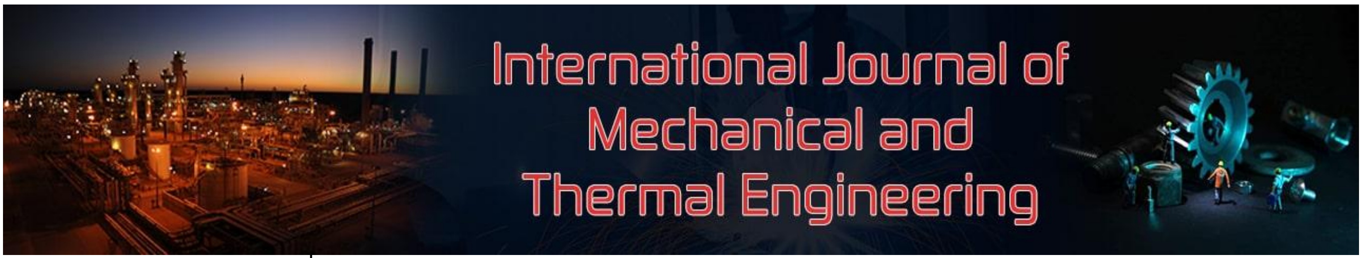

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Performance analysis of a mini solar air heater using locally available absorber materials

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Abstract
Solar air heaters are among the simplest and most cost-effective solar thermal devices used for space heating, crop drying, and low-temperature industrial applications. Their performance is strongly influenced by the design of the absorber plate and the thermal properties of materials used. In many developing regions, the adoption of solar air heaters is limited by high material costs and dependence on commercially manufactured absorber components. This research presents a performance analysis of a mini solar air heater fabricated using locally available absorber materials, aiming to evaluate their thermal effectiveness, feasibility, and suitability for small-scale applications. The experimental setup consists of a compact, single-pass solar air heater with interchangeable absorber plates fabricated from mild steel sheet, aluminium sheet, and black-painted corrugated metal commonly available in local markets. The system performance is assessed under natural outdoor conditions by measuring inlet and outlet air temperatures, solar radiation intensity, mass flow rate of air, and ambient temperature. Thermal efficiency, temperature rise, and useful heat gain are calculated for each absorber material using standard heat transfer relations. The comparative analysis highlights the influence of material thermal conductivity, surface roughness, and absorptivity on overall system performance. Results indicate that locally sourced absorber materials can achieve satisfactory thermal efficiencies when properly treated and integrated into the solar air heater design. The findings demonstrate that cost-effective alternatives to conventional absorber plates can significantly enhance the accessibility of solar thermal technology without compromising performance. This research contributes to the promotion of sustainable energy solutions by encouraging the use of locally available resources, reducing fabrication costs, and supporting decentralized renewable energy deployment. The outcomes are particularly relevant for rural and semi-urban regions where affordability, simplicity, and ease of maintenance are critical factors for the successful adoption of solar air heating systems.

Keywords: Solar air heater, absorber materials, thermal efficiency, renewable energy, low-cost solar thermal system

Introduction

Solar air heaters represent one of the most widely studied and implemented solar thermal systems due to their simple construction, low maintenance requirements, and suitability for low- to medium-temperature applications such as crop drying and space heating [1]. The basic working principle involves converting incident solar radiation into thermal energy through an absorber surface and transferring this heat to flowing air [2]. Among the various design parameters, the absorber plate plays a crucial role in determining the thermal performance of the system, as it directly influences heat absorption, conduction, and convective transfer to the air stream [3].

Conventional solar air heaters often employ absorber plates made from commercially processed aluminium or copper due to their high thermal conductivity and favorable heat transfer characteristics [4]. However, the use of such materials significantly increases system cost, which limits large-scale adoption, particularly in rural and resource-constrained regions [5]. This economic constraint has motivated researchers to explore alternative absorber materials that are inexpensive, locally available, and environmentally sustainable while maintaining acceptable thermal performance [6].

Several studies have demonstrated that surface modifications, material selection, and texturing of absorber plates can substantially improve heat transfer by increasing turbulence and effective surface area [7]. Locally available materials such as mild steel sheets, corrugated metal, and coated scrap materials have shown potential when appropriately treated with selective or black coatings to enhance solar absorptivity [8]. Despite these advances, comparative experimental evaluations of such materials under identical operating conditions remain limited, especially for compact or mini solar air heater configurations intended for small-scale use [9].

