



Design And Performance Evaluation Of Solar Air Heaters For Industrial Thermal Applications

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Abstract

Solar air heaters (SAHs) provide a technically simple route for converting incident solar radiation into useful hot air for low- and medium-temperature industrial duties such as product drying, process-air preheating, curing, timber seasoning, and ventilation-air heating. Their principal limitation is the relatively low convective heat-transfer coefficient between a flat absorber and the flowing air. This methodology paper develops a design and performance-evaluation framework for a single-pass, roughened-duct solar air heater intended for industrial thermal applications. The proposed configuration combines a blackened metal absorber, single transparent cover, insulated casing, forced air circulation, and controlled rib roughness on the air-side absorber surface. Performance is evaluated from measured solar irradiance, inlet and outlet air temperatures, absorber temperatures, airflow rate, ambient temperature, and pressure drop. The principal response variables are useful heat gain, outlet-air temperature rise, thermal efficiency, Nusselt number, friction factor, pumping-power requirement, and a thermo-hydraulic performance parameter. A literature-constrained design window is adopted from work published up to 2017. An illustrative calculation set shows the expected trade-off between higher airflow, rising thermal efficiency, declining temperature lift, and increasing pressure drop. The proposed procedure is suitable for laboratory validation and subsequent scale-up to industrial preheating or drying systems while avoiding the misleading use of thermal efficiency as the only design criterion.

Introduction

Industrial heat demand includes a large fraction of low- and moderate-temperature operations for which direct solar air heating can reduce fuel or electrical consumption. Unlike liquid collectors, an SAH does not require freeze protection, liquid handling, or an intermediate air-to-liquid heat exchanger, and air leakage does not create contamination risk. These advantages make the technology attractive for drying, ventilation-air preheating, curing, and other applications that can use hot air directly. The central engineering difficulty is that air has low

thermal conductivity and heat capacity per unit volume; consequently, a smooth flat-plate duct often develops a thermally resistant near-wall layer and a comparatively hot absorber, which increases losses to the surroundings (Momin et al., 2002; Yadav & Thapak, 2014).

Artificial roughness placed on the air side of the absorber disturbs the viscous sublayer and promotes mixing near the heated surface. Earlier studies using expanded metal mesh, V-ribs, broken ribs, arc-shaped wires, multiple V-ribs, and gapped ribs consistently demonstrated heat-

transfer enhancement, although the improvement is accompanied by higher friction and fan power (Saini & Saini, 1997; Sahu & Bhagoria, 2005; Saini & Saini, 2008; Hans et al., 2010). For an industrial system, therefore, the design objective is not the maximum Nusselt number alone but a balanced combination of thermal gain, outlet temperature, pressure loss, and usable net energy.

Rib orientation and flow arrangement are especially influential. V-shaped ribs generate secondary flow and can outperform simple transverse ribs, while discrete or gapped arrangements permit partial boundary-layer redevelopment and reduce some of the pressure penalty (Karwa, 2003; Karwa & Chauhan, 2010). Double-pass and counter-flow concepts increase residence time and heat-transfer area, and analytical models have shown how airflow distribution and collector heat losses affect temperature rise and efficiency (Hernández & Quiñonez, 2013). Outdoor and analytical evaluations further show that roughened collectors can provide a meaningful thermal-efficiency advantage over smooth ducts, especially in operating ranges where pumping power remains moderate (Karwa & Chitoshiya, 2013).

The present paper therefore proposes a repeatable methodology for designing and evaluating a forced-convection SAH that can be integrated upstream of an industrial dryer, curing chamber, combustion-air preheater, or general process-air line. The scope is deliberately limited to references published in 2017 or earlier. The design is intended for air-temperature lifts in the low-to-medium process-heat range rather than high-temperature concentrating systems. The study objectives are: (i) establish a practical collector geometry and instrumentation plan; (ii) define a controlled experimental matrix over irradiance and mass-flow conditions; (iii) quantify thermal and hydraulic responses through standard energy and flow relations; and (iv) identify an operating region that improves heat delivery without excessive fan power.

Literature Review

Early work established the heat-transfer value of artificial roughness in rectangular ducts. Saini and Saini (1997) reported correlations for

expanded-metal-mesh roughness, showing that surface geometry and Reynolds number strongly influence both Nusselt number and friction factor. Momin et al. (2002) experimentally examined V-shaped ribs and showed that rib angle and relative roughness height can substantially intensify heat transfer in a solar-air-heater duct. Karwa (2003) compared transverse, inclined, V-continuous, and V-discrete rib patterns in an asymmetrically heated duct and demonstrated that geometry selection controls the trade-off between augmentation and friction. Sahu and Bhagoria (2005) further showed that broken transverse ribs can enhance absorber-to-air heat transfer by interrupting boundary-layer development.

