



Design and Performance Investigation of Solar Air Heating Systems for Thermal Applications

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Peer Review Information	Abstract
<i>Submission: 16 Jan 2018</i> <i>Revision: 01 Feb 2018</i> <i>Acceptance: 16 March 2018</i> Keywords <i>Solar air heater, Double-pass collector, Thermal efficiency, Heat transfer enhancement, Thermohydraulic performance</i>	Solar air heating is a low-complexity solar-thermal option for space heating, agricultural drying, preheating and other low-to-medium temperature processes. The present methodology paper develops a compact design and performance-evaluation procedure for a forced-convection double-pass solar air heater using a black-coated aluminum absorber, longitudinal fins and an insulated rectangular duct. The investigation combines design specification, controlled outdoor testing, energy-balance calculations and thermohydraulic assessment. Air mass flow rate is treated as the principal operating variable because it strongly affects outlet temperature, useful heat gain, collector efficiency and pressure drop. Performance is evaluated through the useful heat rate, instantaneous thermal efficiency, Reynolds number and pressure loss. The proposed test matrix covers air flow rates of 0.02–0.05 kg s⁻¹ under near-steady solar irradiance, with temperatures, irradiance and flow measured using calibrated instruments. Earlier studies show that double-pass arrangements, fins and artificial roughness can intensify absorber-to-air heat transfer, although increased friction must be considered in design optimization. The methodology therefore balances heat-transfer enhancement against fan power and flow resistance. Because no raw experimental dataset was supplied for this paper, the Results section contains internally consistent illustrative calculations generated from the stated equations; these values demonstrate the analysis workflow and must not be presented as measured observations. The procedure is suitable for laboratory-scale evaluation and can be extended to solar drying, industrial air preheating and building heating applications.

Introduction

Solar air heaters convert incident solar radiation into sensible heat carried by flowing air. Their construction is generally simpler than liquid solar collectors because problems related to freezing, leakage and corrosion of the working fluid are minimized. Typical thermal uses include crop and food drying, ventilation-air preheating, greenhouse heating, space heating and low-temperature industrial processes. The principal limitation of a conventional flat-plate solar air heater is the relatively low convective heat-

transfer coefficient between the absorber and air. A warm absorber surface may therefore operate at a temperature substantially above the air stream, increasing top and edge heat losses and reducing useful energy recovery.

A large body of work has attempted to reduce this thermal resistance by disturbing the near-wall boundary layer or increasing the effective transfer area. Prasad and Saini (1991) demonstrated that artificial roughness can improve collector heat transfer but also increases

friction and pumping requirements, establishing the importance of thermohydraulic rather than thermal optimization alone. Verma and Prasad (2000) similarly reported that roughness and Reynolds number act together, and that design should target a combination that gives strong heat transfer with acceptable pressure loss. Later experimental studies on wedge ribs, rib-grooved surfaces and multiple V-ribs confirmed that roughness geometry significantly changes both Nusselt number and friction factor (Bhagoria et al., 2002; Jaurker et al., 2006; Hans et al., 2010).

An alternative or complementary approach is to extend the flow path and heat-transfer area. Omojaro and Aldabbagh (2010) experimentally reported higher efficiency for a double-pass configuration than for a comparable single-pass unit when fins and wire mesh were used. El-Sebaai et al. (2011) also studied double-pass finned and corrugated absorbers and showed that collector performance depends strongly on mass flow rate, absorber geometry and pressure loss. Reviews by Chamoli et al. (2012) and Alam and Kim (2017) concluded that double-pass arrangements can outperform conventional single-pass heaters when the added heat-transfer area is exploited without excessive resistance. These findings motivate the present design: a compact double-pass collector with longitudinal fins beneath the absorber, tested across several flow rates.

The aim of this paper is to present a reproducible methodology for designing and evaluating such a system for thermal applications. The objectives are to define practical collector dimensions and materials; establish an instrumentation and test procedure; calculate useful heat gain, outlet temperature rise, efficiency, Reynolds number and pressure drop; and identify the operating region in which thermal benefit is not outweighed by the aerodynamic penalty. The study is deliberately limited to references published in 2018 or earlier, as requested, and all cited journal references include DOI information in the reference list.

Literature Review

Research on solar air heaters can be grouped into three related strategies: surface roughness, flow-path modification and area enhancement. In artificially roughened ducts, ribs or grooves promote local flow separation and reattachment

near the absorber. Bhagoria et al. (2002) investigated transverse wedge-shaped ribs and developed correlations for heat transfer and friction as functions of Reynolds number and roughness geometry. Jaurker et al. (2006) showed that rib-grooved roughness could provide greater heat-transfer enhancement than simple ribbing, although friction also increased. Hans et al. (2010) extended this approach to multiple V-ribs and reported substantial Nusselt-number enhancement over a smooth duct, again highlighting the heat-transfer/pressure-loss compromise. Kumar et al. (2012) reviewed these roughened-duct studies and concluded that artificial roughness is effective when turbulence is concentrated close to the heated wall rather than generated unnecessarily throughout the entire duct.