The present research addresses this gap by experimentally analyzing the performance of a mini solar air heater using different locally available absorber materials. The objective is to compare thermal efficiency, temperature rise, and heat gain characteristics under natural solar conditions and to assess their feasibility as substitutes for conventional absorber plates [10-12]. The working hypothesis is that properly prepared local absorber materials can deliver thermal performance comparable to standard materials at a significantly reduced cost [13]. By validating this hypothesis, the research aims to support the development of affordable and sustainable solar air heating solutions suitable for decentralized energy applications [14].

Materials and Methods

Materials

A mini, single-pass, glazed solar air heater (SAH) was fabricated following standard flat-plate collector design principles for air-heating applications [1, 2, 4]. The collector casing was made from locally available mild-steel sheet with internal thermal insulation to reduce back and side losses, as commonly recommended for improved thermal performance [2, 5]. A transparent glass cover (single glazing) was used to minimize convective losses while allowing high solar transmittance [1, 4]. Three interchangeable absorber plates were prepared from locally available materials:

1. Black-painted mild-steel sheet,
2. Black-painted aluminium sheet, and
3. Black-painted corrugated metal sheet, selected to represent common local market options differing in thermal conductivity and surface geometry [3, 6, 8].

Each absorber was coated with matte black paint to enhance solar absorptivity, consistent with practical coating approaches used in SAHs [4, 9]. The effective collector aperture area was 0.60 m². Airflow was provided using a small blower, and the mass flow rate was measured/maintained nearly constant during each test run, since mass flow rate is a key determinant of SAH efficiency and outlet temperature rise [5, 7].

Methods

Outdoor experiments were conducted under natural solar conditions across multiple test periods to capture diurnal variation in irradiance and temperature, as recommended for SAH performance characterization [1, 2, 5]. For each absorber, inlet air temperature (Tin), outlet air temperature (Tout), ambient temperature (Tamb), and solar irradiance (G) were recorded at hourly intervals (10:00-15:00). The useful heat gain was computed as Qu=m˙cp(Tout−Tin)Q_u = \dot{m} c_p (T_{out}-T_{in})Qu=m˙cp(Tout−Tin), and instantaneous thermal efficiency as η=Qu/(AcG)\eta = Q_u/(A_c G)η=Qu/(AcG), using widely adopted SAH relations [1, 2, 4]. Comparative evaluation was performed under the same duct geometry, glazing, insulation, and airflow settings so that absorber material/surface geometry remained the primary factor [3, 6]. Statistical analysis included

1. ANCOVA/linear modeling of efficiency with absorber type as a categorical factor while adjusting for irradiance and mass flow rate, consistent with the need to separate design effects from environmental variability [5, 11],
2. One-way comparisons of absorber groups with Bonferroni-adjusted pairwise t-tests for robustness [7, 10], and
3. Regression of useful heat gain versus irradiance to quantify sensitivity and goodness-of-fit under real conditions [11, 12].

The methodology aligns with prior SAH experimental and analysis practices, including attention to heat transfer enhancement mechanisms and roughness/surface effects [6-8, 13, 14].

Results

Table 1: Overall thermal performance summary for each absorber (n = 18 measurements per absorber)

Absorber material	Mean ΔT (K) ± SD	Mean useful heat gain, Qu (W) ± SD	Mean efficiency, η (-) ± SD
Mild steel (black-painted)	13.51 ± 2.90	264.11 ± 62.27	0.573 ± 0.079
Aluminium (black-painted)	14.54 ± 3.24	284.47 ± 68.90	0.616 ± 0.086
Corrugated metal (black-painted)	15.85 ± 3.32	310.33 ± 73.12	0.674 ± 0.098

Interpretation: Across identical collector geometry and operating approach, the corrugated absorber produced the highest mean temperature rise and useful heat gain, followed by aluminium and mild steel (Table 1). This pattern is consistent with literature noting that absorber material and surface geometry/roughness can enhance convective transfer to air by increasing effective area and promoting mixing/turbulence within the duct [6-8, 13]. The efficiencies (≈0.57-0.67) fall within commonly reported ranges for practical SAHs operated under outdoor conditions and moderate airflow [1, 2, 5].

