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Design and Thermal Analysis of Solar Air Heaters for Industrial Heating Applications

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Abstract

Solar air heaters offer a direct and mechanically simple route for converting solar radiation into useful sensible heat for low- and medium-temperature industrial processes. Their wider application is nevertheless constrained by the low convective heat-transfer coefficient of air, thermal losses from the collector, and the pumping penalty associated with aggressive heat-transfer enhancement. This methodology paper develops a compact design and thermal-analysis framework for a forced-convection, single-pass solar air heater intended for industrial preheating and drying duties. The proposed collector combines a black selective absorber, single glazing, insulated casing, and a rib-enhanced air channel. The method links solar energy balance, internal forced convection, pressure-drop estimation, and performance indicators including useful heat gain, outlet-air temperature, thermal efficiency, Reynolds number, and thermohydraulic behavior. A nominal 2.0 m² collector is analyzed at an inlet temperature of 30 °C, irradiance near 800 W/m², and air mass-flow rates of 0.02–0.05 kg/s. Model-based results indicate the expected design trade-off: increasing mass flow raises collector efficiency from approximately 45% to 62% but reduces the temperature lift from about 36 °C to 20 °C while increasing pressure drop. The framework therefore supports selection of an operating point according to the industrial process temperature requirement rather than thermal efficiency alone. The paper also integrates findings from solar-air-heater research published up to 2019 and provides a reproducible step-by-step methodology for later experimental or CFD validation.

Introduction

Industrial heating accounts for a large share of final energy demand, and many operations such as product drying, paint curing, ventilation-air preheating, timber seasoning, food processing, and low-temperature material conditioning require hot air rather than steam. For these duties, solar air heaters (SAHs) are attractive because the working fluid is non-freezing, leakage is environmentally benign, the collector construction is comparatively simple, and the heated air can often be supplied directly to the

process. The principal engineering limitation is the poor heat-transfer capability of air. A conventional flat absorber can reach a relatively high surface temperature while the bulk air remains cooler, causing avoidable top and edge losses and limiting useful heat recovery.

Research on SAHs has therefore focused on increasing the absorber-to-air heat-transfer coefficient without creating excessive fan power. Artificial roughness, ribs, dimples, fins, baffles, packed beds, double-pass flow arrangements,

thermal storage, and impinging jets have all been explored. Reviews by Hans et al. (2009), Bhushan and Singh (2010), and Kumar et al. (2012) established that repeated roughness can disturb the viscous sublayer and increase Nusselt number, but the friction factor rises simultaneously. This makes a thermohydraulic criterion more useful than heat-transfer enhancement alone when designing a practical forced-convection unit.

The industrial design problem is consequently multi-objective. The collector must deliver a useful air temperature at the required flow rate, retain acceptable thermal efficiency under changing irradiance, and limit pressure losses so that parasitic electrical consumption does not erase the solar benefit. The optimum condition also depends on the application: a dryer may favor a high temperature rise at moderate flow, while ventilation preheating may favor higher flow and higher collector efficiency. A robust methodology should therefore calculate heat gain, outlet temperature, efficiency, flow regime, and pressure drop together, and then identify the operating region that satisfies the process constraint.

The objective of this paper is to formulate such a methodology for a compact, single-pass SAH using an insulated rectangular duct and a ribbed black absorber. The analysis is deliberately based on parameters that can be measured during later testing: solar irradiance, ambient and inlet temperatures, outlet temperature, duct dimensions, air velocity or mass flow, and static pressure difference. The proposed model also follows the design lessons reported for thermal storage, ribbed absorbers, fins and baffles, and enhanced surfaces published up to 2019 (Saxena et al., 2015; Kalaiarasi et al., 2016; Kumar & Kim, 2017; Saravanakumar et al., 2019). The resulting

procedure can be used as a pre-design tool before fabrication and as a data-reduction procedure after experiments.

Literature Review

The literature shows a consistent evolution from conventional flat-plate collectors toward surface and flow modifications that intensify air-side convection. Hans et al. (2009) reviewed artificially roughened collectors and emphasized that roughness geometry should be judged through the combined heat-transfer and friction response. Bhushan and Singh (2010) organized the available roughness methodologies and correlations, reinforcing the importance of roughness height, pitch, angle, and hydraulic diameter. Kumar et al. (2012) extended this view by comparing heat-transfer and fluid-flow characteristics across roughened ducts and highlighting the usefulness of CFD, thermography, and flow visualization in addition to conventional experiments.