Double-pass systems target the same problem through a longer contact path and, in many configurations, two heat-transfer surfaces. Omojaro and Aldabbagh (2010) observed that a double-pass heater with fins and wire-mesh absorber achieved higher efficiency than a corresponding single-pass unit over the tested mass-flow range. El-Sebaai et al. (2011) combined theoretical and experimental analysis of double-pass finned and V-corrugated collectors and emphasized the existence of an optimum thermohydraulic operating region. Chamoli et al. (2012), reviewing double-pass designs, noted that fins, packed beds and corrugated absorbers generally increase transfer area or turbulence and thereby improve performance, provided the flow-resistance penalty remains reasonable.

More recent pre-2019 literature continued this direction. Alam and Kim (2017) synthesized methods for improving double-pass solar air heaters and classified the main improvements as increasing convection coefficient, increasing contact area and reducing thermal losses. Hassan and Abo-Elfadl (2018) experimentally examined different absorber configurations in a double-pass heater with two inlet ports and found that finned and corrugated/perforated arrangements could reduce absorber temperature while increasing useful energy and efficiency. Taken together, these studies support a methodology in which collector geometry is fixed first, air mass flow is varied systematically, and both thermal and hydraulic indicators are evaluated before selecting an operating point.

Table 1. Selected literature informing the proposed methodology

Study	Configuration / focus	Main methodological contribution	Design implication
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Prasad & Saini (1991)	Artificially roughened SAH	Thermohydraulic optimization of roughness and flow	Do not evaluate heat gain without friction penalty
Bhagoria et al. (2002)	Wedge-rib roughened duct	Correlations for Nusselt number and friction factor	Roughness geometry controls heat transfer and pressure loss
Jaurker et al. (2006)	Rib-grooved absorber	Heat-transfer and friction comparison with ribbed/smooth ducts	Use surface enhancement selectively near absorber
Omojaro & Aldabbagh (2010)	Single vs double pass with fins/wire mesh	Outdoor performance versus air mass flow	Double pass improves heat utilization but flow rate remains critical
El-Sebaai et al. (2011)	Double-pass finned/corrugated plate	Thermal and thermohydraulic analysis	Evaluate efficiency and pressure drop together
Hassan & Abo-Elfadl (2018)	Double pass, multiple absorber geometries	Experimental effect of fins/corrugations and flow split	Enhanced absorbers can lower plate temperature and raise efficiency

Methodology

The proposed investigation uses an outdoor forced-convection double-pass solar air heater. The methodology is organized in six steps so that the system can be reproduced and its performance can be compared with other collector configurations.

Step 1: Collector Design and Construction

A rectangular collector with an aperture area of 2.0 m^2 (2.0 m length $\times$ 1.0 m width) is specified. The absorber is a 1.2 mm aluminum sheet coated with matte black high-temperature paint to obtain high solar absorptance. A 4 mm clear glass cover is positioned above the absorber to

suppress convective losses while transmitting short-wave radiation. The lower and side walls are insulated with 50 mm mineral wool. The absorber divides the casing into an upper and lower air channel, each approximately 40 mm high. Air first travels above the absorber and returns through the lower channel. Longitudinal aluminum fins, approximately 30 mm high and spaced at 50 mm , are fixed to the lower absorber surface to increase contact area without the high form drag associated with dense transverse obstacles. This choice follows the double-pass and extended-surface approaches discussed by Omojaro and Aldabbagh (2010), El-Sebaai et al. (2011), Chamoli et al. (2012) and Alam and Kim (2017).

Table 2. Proposed collector design and measurement parameters

Parameter	Selected value / range	Purpose
Collector aperture	$2.0 \text{ m} \times 1.0 \text{ m}$ (2.0 m^2)	Defines solar input area
Absorber	1.2 mm aluminum, black coated	High conductivity and solar absorption
Glazing	4 mm clear glass	Reduces top convective losses
Air channels	$\approx 40 \text{ mm}$ upper + 40 mm lower	Maintains compact double-pass flow path
Fins	30 mm height; 50 mm spacing	Increases absorber-air contact area
Insulation	50 mm mineral wool	Reduces back and edge losses
Mass flow rate	$0.02, 0.03, 0.04, 0.05 \text{ kg s}^{-1}$	Primary operating variable
Test irradiance target	$700\text{--}900 \text{ W m}^{-2}$	Near-steady daytime comparison