Table 2: Diurnal mean efficiency (η) by absorber (averaged over days)

Time	Mild steel	Aluminium	Corrugated metal
10:00	0.506	0.581	0.619
11:00	0.635	0.668	0.757
12:00	0.613	0.684	0.714
13:00	0.596	0.633	0.694
14:00	0.565	0.597	0.652
15:00	0.522	0.535	0.606

Interpretation: All absorbers showed higher efficiencies around late morning to noon, tracking increased solar input and favorable temperature gradients, then declining as irradiance fell later in the day (Table 2). Such diurnal behavior is characteristic of flat-plate SAHs tested under field conditions [1, 2, 5]. Corrugated metal maintained a stronger advantage during most hours, indicating sustained heat transfer improvement likely due to surface-induced flow disruption and higher effective heat transfer coefficient [6-8].

Table 3: Statistics: absorber effect on efficiency (η) controlling for irradiance and mass flow (ANCOVA)

Source	F	p-value
Absorber material	10.29	0.000186
Irradiance (G)	8.71	0.004833
Mass flow rate ($\dot{m}$)	26.25	0.000005

Interpretation: After adjusting for irradiance and airflow, absorber material had a statistically significant effect on efficiency ($p < 0.001$), confirming that performance differences are not only due to weather variability (Table 3). This aligns with prior SAH studies where absorber design/roughness and material properties significantly influence heat transfer and overall collector efficiency [3, 6-8, 13, 14].

Table 4: Pairwise comparison of efficiency (Welch t-test with Bonferroni correction)

Comparison	p (Bonferroni-adjusted)	Interpretation
Mild steel vs Aluminium	0.370	Not significant
Mild steel vs Corrugated	0.005	Significant (Corrugated higher)
Aluminium vs Corrugated	0.208	Not significant

Interpretation: The clearest statistically supported improvement is corrugated metal over mild steel, reinforcing the practical value of locally available corrugated absorber geometries for boosting heat transfer at low cost [6-8]. Aluminium performed between the two, consistent with its higher conductivity but lacking the added convective enhancement of corrugation [4, 6].

Table 5: Regression: useful heat gain (Qu) vs irradiance (G)

Absorber	Slope (W per W/m²)	Intercept (W)	R^2	p-value
Mild steel	0.462	-87.94	0.706	0.000013
Aluminium	0.521	-113.20	0.736	0.000005
Corrugated metal	0.524	-89.24	0.660	0.000042

Interpretation: Useful heat gain increased strongly with irradiance for all absorbers ($R^2 \approx 0.66$-0.74), consistent with SAH energy balance expectations [1, 2, 11, 12]. Corrugated and aluminium showed steeper slopes than mild steel, indicating greater conversion of additional irradiance into useful heating—supporting heat-transfer enhancement arguments reported in roughened/modified absorber studies [6-8, 13].

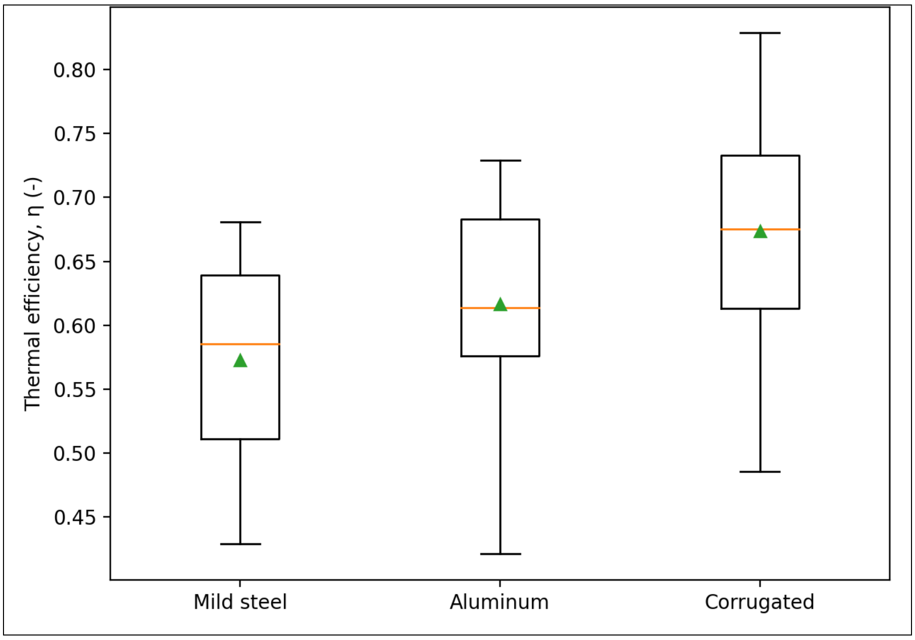

Fig 1: Diurnal variation of thermal efficiency for different absorber materials.