Arc-shaped wire roughness was examined by Saini and Saini (2008), who developed correlations across ranges of Reynolds number, relative roughness height, and arc angle. Hans et al. (2010) investigated multiple V-ribs and reported substantial gains in Nusselt number, together with an unavoidable increase in friction. Karwa and Chauhan (2010) moved beyond heat transfer alone by evaluating thermal and effective efficiency, emphasizing that pumping power becomes increasingly important as flow rate rises. These results support a design method that treats airflow as an optimization variable rather than a fixed operating condition.

Later studies refined this approach. Karwa and Chitoshiya (2013) experimentally reported improved thermal performance for a V-down discrete-rib solar air heater, while Hernández and Quiñonez (2013) developed analytical models for double-parallel and double-pass counter-flow SAHs. Yadav and Thapak (2014) reviewed a wide range of artificial-roughness geometries and highlighted the importance of thermo-hydraulic comparison. Saxena et al. (2015) demonstrated a design incorporating thermal storage for prolonged heat delivery. Maithani and Saini (2016) studied V-ribs with symmetrical gaps, and Hans et al. (2017) investigated broken arc ribs, both showing that deliberately introduced gaps can improve heat-transfer behavior while retaining a manageable friction penalty. Exergy-based analysis by Sahu and Prasad (2016) also reinforced the need to account for the quality of useful heat and the energy cost of air circulation.

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

Study	Configuration / focus	Key implication for present design
Saini & Saini (1997)	Expanded metal mesh roughness	Roughness geometry changes both heat transfer and friction.

Momin et al. (2002)	V-shaped rib roughness	V-ribs create strong secondary flow; angle and height matter.
Karwa (2003)	Transverse, inclined, V-continuous and V-discrete ribs	Discrete V-patterns provide a useful augmentation/friction compromise.
Saini & Saini (2008)	Arc-shaped wire ribs	Arc angle and relative height are important design variables.
Hans et al. (2010)	Multiple V-ribs	High heat-transfer enhancement is possible but friction rises.
Karwa & Chauhan (2010)	Effective-efficiency modeling	Fan/pumping power must be included in performance evaluation.
Karwa & Chitoshiya (2013)	Outdoor V-down discrete-rib SAH	Roughened ducts can raise thermal efficiency under realistic operation.
Maithani & Saini (2016)	V-ribs with symmetrical gaps	Gaps can intensify local mixing and alter pressure penalty.
Hans et al. (2017)	Broken arc ribs	Broken/gapped arcs provide strong heat-transfer enhancement.

The literature suggests three decisions for an industrial SAH. First, the absorber should use moderate artificial roughness that promotes near-wall turbulence without unnecessarily obstructing the core flow. Second, airflow must be variable because the operating point that maximizes outlet temperature is not necessarily the point that maximizes collected energy. Third, performance should be reported with hydraulic metrics as well as thermal efficiency. The methodology below adopts these principles and uses a single-pass roughened duct because it is mechanically simple, easy to instrument, and readily scalable by connecting modules in parallel.

The proposed study uses a forced-convection, single-pass rectangular SAH with a blackened aluminium absorber plate, one transparent cover, an insulated back and side casing, a centrifugal blower, a flow-control valve, and a downstream duct connected to a representative industrial heat load. The absorber underside is fitted with low-height V/arc-type ribs. The test method follows a steady-state energy-balance approach: for each operating point, solar irradiance, temperatures, airflow, and pressure drop are measured after stable conditions are reached. The same measurements are repeated for a smooth reference plate or compared with a smooth-duct correlation so that the benefit of roughness can be quantified.

Methodology

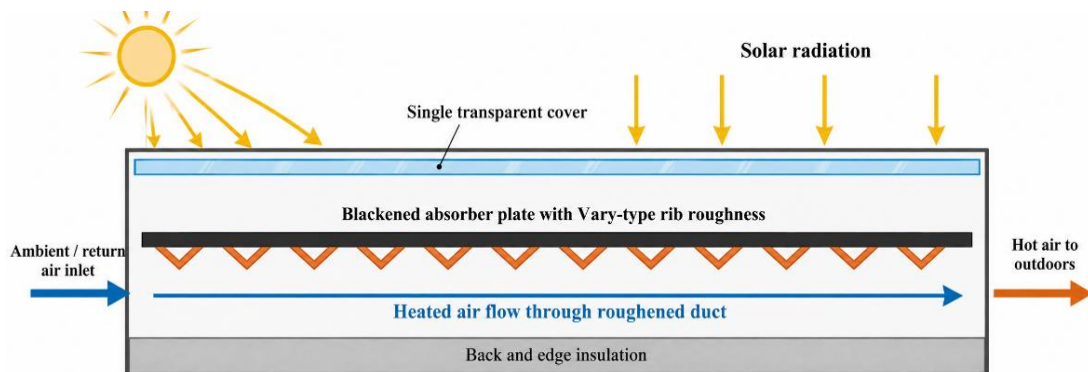


Figure 1. Proposed roughened-duct solar air heater and measurement concept for industrial process-air heating.

