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A novel gridded solar air heater and an investigation of its conversion efficiency

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ABSTRACT

A new design of a cost-effective single pass gridded solar air heater (SAH) is presented featuring the optimization of flow resistance, mass flow rate, and efficiency. The SAH uses six layers of blackened aluminum grids as an absorber. The ensemble of six grids are corrugated in a triangular fashion such that the air has to traverse the six grids 16 times on one passage through the SAH. A special distribution manifold is used to achieve a relatively uniform flow profile across the width of the collector. Our investigation particularly studies the effect of mass flow rate on the output efficiency. We found that the conversion efficiency of our SAH approaches 80% as the mass flow rate is increased to $\dot{m} \approx 0.06$ kg/s. The increased efficiency can be attributed to reduced conductive, radiative, and convective losses at the higher mass flow rates. The experimental data confirms the theoretical prediction of the SAH's efficiency as a function of mass flow rate. Our findings have important implications for studies of matrix absorber SAHs, packed bed SAHs, and passive SAHs.

1. Introduction

Given the present status of our planet with regards to climate change it is of paramount importance that we focus our efforts on switching from fossil fuels to renewable energies and increasing our energy efficiency. One way to reduce carbon emissions is utilizing renewable resources. Solar air heaters are a resource that is renewable, providing low cost thermal energy.

Solar air heaters (SAHs) directly convert solar energy to thermal energy. Solar rays enter a rectangular box through a single or double-glazing and are absorbed by a specially designed absorber material (cf. below for a variety of absorbers). Air enters the SAH through an intake, and streams through the box (cf. below for various air flow patterns) interacting with the hot absorber surface, and leaves through an outflow aperture.

SAHs are typically used as supplemental space heating for homes and industrial buildings and are ideally suited to heat a garage, workshop, or woodshop. In some countries SAHs find application in drying food, such as dates, prunes, apples, and raisins, for preservation (Kareem et al., 2014; Dhanemozhi et al., 2013; El-Sebaii et al., 2012; Hanif et al., 2012). Solar air heaters can also be used for water desalination and purification (Kabeel and El-said, 2013; Yuan et al., 2011; Fath and Ghazy, 2002).

The most common and straightforward design is a SAH with a flat plate absorber, however SAHs come in a large variety of designs. SAHs are often designed to maximize thermal efficiency, and there are many different components of an SAH that can be modified in order to accomplish this goal. Various researchers have looked into comparing single-, double-, and triple-pass SAHs. Other design components that are investigated are the level of glazing (no glazing, single glazing, double glazing, and transpired glazing), the absorbing material (various metals, materials, colors/paints and geometries), and flow enhancing materials (ribs, fins, baffles and grids). Researchers also investigate passive SAHs (without a fan or other type of equipment to move the air), and SAHs with thermal storage. For more information about the theory, Eicker (2003) describes in great detail the basic physics of solar air heaters. Tchinda (2009) provides an excellent review of mathematical models for the performance of SAH systems.

The investigation of this article is primarily concerned with our SAH's mass flow rate and the corresponding thermal efficiency. As such, we provide a table of mass flow rates and efficiencies of researchers' recent SAHs for comparison. Each of the teams of researchers listed in Table 1 designed and published an article about the specified SAH. The last column (η) is the maximum efficiency the researchers achieved with their SAH and reported in their article. The second to last column ($\dot{m}$) is their SAH's mass flow rate when they achieved the maximum efficiency. We would like to point out that the reported efficiencies cannot strictly be