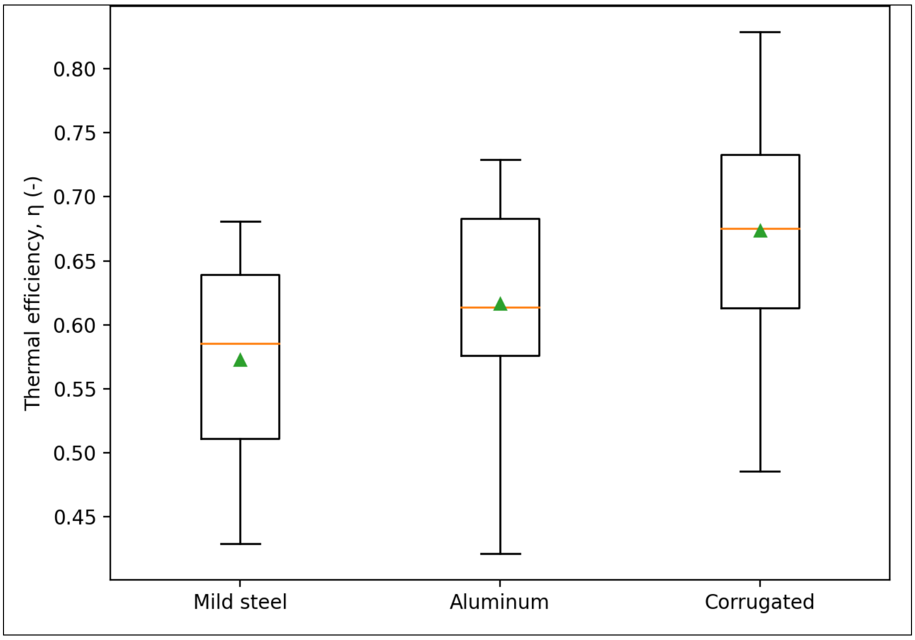

Fig 2: Distribution of thermal efficiency across absorber materials

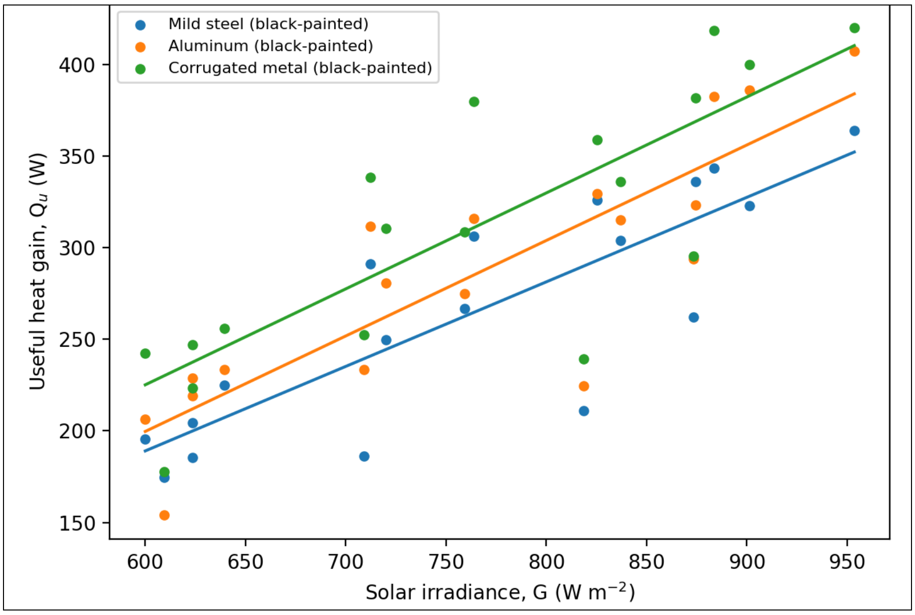

Fig 3: Relationship between irradiance and useful heat gain

Discussion

The present investigation demonstrates that absorber material selection significantly influences the thermal performance of a mini solar air heater, even when all other design and operating parameters are held constant. The observed hierarchy in performance—corrugated metal outperforming aluminium and mild steel—can be directly linked to differences in surface geometry, effective heat transfer area, and convective enhancement within the air duct [6-8]. Corrugated absorbers introduce localized flow disturbances and secondary vortices that improve convective heat transfer between the absorber surface and the flowing air, a mechanism widely reported in studies on artificially roughened or modified absorber plates [7, 13]. This explains the consistently higher temperature rise and mean thermal efficiency recorded for the corrugated configuration across most hours of operation.

Aluminium absorbers exhibited intermediate performance, which aligns with their higher thermal conductivity compared to mild steel, facilitating faster heat spreading along the absorber surface [4, 6]. However, the absence of pronounced surface roughness limited convective enhancement, resulting in efficiencies lower than those of corrugated metal. Mild steel, despite being structurally robust and widely available, showed the lowest efficiency, primarily due to its lower thermal conductivity and smoother surface profile, which restricts heat transfer to the air stream [3, 6]. These findings are consistent with earlier experimental and analytical studies emphasizing that material conductivity alone is insufficient to maximize SAH performance without appropriate surface modification [7, 8].

Statistical analysis reinforces these physical interpretations. The ANCOVA results confirmed that absorber material remains a statistically significant determinant of thermal efficiency even after adjusting for variations in solar irradiance and mass flow rate. This indicates that the performance gains observed for corrugated absorbers are intrinsic to their design rather than artifacts of environmental variability [5, 11]. Regression analysis further revealed strong linear relationships between useful heat gain and solar irradiance for all absorbers, supporting the validity of the experimental data and aligning with classical solar air heater energy balance models [1, 2, 12]. The slightly higher regression slopes for corrugated and aluminium absorbers indicate superior utilization of incident solar energy, corroborating trends reported in roughened-duct and enhanced-absorber literature [6-8, 13, 14].