Later work broadened the design space. Saxena et al. (2015) demonstrated a solar air heater incorporating thermal storage, showing the potential for maintaining useful outlet temperature beyond strong sunshine periods. Kalaiarasi et al. (2016) combined a specially constructed absorber with sensible heat storage and reported improved energy and exergy behavior compared with a conventional unit. Kumar and Kim (2017) reviewed packed-bed solar air heating and concluded that packing geometry, void fraction, and single- versus double-pass configuration strongly influence thermal performance. These studies are particularly relevant to industry, where thermal continuity and process stability can be as important as peak efficiency.

Table 1. Selected solar air heater literature used to define the design methodology

Reference	Approach	Main contribution	Design relevance
Hans et al. (2009)	Review of artificial roughness	Roughness can raise heat transfer substantially, but friction must be considered.	Basis for thermohydraulic design.
Bhushan & Singh (2010)	Review of roughness methodology	Geometry and relative roughness parameters control Nu and f.	Select practical rib dimensions.
Kumar et al. (2012)	Review of roughened ducts	Combines experimental, CFD and visualization approaches.	Supports validation pathway.
Saxena et al. (2015)	Novel SAH with storage	Thermal storage can extend useful heating period.	Optional industrial load smoothing.
Kalaiarasi et al. (2016)	Energy/exergy study with storage	Storage-assisted unit outperformed conventional design.	Use energy plus second-law thinking.

Kumar & Kim (2017)	Packed-bed review	Packed-bed and double-pass layouts can improve performance.	Alternative for high heat capacity.
Komolafe et al. (2019)	Rectangular-rib SAH	Reported thermal efficiency range of 14–56.5%.	Direct 2019 benchmark.
Saravanakumar et al. (2019)	Arc ribs + fins/baffles	Combined enhancement improved thermal/effective efficiency.	Shows value of integrated enhancement.
Singh et al. (2019)	Experiment + CFD on broken ribs	Higher heat transfer accompanied by pumping penalty.	Validates coupled thermal-flow analysis.
Perwez & Kumar (2019)	Dimple absorber comparison	Dimpled surface improved heat transfer and efficiency.	Alternative enhanced absorber.

The 2019 literature provides especially useful design benchmarks. Komolafe et al. (2019) experimentally studied a rectangular-rib absorber and reported thermal efficiency values ranging from 14% to 56.5% under the tested conditions, demonstrating that a locally fabricated roughened collector can reach useful process-heating temperatures. Saravanakumar et al. (2019) analytically combined arc-shaped roughness with fins and baffles and reported meaningful gains in both thermal and effective efficiencies. Singh et al. (2019) used both experiment and CFD for multiple broken ribs and showed explicitly that strong heat-transfer enhancement carries a significant pumping-power penalty. Perwez and Kumar (2019) compared flat and spherical-dimple absorbers and observed stronger heat transfer for the dimpled configuration. Collectively, these works justify the present choice of a moderately roughened absorber rather than an extremely restrictive enhancement geometry.

A major gap in many performance comparisons is that maximum thermal efficiency is sometimes treated as the only objective. For industrial heating, however, the outlet-air temperature and required process heat rate are equally important. A collector operating at high mass flow may be very efficient but deliver only a modest temperature lift; conversely, a low-flow collector may provide hotter air but lose a larger fraction of the absorbed energy to the surroundings. The present methodology therefore uses a process-oriented design criterion: first satisfy a target outlet-temperature band, then maximize useful heat gain subject to an acceptable pressure drop. This approach is consistent with the combined thermal and hydraulic perspective established in the earlier literature.

Methodology

The study is organized as a reproducible design-analysis sequence. The collector is treated as a

steady-state control volume over short sampling intervals, with solar irradiance and inlet conditions assumed quasi-steady. The baseline configuration is a single-glazed, forced-convection, single-pass rectangular collector with a blackened metallic absorber and transverse rectangular ribs on the air side. The ribs are intended to interrupt the near-wall thermal boundary layer while remaining simple to manufacture and clean in an industrial environment.

Step 1: Define the industrial heat requirement. Specify the target air temperature, required air flow, operating hours, and acceptable electrical fan power. For the present design study, an inlet temperature of 30 °C and a useful outlet range of approximately 50–70 °C are selected to represent low-temperature industrial preheating and drying.

