement in thermal efficiency of 22.56 percent was obtained by combining fins with twisted tape inserts, as opposed to an improvement of 11.49 percent when only fins were used. Investigated the exergy and thermal performance of a single pass double duct SAH [2]. The thermal performance of the SAH was increased by 21.2 percent when the two-duct arrangement was used. Furthermore, the exergy efficiency increased by 22.4 percent. These findings highlight the benefits and potential of using a single pass double duct design in SAH, resulting in improved thermal and exergy performance. Investigated the thermal performance associated with baffles SAH. These results indicated that the specific combination of a BR of 0.7 and a PR of 2 yielded the most efficient thermos-hydraulic performance in the SAH system, highlighting the importance of careful design considerations for optimizing the overall performance of SAH [3]. The use of a V-corrugated absorber surface to improve heat transfer in a SAH. The results showed that the contact factor for this configuration was slightly higher than for the PSAH [4]. These findings imply that using a short-impacted V-corrugated absorber surface improves heat transfer performance in the SAH system, highlighting the potential for heat transfer improvement strategies to improve SAH efficiency. Looked into how amplitude and wavelength affect the performance of a wavy finned SAH [5]. The results show that as the wavelength grows, both effective and thermal efficiency drop across the whole range of MFR while keeping constant amplitude of 0.75 cm. Furthermore, it was discovered that increasing the amplitude at a fixed wavelength increases the thermal performance of the SAH. These findings highlight the importance of optimizing the wavelength and amplitude of wavy finned SAHs to achieve higher thermal efficiency and effective performance across different flow rates. Investigated the thermos-hydraulic performance of an offset-fin SAH. The finding indicated that as the MFR increases, the thermal performance of the SAH increases steadily [6]. Furthermore, the system's effective efficiency grows up to a specific fluid flow rate, reaching a maximum value. However, when considering a certain fin height and fin pitch, the effective efficiency declines dramatically beyond this optimal flow rate. These findings highlight the significance of choosing a proper flow rate and optimizing the fin characteristics to maximize the thermal performance and effective efficiency of SAHs with offset fins. Evaluated the performance of a wavy-fin SAH [7]. The results showed that the thermal efficacy of the wavy fin absorber SAH ranged from 67.44% to 121.43% for fin pitches ranging from 2 cm to 6 cm and MFR ranging from 0.00312 kg/s to 0.0158 kg/s. The results of this study indicate that utilizing wavy fins has the capacity to enhance the thermal efficiency and effectiveness of SAHs, regardless of the combination of flow rates and fin pitch. Under various operating situations, investigated the performance of a triangular channel SAH [8]. The findings revealed that the developed model achieved a significant 50% decrease in inaccuracies when estimating thermal efficiency and output air temperature. These findings demonstrate the usefulness of the triangle channel SAH with a U-turn pattern, as well as the need of optimizing the internal channel angle in SAH for maximum thermohydraulic performance. Studied the performance of a tabular solar air heater (TSAH) [9]. When compared to a PSAH, the TSAH obtained a maximum exit temperature rise of 13.2 °C when the inlet air MFR was 0.025 kg/s. Furthermore, for air mass fluxes of 0.075 kg/s, 0.05 kg/s, and 0.025 kg/s, the daily average efficiency of the TSAH was determined to be approximately 83.7%, 76.3%, and 59.8%, respectively. These data demonstrate the TSAH improved performance in terms of outlet temperature rise and daily average efficiency, particularly at lower MFR [10]. Singh and Vardhan investigated the performance of a SAH with evacuated tube collectors and coil inserts [11]. The ETC-HI setup reached a maximum outlet temperature of 112.6 °C and a thermal efficiency of 70.9%, according to the results. Furthermore, when compared to a simple ETC, the pressure drop increased by 2.45 times. Despite the greater pressure loss, the ETC-HI arrangement outperformed the standard ETC in thermohydraulic performance. These findings illustrate the efficacy of using helical coiled inserts in an evacuated tube collector SAH to improve thermal efficiency and overall performance. Studied the effectiveness of a SAH with baffles installed at various points [11]. The findings demonstrated that adequate baffle positioning increased thermo-hydraulic performance. The optimal thermo-hydraulic output factor was obtained when the baffles were positioned within the first half of the air channel, occupying 50% of the SAH. These findings emphasize the importance of carefully positioning the baffles in a SAH system, since it has a substantial impact on the overall performance and efficiency of the system. The performance of a jet plate SAH with attached fins was tested by [12]. The results showed a significant increase in thermal efficiency ranging from 3% to 14.7% for Reynolds numbers ranging from 3,000 to 15,000. This increase in thermal efficiency was noticed while comparing smooth and roughened type SAH designs. Furthermore, the study discovered an improvement in heat transport ranging from 28% to 39%. These studies demonstrate the effectiveness of adding fins in a jet plate SAH, resulting in better thermal efficiency and heat transfer performance when compared to alternative SAH designs. Evaluated the thermal performance of a FSAH with arc surface baffles [13]. The results showed that including fins into the SAH increased the effective efficiency by 27.1% and the thermal efficiency by 28.3% when compared to a SAH with an arc shape rib structure. These findings demonstrate the efficacy of employing fins and arc surface baffles to improve the overall performance and efficiency of SAH systems. Investigated a wavy channel SAH experimentally and analytically. The results showed that the SAH achieved a thermal performance of 66% and a pressure drop of 3 Pa at a flow rate of 0.04 kg/s [14]. However, computer simulations revealed that the current SAH design's large thermal output caused flow circulation in the second and third channels. These findings emphasize the significance of balancing thermal performance and flow characteristics in wavy channel SAHs in order to optimize overall efficiency and performance. Investigated the performance of an impinging jet linked to a corrugated wavy double pass SAH [15]. Under particular operating conditions, the results showed that the new SAH design had the maximum thermal efficiency. At a mass flux of 0.04 kg/s, a bed porosity of 98%, and an imping-