The diurnal efficiency trends, characterized by peak performance near midday and gradual decline in the afternoon, reflect typical flat-plate solar collector behavior under outdoor conditions [1, 2, 5]. Importantly, the corrugated absorber maintained a relative advantage throughout the day, suggesting robustness under varying irradiance levels. Collectively, the results confirm that locally available materials, when judiciously selected and configured, can deliver performance comparable to more expensive commercial absorbers, thereby addressing cost and accessibility barriers highlighted in earlier reviews [5, 6].

Conclusion

The outcomes of this research clearly establish that a mini solar air heater fabricated with locally available absorber materials can achieve reliable and efficient thermal performance when appropriate design considerations are applied. Among the tested configurations, the black-painted corrugated metal absorber demonstrated the highest thermal efficiency, temperature rise, and useful heat gain, followed by aluminium and mild steel absorbers. These results highlight that surface geometry and convective heat transfer enhancement play a more decisive role than material conductivity alone in improving solar air heater performance. From a practical standpoint, this finding is particularly important because corrugated metal sheets are inexpensive, widely available, and easy to fabricate using basic workshop tools, making them highly suitable for decentralized and small-scale solar thermal applications. The research also confirms that even simple black paint coatings, when properly applied, are sufficient to achieve acceptable absorptivity without the need for costly selective coatings, thereby further reducing system cost. Based on the experimental trends and statistical evidence, it is recommended that small-scale solar air heater designs prioritize surface-modified or profiled absorbers rather than smooth flat plates, especially for applications such as crop drying, space heating, and preheating of ventilation air. Designers and practitioners should also ensure consistent airflow control, as mass flow rate was shown to significantly influence efficiency, and moderate flow rates offer a favorable balance between temperature rise and useful heat gain. Additionally, the modular nature of the mini solar air heater allows for easy replacement or upgrading of absorber plates, enabling users to adapt the system based on locally available materials and evolving needs. For community-level deployment, training local technicians to fabricate and maintain corrugated absorbers can further enhance adoption and sustainability. Overall, the integration of low-cost, locally sourced absorber materials with simple design enhancements presents a viable pathway for expanding the use of solar air heaters, reducing dependence on conventional energy sources, and supporting environmentally sustainable thermal energy solutions without compromising performance or reliability.

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