Step 2: Select collector geometry and materials. Use a 2.0 m² gross collector area, one transparent cover, a blackened metallic absorber, a rectangular air channel, and back/edge insulation. The absorber is provided with modest repeated ribs. Dimensions are selected so that the expected Reynolds number lies mainly in the turbulent regime during forced convection.

Step 3: Measure or prescribe boundary conditions. Use global solar irradiance on the collector plane, ambient temperature, air inlet temperature, air mass-flow rate, and wind condition as inputs. For analytical screening, irradiance is set to 800 W/m² and air mass flow is varied from 0.02 to 0.05 kg/s.

Step 4: Perform the useful-energy balance. Calculate useful heat delivered to the air from its sensible temperature increase and compare it with incident solar power. This gives both the heat rate required by the process and the first-law collector efficiency.

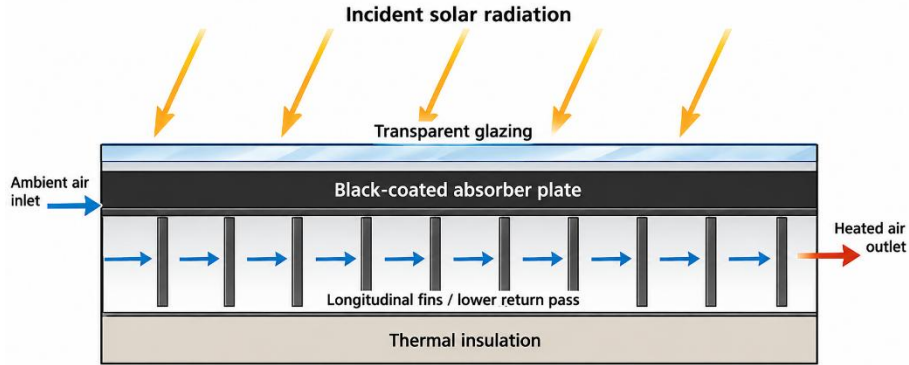


Figure 1. Proposed solar air heater configuration for low- and medium-temperature industrial process heating.

Table 2. Baseline design parameters used for the analytical thermal assessment.

Parameter	Design value	Purpose / note
Collector gross area, A	2.0 m ²	Compact industrial module
Air duct width × height	0.50 m × 0.05 m	Hydraulic diameter ≈ 0.091 m
Collector length	4.0 m	Provides 2.0 m ² plan area
Absorber	Blackened aluminum / galvanized steel	High absorptance, low cost
Glazing	Single transparent cover	Reduces convective losses
Back insulation	40–50 mm mineral wool / equivalent	Limits conduction loss
Air mass-flow range	0.02–0.05 kg/s	Process and fan controlled
Design irradiance	800 W/m ²	Representative clear-sky screening value
Inlet air temperature	30 °C	Illustrative industrial inlet condition
Specific heat of air, cp	1005 J/(kg·K)	Approximation over studied range

Step 5: Calculate thermal performance indicators. The useful heat gain is obtained from $Q_u = \dot{m} c_p (T_o - T_i)$. Collector thermal efficiency is the ratio of useful heat gain to incident solar power, $\eta_{th} = Q_u / (I A)$. The outlet temperature may be predicted from $T_o = T_i + Q_u / (\dot{m} c_p)$ after estimating collector heat removal from the energy balance or an experimentally calibrated efficiency relation.

$$Q_u = \dot{m} c_p (T_o - T_i) \quad \text{and} \quad \eta_{th} = Q_u / (I A)$$

Step 6: Evaluate internal flow and pressure loss. Compute hydraulic diameter $D_h = 4A_c/P$ and Reynolds number $Re = \rho V D_h / \mu$. Pressure drop is evaluated from an appropriate duct friction factor and the total equivalent flow length. Roughness-induced enhancement must be rejected if the required fan power becomes disproportionate to the additional solar heat recovered.

$$Re = \rho V D_h / \mu \quad \text{and} \quad \Delta P = f (L/D_h) (\rho V^2/2) + \Sigma K (\rho V^2/2)$$

Step 7: Select the operating point and validate. Choose the air-flow rate that satisfies the process outlet-temperature band with the highest useful

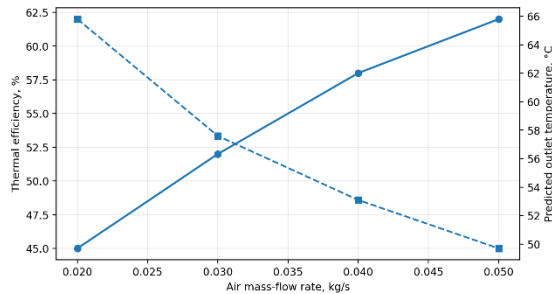
heat delivery at an acceptable pressure loss. The final fabricated system should then be validated using calibrated thermocouples, a pyranometer, flow measurement and differential-pressure measurement; CFD may be used to examine local temperature and velocity fields as demonstrated by Singh et al. (2019).