ing plate perforation of 0.48%, the best thermal efficiency was reached. These findings highlight the necessity of taking specific operational parameters and design aspects into account, such as mass flux, bed porosity, and plate perforation, in order to maximize the thermal efficiency of impinging jet-based corrugated wavy double passes. Evaluated the performance of a porous serpentine wavy wire mesh packed bed SAH using experimental and analytical methods [16]. When using a 93% porous double-passed serpentine bed structure, the SAH achieved thermal and effective efficiencies of roughly 80% and 74%, respectively. Furthermore, the findings revealed that a serpentine-packed SAH beat a flat-packed bed SAH in terms of effective efficiency, with a maximum improvement of 24.33%. These findings support the use of a porous serpentine wavy wire mesh packed bed structure to improve the overall thermal and effective efficiency of solar air heaters. Analysed the thermal performance of LFSAH at different louvered parameters [17]. The results indicated that the thermal performance enhanced 43.14 to 76.79% with use of louvered fines in solar collectors.

The aim of this research is to investigate the effect of collector aspect ratio on the thermal performance of LFSAH. The impacts of changing aspect ratios on heat transfer rates, pressure drop, temperature distribution, and overall system efficiency will be investigated using numerical simulations [18-21]. The findings of this study will contribute to the development of more efficient and sustainable solar thermal systems by providing significant insights for the design and optimization of LFSAH.

Experimentation - Thermal Analysis

The analysis of a LFSAH involves assessing the performance and heat transfer characteristics of the system. Perform a heat transfer characteristics analysis to identify the system's convective and conductive heat transfer. Analysing the airflow patterns, convective heat transfer coefficients, and temperature distribution over the collector surface and within the fins are all part of this. Figure 1 and figure 2 illustrate all geometrical parameters and the heat transfer coefficients for the louvered fin connected with the system. Let's consider the width of the absorber plate as 'L2' and its length as 'L1'. The collector plate is joined to the 'n' number of louvered fins, each with a height of 'Hf' and thickness 't'. These fins are placed at an average distance of 'w' as depicted in figure 1. Figure 2 provides a graphical representation of the louvered fin, illustrating its louvered length 'll' and louvered pitch 'lp'.