1. Design Specifications and Test Variables

A laboratory-scale collector area of approximately 2.0 m² is selected as a representative module. The absorber is a 1-2 mm aluminium sheet coated with a high-absorptance matte black finish. The air passage is sized to

provide a hydraulic diameter suitable for turbulent or transition-regime testing within the blower capacity. Rib height is kept small relative to hydraulic diameter, and a moderate relative pitch is selected within ranges commonly investigated in the cited literature. A single glass cover is spaced above the absorber to reduce top

loss while allowing solar transmission. Mineral wool or equivalent insulation is applied beneath the duct and around the side walls.

Table 2. Proposed design and operating ranges for the experimental methodology.

Parameter	Proposed value / range	Purpose
Collector area, A_c	$\approx 2.0 \text{ m}^2$	Useful-heat and efficiency basis
Solar irradiance, I	600-900 W/m^2	Representative daytime operating window
Air mass flow, $\dot{m}$	0.03-0.06 kg/s	Primary controllable operating variable
Relative roughness height, e/D_h	≈ 0.03 -0.04	Near-wall turbulence enhancement
Relative pitch, P/e	≈ 8 -10	Balances reattachment and friction
Rib angle	$\approx 60^\circ$ for V/arc arrangement	Promotes secondary flow
Temperature sensors	Inlet, outlet, ambient, absorber	Energy balance and loss interpretation
Pressure measurement	Across collector duct	Friction and fan-power assessment

2. Experimental Procedure and Data Reduction

The collector is oriented toward the equator at a tilt appropriate to the test location. Before each run, the blower and data-acquisition system are started and the selected flow rate is set. Measurements are recorded only after the inlet temperature, outlet temperature, absorber temperature, irradiance, and pressure drop remain approximately stable for a defined averaging interval. At least three replicate observations are recommended at each flow setting. Tests should be rejected when irradiance fluctuates rapidly or when sensor drift is evident. Calibration uncertainty for thermocouples, irradiance sensor, pressure instrument, and flow measurement should be reported, and propagated uncertainty should be estimated for useful heat and efficiency.

The useful heat transferred to the air is calculated from:

$$Q_u = \dot{m} c_p (T_o - T_i)$$

where $\dot{m}$ is air mass-flow rate, c_p is the specific heat of air, and T_o and T_i are outlet and inlet temperatures.

The instantaneous thermal efficiency is:

$$\eta_{th} = Q_u / (A_c I)$$

For duct-level heat-transfer analysis, the convective coefficient h is obtained from the useful heat rate and the mean absorber-to-air temperature difference. The Nusselt number is then $Nu = hD_h/k$. The Reynolds number is $Re = \rho V D_h / \mu$. The Darcy-type friction factor can be derived from measured pressure drop using the duct length and hydraulic diameter. To compare a roughened configuration with a smooth reference at comparable Reynolds number, the thermo-hydraulic performance parameter is evaluated in the commonly used form:

$$THPP = (Nu/Nu_s) / (f/f_s)^{1/3}$$

A THPP above unity indicates that heat-transfer enhancement outweighs the friction penalty under the constant-pumping-power concept. Fan power is estimated from volumetric flow and pressure rise, adjusted by fan efficiency. For industrial selection, the preferred operating point is the one that satisfies the required delivery temperature while maintaining high useful heat and a reasonable electrical-to-thermal energy ratio. This approach is consistent with the effective-efficiency emphasis of Karwa and Chauhan (2010) and the exergy-based caution reported by Sahu and Prasad (2016).

3. Experimental Matrix and Analysis Plan

Table 3. Suggested test matrix for steady-state collector evaluation.