Results

Because this paper defines a methodology rather than reporting a completed laboratory campaign, the following results are analytical design outputs generated from the baseline conditions in Table 2. They are intended to demonstrate data reduction, show expected operating trends, and provide target values for subsequent testing. The incident solar power is 1.60 kW at 800 W/m² over 2.0 m². The assumed thermal-efficiency trend reflects improved convective heat removal as mass flow increases, while the outlet temperature is obtained directly from the useful heat balance.

Table 3. Model-based design results at 800 W/m² irradiance and 30 °C inlet temperature.

$\dot{m}$ (kg/s)	η_{th} (%)	Q_u (W)	ΔT (°C)	T_o (°C)	Re	ΔP (Pa)
0.020	45	720	35.8	65.8	$\sim 2.5 \times 10^3$	18
0.030	52	832	27.6	57.6	$\sim 3.8 \times 10^3$	32
0.040	58	928	23.1	53.1	$\sim 5.0 \times 10^3$	51
0.050	62	992	19.7	49.7	$\sim 6.3 \times 10^3$	74

**Figure 2.** Predicted trade-off between collector efficiency and outlet-air temperature with increasing mass-flow rate.

The results show two competing trends. Raising mass flow from 0.02 to 0.05 kg/s increases the assumed heat-removal efficiency from 45% to 62%, so useful heat gain rises from about 0.72 to 0.99 kW. At the same time, the energy is distributed across a larger mass of air, and the predicted temperature rise drops from approximately 35.8 °C to 19.7 °C. Consequently, the highest outlet temperature occurs at the lowest investigated flow rate, whereas the highest useful heat rate occurs at the highest flow rate. This is the expected behavior of a sensible-heating collector and explains why efficiency alone is not a sufficient industrial design criterion.

For a process requiring air near 55–60 °C, the 0.03 kg/s case provides a balanced operating point, delivering roughly 0.83 kW of useful heat and an outlet temperature near 58 °C. If the process can accept approximately 50–55 °C, the 0.04–0.05 kg/s range is preferable because more solar heat is recovered. Conversely, a drying process that prioritizes higher temperature could use the 0.02 kg/s condition, potentially with recirculation or a larger collector area to increase heat capacity without sacrificing outlet temperature.

Pressure drop is predicted to rise nonlinearly with air flow, from approximately 18 Pa at 0.02 kg/s to roughly 74 Pa at 0.05 kg/s for the simplified duct estimate. Although these values are modest for a small module, additional losses from inlet transitions, filters, bends, dampers and real roughness elements must be included during detailed fan selection. The literature warns that stronger roughness can deliver large Nusselt-

number enhancement while imposing a disproportionately high friction penalty (Hans et al., 2009; Singh et al., 2019). The selected rib geometry should therefore be optimized around the actual fan and process requirement rather than maximum local turbulence.

The predicted efficiency range is also consistent with the broad behavior reported in earlier studies. Komolafe et al. (2019) reported experimental thermal efficiencies extending to the mid-50% range for a rectangular-rib collector, while Perwez and Kumar (2019) demonstrated that an enhanced dimple surface can increase heat transfer relative to a flat plate. More elaborate integrated configurations can achieve additional gains: Saravanakumar et al. (2019) found that combining roughness with fins and baffles improved thermal and effective efficiencies, and storage-assisted systems have shown benefits for maintaining useful output when solar input varies (Saxena et al., 2015; Kalaiarasi et al., 2016). These comparisons suggest that the proposed single-pass design is a reasonable baseline for fabrication and can later be upgraded when process continuity or higher performance justifies the extra complexity.