Energy balance equation for absorber plate:

$$Ia_1\tau_c = h_{c,1f}\left(T_1 - T_f\right) + U_t\left(T_1 - T_a\right) h_{ff}\varphi_{fin}\left(T_1 - T_f\right) + h_{r,12}\left(T_1 - T_2\right) \quad (1)$$

For bottom plate

$$h_{c,f2}\left(T_f - T_2\right) + h_{r,12}\left(T_1 - T_2\right) = U_b\left(T_2 - T_a\right) \quad (2)$$

For airstream

$$\frac{mC_p}{L_2}\frac{dT}{dx} = h_{c,1f}\left(T_1 - T_f\right) + h_{c,2f}\left(T_2 - T_f\right) + h_{ff}\varphi_{fin}\left(T_1 - T_f\right) \quad (3)$$

$$F = \frac{h_{c,1f}h_{r,12} + \left(h_{c,1f} + h_{ff}\varphi_{fin}\right)\left(h_{r,12} + h_{c,1f} + U_b\right)}{\left(\left(h_{r,12} + h_{ff} + U_b\right)\left(U_t + h_{c,ff} + h_{r,12} + h_{ff}\varphi_{fin}\right) - \left(h_{r,12}\right)^2\right)} \quad (4)$$

$$U_L = U_t + \frac{1}{F}\left(\frac{h_{c1,f}U_b}{h_{r,12} + h_{c,1f} + U_b}\right) + \frac{h_{r,12}U_b}{h_{r,12} + h_{c,ff} + U_b} \quad (5)$$

The overall heat loss coefficient (UL) and collector efficiency factor (F) are fundamental parameters in solar collector design. They are essential for evaluating the performance of the collector across different fluid flow rates and guiding the design process to achieve optimal energy conversion and thermal performance.

Useful heat gain:

$$Q_u = F_r A_p\left(Ia_1\tau_c - U_L\left(T_{fi} - T_a\right)\right) \quad (6)$$

Heat removal factor:

$$F_r = \frac{mC_p}{U_L A_p}\left\{1 - \exp\left[-\frac{FU_L A_p}{mC_p}\right]\right\} \quad (7)$$

Kishore et al. [22] proposed an experiential equation to calculate the top loss coefficient, providing a mathematical representation based on their own research and analysis.

$$U_t = \left[\frac{M}{\left(\frac{C}{T_1}\right)\left(\frac{T_1 - T_a}{M + f}\right)^{0.252}} + \frac{1}{h_w}\right]^{-1} + \left[\frac{\sigma\left(T_1^2 + T_a^2\right)\left(T_1 + T_a\right)}{\frac{1}{\varepsilon_p + 0.0425M\left(1 - \varepsilon_p\right)} + \frac{2M + f - 1}{\varepsilon_c} - M}\right] \quad (8)$$

Bottom loss coefficient:

$$U_b = \frac{K_{ins}}{t_{ins}} \quad (9)$$

Dhinakaran et al. [23] proposed a heat transfer coefficient correlation in turbulent flow within a rectangular channel.

$$Nu_{12} = 0.00158\,\mathrm{Re}^{0.8} \quad (10)$$

Midhun et al. [24] utilized a correlation in terms of the Colburn factor (j) to calculate the Nusselt number for a SAH with attached louvered fins.

$$j = 0.26712\left(\mathrm{Re}_{Ip}\right)^{-0.1944}\left(\frac{\theta_I}{90}\right)^{0.257}\left(\frac{w}{I_p}\right)^{-0.5177}\left(\frac{H_f}{I_p}\right)^{-1.9045}\left(\frac{I_I}{I_p}\right)^{1.7159}\left(\frac{L_1}{I_p}\right)^{-0.2147}\left(\frac{t}{I_p}\right)^{-0.05} \quad (11)$$

In the given context, the variables represent the louvered angle (θ_I), louvered pitch (I_p), louvered length, louvered Reynolds number (Re_{IP}), and fin thickness (t), respectively.

$$Nu_{12} = j\,\mathrm{Re}\,\mathrm{Pr}^{0.4} \quad (12)$$

Convective heat transfer coefficient,

$$h_{c,1f} = h_{c,ff} = h_{c,2f} = \frac{Nu_{12}k_{air}}{D_h} \quad (13)$$

The pressure drop in a rectangular tubes with louvered fins connected is given by the equation below.