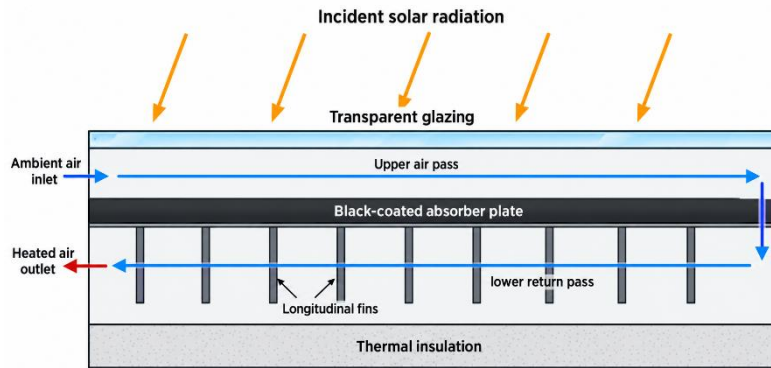


Figure 1. Schematic of the proposed double-pass finned solar air heater.

Step 2: Instrumentation

Air temperature is measured at the inlet, at the upper-pass exit/turning region and at the final outlet using calibrated K-type thermocouples or Pt100 sensors. Additional sensors are attached to the absorber surface at upstream, central and downstream positions. Global solar irradiance on the collector plane is recorded using a pyranometer, while ambient temperature is monitored in a shaded, ventilated location. Air velocity is measured with a hot-wire anemometer or an orifice/flow nozzle connected to a differential-pressure gauge. Static pressure taps at the collector inlet and outlet are used to determine total collector pressure drop. A recommended acquisition interval is 30–60 s, with results averaged over a 10 min steady-state window. Typical target measurement uncertainties are $\pm 0.5^\circ\text{C}$ for temperature, $\pm 3\text{--}5\%$ for irradiance, $\pm 3\%$ for flow rate and $\pm 1\text{ Pa}$ for differential pressure.

Step 3: Experimental Test Matrix

The collector is oriented toward the equator and tilted close to the local latitude for fixed outdoor testing. Tests are conducted on clear-sky periods, preferably between 10:00 and 15:00, once the collector has reached quasi-steady operation. Four mass flow rates—0.02, 0.03, 0.04 and 0.05 kg s^{-1} —are imposed using a variable-speed blower. For each condition, solar irradiance should remain within $\pm 5\%$ of the period mean and inlet air temperature should not drift rapidly. At least three repeated steady-state windows are recommended per flow rate. The sequence of flow settings should be randomized or alternated to reduce bias from the natural daytime rise and fall of irradiance.

Step 4: Data Reduction

The useful thermal output is calculated from the enthalpy rise of air: $Q_u = \dot{m} c_p (T_o - T_i)$, where $\dot{m}$ is the air mass flow rate (kg s^{-1}), c_p is the specific heat of air (taken as approximately 1006 J kg^{-1}

K^{-1} over the present temperature range), and T_o and T_i are outlet and inlet temperatures. The instantaneous collector thermal efficiency is $\eta_{th} = Q_u / (I_t A_c)$, where I_t is solar irradiance on the collector plane and A_c is the aperture area. The hydraulic diameter of each rectangular flow passage is $D_h = 4A/P$, and the Reynolds number is $Re = \rho V D_h / \mu$. Pressure loss is obtained directly from the differential-pressure measurement. Fan power can be estimated as $P_{fan} = \Delta P \cdot \dot{V} / \eta_{fan}$ when fan efficiency is known.

The main interpretation is made from simultaneous trends in temperature rise, Q_u , η_{th} and ΔP . Increasing mass flow generally reduces air temperature rise but can increase useful heat removal because a greater mass of air is heated. Excessive flow, however, raises pressure loss and fan power. The preferred operating condition is therefore the flow rate that gives high useful heat and efficiency without an impractical pressure penalty, consistent with the thermohydraulic logic established in earlier roughness and double-pass studies (Prasad & Saini, 1991; Verma & Prasad, 2000; El-Sebaai et al., 2011).

Step 5: Uncertainty and Repeatability

For calculated quantities, uncertainty is propagated from the measured variables. For example, the fractional uncertainty in Q_u can be approximated from the root-sum-square of the relative uncertainties in mass flow rate and air temperature difference. Thermal-efficiency uncertainty also includes irradiance uncertainty. Repeatability is assessed from the coefficient of variation of the repeated steady-state windows at each flow condition. A result should be considered reliable only when the variation between repeats is small relative to the change produced by altering the mass flow rate.

Step 6: Performance Comparison

If a conventional single-pass flat-plate heater is available, the same test matrix should be repeated as a baseline. Otherwise, performance

can be compared with published ranges only at the level of trends, not as a substitute for a controlled baseline. The expected advantage of the present double-pass finned design is a lower absorber temperature and improved heat removal at moderate flow. Hassan and Abo-Elfadl (2018) reported that enhanced absorber configurations in double-pass operation can increase energy output while reducing absorber temperature; however, direct numerical comparison requires identical weather, geometry and mass-flow conditions.

