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Thermal performance of a packed bed double-pass solar air heater

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Abstract

The thermal performance of a double-glass double-pass solar air heater with a packed bed (DPSAHPB) above the heater absorber plate was investigated experimentally and theoretically. Suitable computer program was developed for the analytical solution of the energy-balance equations for the various elements of the system. Limestone and gravel were used as packed bed materials. Numerical calculations were carried out, on typical summer days of 2003, to study the effect of different operational and configurational parameters on the heater performance. Effects of the mass flow rate of air $\dot{m}_f$ and the mass and porosity of the packed bed material were also studied. It was inferred that for increasing the outlet temperature T_{flo} of the flowing air after sunset, it is advisable to use the packed bed materials with higher masses and therefore with low porosities. The thermohydraulic efficiency η_{TH} was found to increase with increasing $\dot{m}_f$ until a typical value of 0.05 kg/s beyond which the increase in η_{TH} becomes insignificant. It is recommended to operate the system with packed bed with values of $\dot{m}_f$ equal 0.05 kg/s or lower to have a lower pressure drop across the system. To validate the proposed mathematical model, comparisons between experimental and theoretical results showed that good agreement was achieved.

Keywords: Packed bed solar air heaters; Pressure drop; Thermal power; Thermohydraulic efficieny

1. Introduction

There are two major limitations of conventional-type solar air heaters. The first is the heat transfer from the metallic plate to the flowing air is rather poor as the conductivity of air is low. The second arises from the combined effect of low heat transfer from the plate to the flowing air due to the relatively small thickness of the absorber plate. This can be tackled by increasing the heat transfer area through the use of matrix or porous bed absorbers. Due to the voids exist within the porous packed bed, the solar radiation penetrates to a greater depth in the bed and is absorbed at successive depths. The packed bed material provides an increase of turbulence of air which increases the heat transfer rate from the bed to the flowing air. The bed also acts as an extended absorbing surface for solar radiation and provides a heat storage capability. On the other hand, the double-pass mode of solar air heaters has the advantage of decreasing the heat losses and provides improvement in heat transfer rate as well as the efficiency without increasing the heater size or cost. In addition, the flowing air gains more heat from the absorber plate on circulation through the lower channel.

The smooth duct single-pass solar air heaters with different shapes of the absorber plate were investigated by Koyuncu [1] and Chaube et al. [2]. Karim and Hawlader [3] investigated experimentally and theoretically flat plate, finned and v-corrugated solar air heaters with single and double-pass modes. The flat plate double and four-pass solar air heaters with external recycle were studied experimentally and theoretically by Ho et al. [4,5].

The single channel packed bed solar air heaters were discussed by several investigators [6–9]. Sharma et al. [6] outlined that the solar air heater with packed bed can provide low grade heat around 15–20 °C above the ambient temperature. Bhagoria et al. [10] concluded that the mild-steel chips, as a packing material, gives better performance than marble chips. Wire-screen matrix bed solar air heaters were experimentally investigated by Prasad and Saini [11]. Mohamad [12] investigated the two-pass solar air heater with various porous media in the lower channel.

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Nomenclature

A	surface area (m^2)
B	width of the heater (m)
C	specific heat (J/kg K)
D	depth of the air channel (m)
dx	a unit length (m)
D_e	characteristic length of the packed bed material particles (m)
D_h	hydraulic diameter (m)
f	friction factor
h	heat transfer coefficient (W/m^2 K)
h_b	convective heat transfer coefficient between the air flowing in the lower channel and the back plate (W/m^2 K)
h_{gl}	convective heat transfer coefficient between the air flowing through the packed bed and the lower glass cover (W/m^2 K)
h_{p1}	convective heat transfer coefficient between the air flowing in the upper channel and absorber plate (W/m^2 K)
h_{p2}	convective heat transfer coefficient between the air flowing in the lower channel and absorber plate (W/m^2 K)
I	global solar radiation on a horizontal surface (W/m^2)
K	empirical constant, Eq. (28c)
k	thermal conductivity (W/m K)
L	length of the heater (m)
M	mass (kg)
$\dot{m}$	mass flow rate of air (kg/s)
N	number of experimental measurements
Nu	Nusselt number (dimensionless)
ΔP	pressure drop (N/m^2)
Pr	Prandtl number (dimensionless)
Q_u	thermal output power (W)
Re	Reynold's number (dimensionless)
RPE	relative percentage error
SE	square errors of the experimental results
T	temperature (K)
U_b	back loss coefficient (W/m^2 K)
U_s	side loss coefficient (W/m^2 K)
V	velocity of flowing air (m/s), volume (m^3)
V_s	total volume of n particles (m^3)
x	thickness of the insulating material (m)
x_i	experimental data
$\hat{x}_i$	theoretical prediction

Subscripts

a	ambient
av	average
b	back
c	convective
f	fluid
g	glass
i	inlet
l	lower
m	packed bed material
o	outlet
p	absorber plate
r	radiative
s	sky, side
TH	thermohydraulic
u	upper
w	wind

Greek

α	absorptivity
τ	transmissivity
ε	porosity
η	efficiency
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m s)

In a previous work [13], the thermal performance of a double-pass solar air heater (DPSAH) without packed bed was investigated experimentally and theoretically for different mass flow rates of air $\dot{m}_f$ and various upper-to-lower channel depth ratios (d_{fu}/d_{fl}). The best performance was achieved with the lower mass flow rates when (d_{fu}/d_{fl}) equal 1. In this paper, experimental and theoretical investigations of the double-pass solar air heater with packed bed (DPSAHPB) above the heater absorber plate (in the upper channel) were performed. Limestone and gravel were used as packed bed materials. Comparisons between experimental and theoretical results showed that good agreement has been achieved.

2. Construction of the DPSAHPB and experiments

A schematic diagram of a double-glass DPSAHPB with 1 m^2 surface area is shown in Fig. 1. The different heat transfer mechanisms in terms of the various heat transfer coefficients are also shown in Fig. 1. The air was firstly forced through the packed bed exists in the upper channel, formed between the lower glass and the absorber plate, and is then re-circulated to flow in opposite direction through the lower channel, formed between the absorber and back plates. The circulated flow was achieved by the simple expedient of shortening the absorber plate relative to the other components of the heater. This allowed for a gap between the absorber plate and the end of the casing. The absorber plate could be moved up and down to vary the depths of the upper and lower channels with a total depth of the gap between the lower glass and back plate equals 0.12 m. The heater was oriented facing south and tilted with an angle of 30° with respect to the horizontal to maximize the solar radiation received by the glass covers all