$$\Delta p = \frac{4 f \rho L_1 V^2}{2 D_h} \qquad (14)$$

The fanning friction factor is calculated in this example utilizing the correlation [24].

$$f = 0.54486 \left(\mathrm{Re}_{lp}\right)^{-0.3068} \left(\frac{L_1}{l_p}\right)^{0.0688} \left(\frac{w}{l_p}\right)^{-0.9925} \left(\frac{\theta_l}{90}\right)^{0.444} \left(\frac{H_f}{l_p}\right)^{0.5458} \left(\frac{l_1}{l_p}\right)^{-0.2003} \qquad (15)$$

Thermal efficiency:

$$\eta = \frac{Q_u}{I \times A_c} \qquad (16)$$

Results and Discussion

This section analyses the performance of a LFSAH by varying its MFR and aspect ratio. A comparison is made with solar air heaters. For numerical calculations, the following fixed and design parameters are used, L1 (1.2 m), L2 (0.2 m to 0.05 m), H (0.2 to 0.05 m), w (0.02 m), Hf (0.0025 m), Kf (50 W/mK), t (0.0025 m), Ta (300 K), lp (0.045 m), l_1 (0.024 m), θ_1 (20°), Vw (2.5 m/s), Ti (303 K), ṁ: (0.0083 - 0.1 kg/s). By varying these parameters within the specified ranges, we evaluate the thermal performance of the LFSAH and compare it to PSAH. These calculations are conducted to gain insights into the efficiency of the LFSAH under different operating conditions.

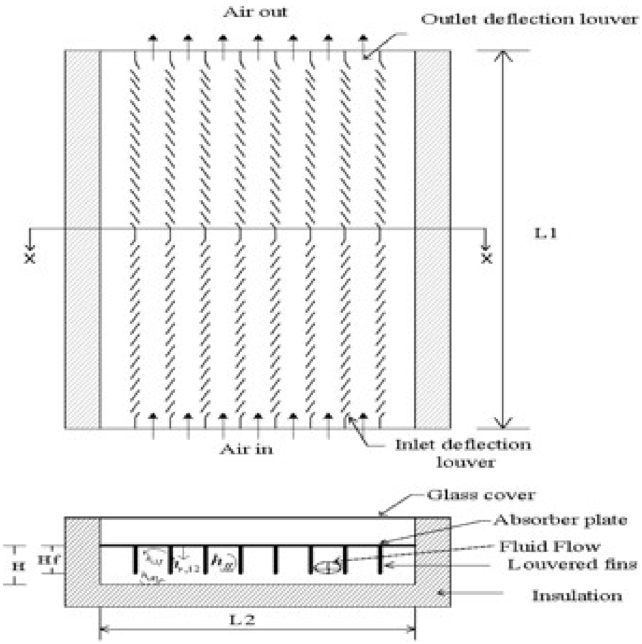

Figure 1: Illustrates a schematic diagram of a SAH with a single-pass design.

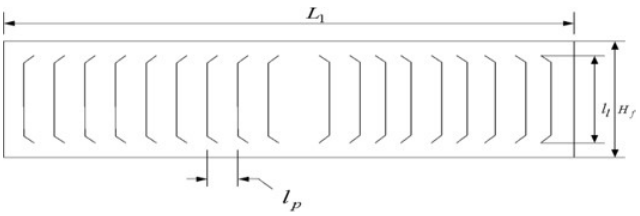

Figure 2: Depicts the geometrical description of a louvered fin.

Figure 3, the relationship between the collector efficiency factor and the MFR is portrayed for different aspect ratios, showcasing the association between these variables. The collector efficiency factor quantifies how effectively the collector converts solar radiation into usable thermal energy, while the MFR represents the speed at which the working fluid passes through the collector. The findings indicate that the highest collector efficiency factors were recorded for LFSAH and PSAH, measuring 0.984 and 0.835 respectively, when considering an aspect ratio of 4:1.

Figure 4 plots the heat removal factor against the MFR for various aspect ratios, providing a visual representation of how different aspect ratios can impact the heat removal efficiency at different MFR. The results demonstrate a positive correlation between the heat removal factor and both the MFR and aspect ratio. Furthermore, the study reveals that LFSAH and PSAH achieved the highest heat removal factors, with values of 0.982 and 0.82 respectively, when considering an aspect ratio of 4:1.