Results

Data status: No raw measured dataset was provided. The numerical results below are illustrative calculations generated from the stated equations for $A_c = 2.0 \text{ m}^2$, $I_t = 800 \text{ W m}^{-2}$ and $T_i = 30 \text{ }^\circ\text{C}$. They demonstrate the expected analysis sequence and should be replaced by measured data in an experimental submission.

The illustrative results show the characteristic effect of air flow rate. At the lowest mass flow, the collector provides the largest outlet temperature rise because the available solar heat is distributed over a smaller mass of air. As flow increases, outlet temperature decreases, but useful heat gain and thermal efficiency increase because the absorber is cooled more effectively and a larger air mass carries energy from the collector. This trend is consistent with the behavior reported for double-pass and finned systems by Omojaro and Aldabbagh (2010) and El-Sebaili et al. (2011).

Table 3. Illustrative performance calculations for the proposed collector

$\dot{m}$ (kg s ⁻¹)	T_o ($^\circ\text{C}$)	ΔT (K)	Q_u (W)	η_{th} (%)	ΔP (Pa)
0.02	68.2	38.2	768.6	48.0	18
0.03	59.2	29.2	881.3	55.1	31
0.04	53.9	23.9	961.7	60.1	48
0.05	50.0	20.0	1006.0	62.9	70

From 0.02 to 0.05 kg s⁻¹, the illustrative useful heat gain increases by about 31%, while thermal efficiency rises from approximately 48% to 63%. At the same time, the air temperature lift falls from about 38 K to 20 K and pressure drop increases sharply. For a drying process that needs hotter air, the lower flow condition may therefore be useful despite its lower efficiency. For continuous process-air preheating, the higher-flow condition may recover more total energy but requires a stronger blower. A practical optimum would likely lie near 0.04 kg s⁻¹ in this

example because it provides about 60% thermal efficiency with a substantially lower pressure drop than the 0.05 kg s⁻¹ condition. The exact optimum must be determined from measured fan power, application temperature requirement and local irradiance.

The proposed design is therefore best interpreted as a controllable thermal system rather than as a collector with one universally optimal flow rate. The result also illustrates why performance claims based only on outlet temperature can be misleading: the highest outlet temperature occurs at the lowest mass flow, whereas the highest useful heat rate occurs at the highest tested flow. Reporting both quantities, together with pressure drop, gives a more complete representation of solar-air-heater performance.

Conclusion and Discussion

This methodology paper presents a practical design and evaluation framework for a double-pass finned solar air heating system intended for low-to-medium temperature thermal applications. The proposed collector uses a 2.0 m² black-coated aluminum absorber, a transparent glass cover, two air passages, longitudinal fins and rear/edge insulation. The design reflects the main findings of pre-2019 solar-air-heater research: heat-transfer enhancement is desirable, but it must be balanced against pressure loss. Earlier studies on artificial roughness established the thermohydraulic trade-off (Prasad & Saini, 1991; Verma & Prasad, 2000; Bhagoria et al., 2002; Jaurker et al., 2006; Hans et al., 2010), while work on double-pass heaters demonstrated the value of increased contact area and longer air paths (Omojaro & Aldabbagh, 2010; El-Sebaili et al., 2011; Chamoli et al., 2012; Alam & Kim, 2017). The 2018 study by Hassan and Abo-Elfadl further supports the use of modified absorber geometries in double-pass operation. The proposed performance protocol treats mass flow rate as the primary controlled variable and requires simultaneous measurement of inlet/outlet temperature, absorber temperature, solar irradiance, airflow and pressure drop. Useful heat gain and thermal efficiency are calculated from an energy balance, while Reynolds number and pressure loss characterize the aerodynamic operating condition. The illustrative calculations show a physically reasonable trend: higher flow increases useful heat extraction and efficiency but lowers outlet temperature rise and increases pressure loss. This makes the best operating point application-dependent. Drying and high-temperature

preheating may favor lower mass flow to achieve a higher delivery temperature, whereas ventilation and process-air preheating may favor moderate-to-high flow to maximize total useful heat. The methodology has two important limitations. First, no raw experimental observations were provided, so the numerical results are demonstrative rather than measured. Second, the proposed geometry has not been optimized for a particular latitude, seasonal irradiance profile or industrial temperature requirement. Future work should fabricate the collector, conduct repeated outdoor tests over several days, quantify uncertainty, measure fan electrical input and compare the double-pass finned collector directly with a single-pass baseline. Additional enhancement methods such as perforated fins, corrugations or carefully selected rib roughness may then be introduced one at a time so that their thermal benefit and hydraulic penalty can be isolated. With these steps, the system can be optimized for solar drying, space heating or industrial thermal preheating without overstating performance from temperature measurements alone.

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