Conclusion and Discussion

A practical methodology has been developed for the design and thermal analysis of a forced-convection solar air heater for industrial heating applications. The approach begins with the industrial temperature and air-flow requirement, defines collector geometry and materials, applies a useful-energy balance, evaluates flow regime and pressure drop, and finally selects the operating point using both thermal and hydraulic criteria. This sequence is intentionally simple enough for preliminary design while retaining the parameters needed for later experimental or CFD validation. For the illustrative 2.0 m² collector at 800 W/m² solar irradiance, the model indicates useful heat delivery of approximately 0.72–0.99 kW over the studied flow range. Increasing mass flow improves collector efficiency but lowers the outlet-air temperature rise. A flow rate near 0.03 kg/s gives a useful compromise for a process target around 55–60 °C, whereas larger flow rates are more suitable when maximizing total

recovered heat is more important than temperature lift. The result reinforces a central conclusion from roughened-SA H research: the best design is not necessarily the one with the largest Nusselt number or thermal efficiency, but the one that provides the required process heat with acceptable fan power and system complexity. The main limitation is that the numerical values reported here are model-based and use prescribed efficiency and simplified pressure-loss estimates rather than measurements from a fabricated prototype. Future work should therefore perform outdoor or solar-simulator testing across varying irradiance, validate absorber and outlet temperatures, quantify uncertainty, and determine the actual friction factor of the selected rib pattern. A parallel CFD study can identify recirculation regions and local hot spots, while an economic analysis can compare collector area, fan electricity, storage, and fuel savings. For industrial operation beyond sunshine hours, packed-bed or sensible/latent thermal storage may be added after the baseline collector is validated. Overall, the framework provides a defensible 2019-era methodology for developing a low-cost SAH that can substitute a portion of conventional fuel use in low- and medium-temperature hot-air processes.

References

- Hans, V. S., Saini, R. P., & Saini, J. S. (2009). Performance of artificially roughened solar air heaters—A review. *Renewable and Sustainable Energy Reviews*, 13(8), 1854–1869. <https://doi.org/10.1016/j.rser.2009.01.030>
- Bhushan, B., & Singh, R. (2010). A review on methodology of artificial roughness used in duct of solar air heaters. *Energy*, 35(1), 202–212. <https://doi.org/10.1016/j.energy.2009.09.010>
- Kumar, A., Saini, R. P., & Saini, J. S. (2012). Heat and fluid flow characteristics of roughened solar air heater ducts—A review. *Renewable Energy*, 47, 77–94. <https://doi.org/10.1016/j.renene.2012.04.001>
- Saxena, A., Srivastava, G., & Tirth, V. (2015). Design and thermal performance evaluation of a novel solar air heater. *Renewable Energy*, 77, 501–511. <https://doi.org/10.1016/j.renene.2014.12.041>
- Kalaiarasi, G., Velraj, R., & Swami, M. V. (2016). Experimental energy and exergy analysis of a flat plate solar air heater with a new design of integrated sensible heat storage. *Energy*, 111, 609–619. <https://doi.org/10.1016/j.energy.2016.05.110>
- Kumar, A., & Kim, M.-H. (2017). Solar air-heating system with packed-bed energy-storage systems. *Renewable and Sustainable Energy Reviews*, 72, 215–227. <https://doi.org/10.1016/j.rser.2017.01.050>
- Komolafe, C. A., Oluwaleye, I. O., Awogbemi, O., & Osueke, C. O. (2019). Experimental investigation and thermal analysis of solar air heater having rectangular rib roughness on the absorber plate. *Case Studies in Thermal Engineering*, 14, 100442. <https://doi.org/10.1016/j.csite.2019.100442>
- Saravanakumar, P. T., Somasundaram, D., & Matheswaran, M. M. (2019). Thermal and thermo-hydraulic analysis of arc shaped rib roughened solar air heater integrated with fins and baffles. *Solar Energy*, 180, 360–371. <https://doi.org/10.1016/j.solener.2019.01.036>
- Singh, I., Vardhan, S., Singh, S., & Singh, A. (2019). Experimental and CFD analysis of solar air heater duct roughened with multiple broken transverse ribs: A comparative study. *Solar Energy*, 188, 519–532. <https://doi.org/10.1016/j.solener.2019.06.022>
- Perwez, A., & Kumar, R. (2019). Thermal performance investigation of the flat and spherical dimple absorber plate solar air heaters. *Solar Energy*, 193, 309–323. <https://doi.org/10.1016/j.solener.2019.09.066>