Figure 5 illustrates the relationship between thermal efficiency and MFR for different aspect ratios. Thermal efficiency represents the effectiveness of converting solar energy into usable thermal energy, while the MFR indicates the rate at which the working fluid passes through the system. The results demonstrate a positive correlation between the thermal efficiency and both the MFR and aspect ratio. Furthermore, the study reveals that LFSAH and PSAH achieved the highest thermal efficiency, with a percentage of 81.63 and 68.13 respectively, when considering an aspect ratio of 4:1.

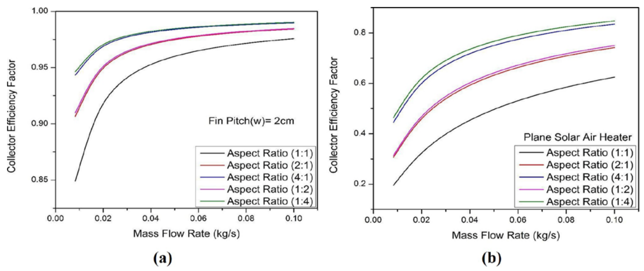

Figure 3: The relationship between the collector efficiency factor and MFR is depicted for **(a)** LFSAH and **(b)** PSAH with various aspect ratios.

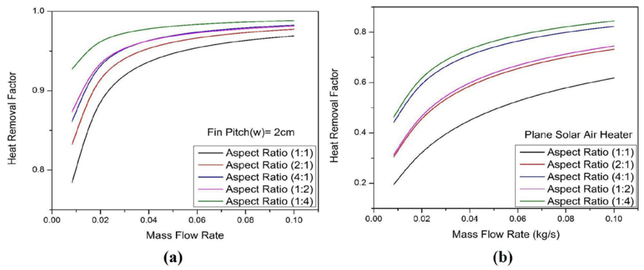

Figure 4: The relationship between the heat removal factor and MFR is depicted for **(a)** LFSAH and **(b)** PSAH with various aspect ratios.

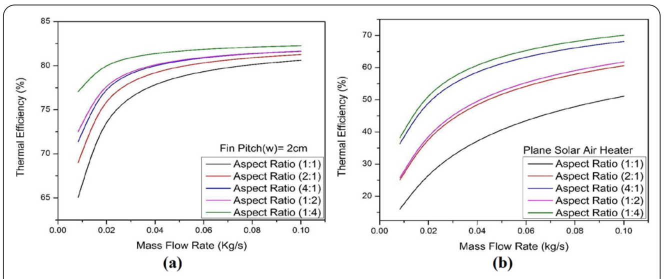

Figure 5: Thermal efficiency versus MFR with different aspect ratio of **(a)** LFSAH and **(b)** PSAH.

Conclusion

An investigation was conducted to assess the thermal performance of a LFSAH based on the aspect ratio of the collector. Analytical research was carried out, involving different collector aspect ratios, to analyse their influence on heat transfer and the overall performance of the system. Based on the results, it was observed that the aspect ratio of the collector significantly affects the thermal efficiency and heat transmission properties of the SAH. The thermal performance was notably improved with an increase in the collector aspect ratio. The inclusion of louvered fins improved heat transfer by increasing turbulence and increasing heat transfer surface area. The study's findings emphasize the need of taking the collector aspect ratio into account while building and operating LFSAH. Choosing a suitable aspect ratio can have a major impact on the system's overall performance and efficiency. As a result, optimizing the collector aspect ratio based on specific requirements and objectives should be given great consideration. In conclusion, the study highlights the paramount significance of taking into account the proportion aspect in the conception and functioning of louvered finned solar air heaters. By fine-tuning this aspect, substantial improvements in thermal efficiency and ecological viability can be attained. These findings provide valuable perceptions for the advancement of higher-performing and environmentally conscious heating systems, ultimately aiding in the establishment of a more pristine and salubrious ecosystem for forthcoming generations.

Acknowledgements

None.

Conflict of Interest

None.

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