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Nomenclature

A_p	aperture area of SAH, m^2
A_B	area of bottom of SAH, m^2
A_G	area of glazing, m^2
A_T	cross sectional area of PVC tube, m^2
A_{VA}	cross sectional area of Vernier Anemometer (VA), m^2
A_W	area of one sidewall, m^2
$A_{W,tot}$	total area for all side walls, m^2
c_p	specific heat capacity of air at constant pressure, kJ/(kg K)
dA_W	infinitesimal area segment of a sidewall, m^2
ds	infinitesimal length segment, m
h_{cond}	conductive heat loss coefficient
h_{conv}	convective heat loss coefficient
h_{rad}	radiative heat loss coefficient
h_{comb}	combined heat loss coefficient
H	height above sea level, m
i_{ILF}	current drawn by inline fan, A
I	solar irradiance, W/m^2
k_b	thermal conductivity of pine board, $W/(m^2\,K)$
k_i	thermal conductivity of insulation, $W/(m^2\,K)$
l_b	thickness of pine board, m
l_i	thickness of insulation, m
$\dot{m}$	mass flow rate of air, kg/s
$p_a(i)$	pressure before aperture i, Pa
$p_b(i)$	pressure after aperture i, Pa
Δp	pressure drop across the SAH, Pa
P_{in}	solar power into SAH, W
P_{ILF}	power consumed by inline fan, W
P_{sol}	solar power incident on glazing, W
$\dot{Q}_{fl}$	heat flow rate to working fluid, W
$\dot{Q}_{cond}$	conductive heat loss rate, W
$\dot{Q}_{cond,W}$	conductive heat loss rate through a side wall, W
$\dot{Q}_{rad}$	heat loss rate due to radiation, W
$\dot{Q}_{loss}$	total heat loss rate, W
r	radial coordinate in PVC tube, cm
R	inner radius of PVC tube, cm
R_b	thermal resistance of pine board, m^2 K/W
R_B	thermal resistance of bottom of SAH, m^2 K/W
R_G	thermal resistance of glazing, m^2 K/W
R_i	thermal resistance of insulation, m^2 K/W
R_W	thermal resistance of sidewall, m^2 K/W
$R_{W,tot}$	thermal resistance of all sidewalls
RH	relative humidity
s	distance along length of SAH, m
S	total length of SAH, m
T_{amb}	temperature of ambient air, K
T_{fl}	temperature of working fluid (air), K
T_{in}	temperature of air at intake, K
T_{ins}	temperature of air inside SAH, K
$\langle T_{ins} \rangle$	average temperature inside SAH, K
T_{out}	temperature of air at outflow, K
v_{eq}	equivalent uniform velocity within PVC tube, m/s
$v_{eq,VA}$	equivalent uniform velocity within plane of Vernier Anemometer, m/s
v_{HW}	velocity of air as measured by Hot Wire Anemometer, m/s
v_{VA}	velocity of air as measured by Vernier Anemometer, m/s
V_{ILF}	voltage across inline fan, V
w_W	width of sidewall, m
α	albedo/reflectivity of glazing
β	calibration factor for Vernier Anemometer
ΔT	temperature difference between outflow and intake, K
ε	emissivity
η	solar to thermal energy conversion efficiency
ρ	density of air, kg/m^3
σ	Stefan–Boltzmann constant ($= 5.6704 \times 10^{-8}\ W/m^2 \cdot K^4$)

Table 1
Mass flow rates and thermal efficiencies for recent SAH designs.

Researchers	Type of SAH	Description	$\dot{m}$ (kg/s)	η (%)
Chabeane et al. (2012)	Baffles/fins	SAH with longitudinal fins	0.016	51.5
Karwa and Srivastava (2013)	Baffles/fins	SAH with V-down discrete rib roughness	0.02	62
Sharma et al. (1991)	Matrix	SAH packed with blackened wire screen matrices	0.021	61.0
Gill et al. (2012)	Packed bed	Packed bed SAH with iron chips	0.03	71.7
Romdhane (2007)	Baffles/fins	SAH with partially transversal baffles	0.033	80
Maheshwari et al. (2012)	Baffles/fins	SAH with baffled duct	0.034	84
Mahmood and Aldabbagh (2013)	Fins, matrix	SAH with 4 transverse fins and wire mesh layers	0.036	65.6
Vaziri et al. (2015)	Transpired	Perforated glazed SAH with different collector colors	0.036	85
Chamoli et al. (2012)	Double pass, matrix	Double pass SAH with steel wire mesh layers	0.038	83.7
Kolb et al. (1999)	Matrix	SAH with metal matrix absorber	0.041	81
El-khawajah et al. (2011)	Double pass, baffles/fins, matrix	Double pass SAH with transverse fins and wire mesh	0.042	85.9
Mohammadi and Sabzpooshani (2013)	Baffles/fins	Single pass SAH with fins and baffles	0.05	72.6
Pfister et al. (2015)	Matrix, distrib. manifold	SAH with corrugated mesh grids and distr. manifold	0.06	80
Yang et al. (2014)	Baffles/fins	SAH with offset strip fin absorber plate	0.061	49.8
Aissa et al. (2012)	Thermal storage	Flat plate with storage	0.08	60
Esakkimuthu et al. (2013)	Thermal storage	SAH with phase change material for thermal storage	0.111	60
Saravanakumar and Mayilsamy (2010)	Flat plate	Forced convection flat plate		60
Saxena et al. (2013)	Thermal storage	SAH with long term heat storage		73.7

compared to each other as some of the SAHs use single-glazing, others use double-glazing, which affects the respective SAH's efficiency. Furthermore, the SAHs were not tested under the same conditions; some were tested in warmer climates, others were tested in colder climates, affecting their respective conductive, convective, and radiative heat losses and thus their efficiencies. Nevertheless, the reported efficiencies allow us to roughly compare these SAHs.

Over the course of the past two years we have developed an improved design of a cost-effective SAH, with design criteria guided by theoretical predictions. However, instead of trying to achieve a record solar to thermal conversion efficiency regardless of cost, our goal was to design a SAH that is easy to manufacture, has a very short return on investment time (ROI) and yet a very high conversion efficiency. Our self-imposed "simplicity requirement" eliminated designs with intricate air paths through the