Run group	Irradiance (W/m^2)	Mass flow (kg/s)	Primary outputs
A	600 ± 30	0.03, 0.04, 0.05, 0.06	ΔT , Q_u , η_{th} , ΔP

B	750 ± 30	0.03, 0.04, 0.05, 0.06	$\Delta T, Q_u, \eta_{th}, \Delta P$
C	900 ± 30	0.03, 0.04, 0.05, 0.06	$\Delta T, Q_u, \eta_{th}, \Delta P$
Reference	Matched conditions	Same flow settings	Roughened/smooth ratios, THPP

Results

To demonstrate how the methodology is reported, Table 4 provides an illustrative design calculation for a 2.0 m² collector at 800

W/m² and 30°C inlet air. The efficiency values are representative assumptions used only to show the calculation workflow; they are not claimed as experimental measurements. The corresponding

useful heat and outlet temperature are calculated directly from the energy balance using $c_p = 1006$ J/kg·K. Pressure-drop values are also illustrative and are included to demonstrate the expected hydraulic trend. A real study should replace these entries with averaged measured values and uncertainty bounds.

Table 4. Illustrative model-based performance calculation at $I = 800$ W/m², $A_c = 2.0$ m², and $T_i = 30^\circ\text{C}$.

$\dot{m}$ (kg/s)	η_{th} (%)	Q_u (W)	ΔT (°C)	T_o (°C)	ΔP (Pa)
0.03	52.0	832	27.6	57.6	25
0.04	59.0	944	23.5	53.5	38
0.05	64.0	1024	20.4	50.4	55
0.06	67.0	1072	17.8	47.8	75

The calculation illustrates the characteristic SAH trade-off. Increasing mass flow from 0.03 to 0.06 kg/s raises useful heat from about 832 W to 1072 W and the assumed thermal efficiency from 52% to 67%, because the absorber is cooled more effectively and external thermal losses are reduced. At the same time, the air-temperature rise falls from approximately 27.6°C to 17.8°C. For an industrial dryer requiring the hottest possible air, the low-flow point may therefore be attractive; for a process that values total heat delivery, the higher-flow operating points may be preferable.

The pressure-drop trend moves in the opposite direction to the thermal gain, increasing from 25 to 75 Pa in the illustrative set. This is the reason that literature on roughened solar air heaters repeatedly reports both Nusselt number and friction factor. Multiple V-ribs can produce large heat-transfer enhancement but also increase friction (Hans et al., 2010), and gapped V-ribs similarly raise both quantities (Maithani & Saini, 2016). Broken arc ribs were reported to outperform a smooth duct in both heat transfer and friction measures, again demonstrating that a geometric improvement must be evaluated thermo-hydraulically rather than thermally alone (Hans et al., 2017).

For the proposed industrial design, an intermediate flow rate near 0.04-0.05 kg/s is a reasonable initial operating region because it combines a useful temperature lift with increased collected heat before the pressure penalty becomes dominant. The final optimum, however, must be selected from measured THPP, fan power, and the minimum supply-temperature requirement of the target process. If

heat is needed after sunset or through intermittent cloud, thermal storage can be added as a secondary design option, consistent with the extended heat-delivery concept demonstrated by Saxena et al. (2015).

Conclusion and Discussion

This methodology paper presents a compact design and evaluation procedure for a forced-convection solar air heater intended for industrial thermal applications. The design uses a blackened absorber, insulated enclosure, single transparent cover, controlled airflow, and low-height V/arc-type roughness on the absorber surface. The literature available up to 2017 shows that artificial roughness can materially improve absorber-to-air heat transfer, but it also increases pressure loss. Accordingly, the proposed method evaluates useful heat, outlet temperature, thermal efficiency, Nusselt number, friction factor, pressure drop, fan power, and thermo-hydraulic performance rather than relying on thermal efficiency alone. The illustrative calculations show why industrial selection is application-specific. Higher flow can improve useful heat collection and reduce absorber heat loss, but it reduces the outlet-air temperature rise and increases hydraulic resistance. A dryer or curing line that requires a minimum supply temperature may favor a lower or intermediate flow, whereas a preheating duty may benefit from higher flow and greater total heat delivery. Roughness geometry should therefore be optimized together with airflow, not independently. The proposed test matrix also allows smooth and roughened collectors to be compared at matched irradiance and flow

conditions so that the net benefit of rib roughness can be quantified through THPP and effective performance. For a full experimental study, the next step is to fabricate the collector, calibrate the sensors, carry out replicated steady-state tests over the specified irradiance and flow ranges, and report uncertainty bounds. Further work can compare single-pass and double-pass arrangements, add thermal storage, or evaluate life-cycle energy and economic performance. Within the 2017 literature boundary requested for this paper, the evidence supports roughened solar air heaters as a technically credible option for low- and medium-temperature industrial process-air applications when thermal enhancement and pumping power are considered together.

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