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Original Research Article

Parametric investigation on thermo-hydraulic performance of wire screen matrix packed solar air heater

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ABSTRACT

This paper presents performance results of a wire screen matrix packed solar air heater based on a mathematical model developed to investigate the effect of various system and operating parameters on the thermo-hydraulic performance. A computer programme is developed in C++ to estimate the temperature rise of the entering air for evaluation of effective efficiency by solving the governing equations numerically using relevant correlations for heat transfer coefficient for packed bed systems. The mathematical model developed is compared with the experimental results as well as previous model and the results are found fairly in agreement. Further, a correlation is developed for determination of extinction coefficient based on the geometrical parameter of matrix. Comparative study of thermo-hydraulic performance of high and low porosity matrices indicate the superiority of high porosity matrices as maximum effective efficiency for high porosity matrix is 76% while for low porosity it is found to be 50%, showing an overall enhancement of about 26%. The effective efficiency value clearly indicates that there exists an optimum duct depth (0.015–0.035 m), duct length (2–5 m) and width (0.2–0.6 m) which results in best thermo-hydraulic performance for various mass flow rates and the maximum effective efficiency is obtained for duct depth of 0.015 m, length 5 m and width 0.5 m.

Introduction

Due to rapid demand of increasing energy day by day there is need to harness non conventional energy sources especially solar energy, else fossil fuels will be completely exhausted. The primary advantage of solar energy is it's free availability and pollution free nature but the major drawback is that it is intermittent in nature.

Solar air heater is the best alternative available for low to moderate temperature applications and being simple and compact it can be efficiently used for space heating, timber seasoning, drying fruits, vegetables, agriculture crops and seeds but the main draw back with solar air heater is that heat transfer rate from absorber to air is poor as the specific heat of air is low and so heat loss to the surroundings is high. Lot of work has been done to enhance the heat transfer rate and eventually thermal performance to have effective utilization of these systems. The various efficiency enhancement techniques includes use of corrugated or extended surfaces named fins thereby increasing the heat transfer area which in turn increases the convective heat transfer coefficient due to turbulence at surface, this method is popularly termed as providing artificial roughness at absorber plate [1–7]. Another approach to enhance heat transfer is to use packed beds of expanded metal foils or matrices between the glazing and the bottom plate. Incoming radiations are absorbed as these travel through a porous bed consisting of packing elements of different shapes, sizes and porosities. Various types of packing elements used for solar air heaters include metal sphere, glass beads, crushed glass, iron turnings, slit and expanded aluminum foils and wire screens. It offers several advantages which include high heat transfer area to volume ratio, high heat transfer coefficient and absorption of energy 'in depth' resulting in reduced top layer temperature and thus less heat losses with higher efficiency.

Solar air heater packed with semi-transparent materials like glass beads or glass tubes have been investigated both experimentally and analytically by Hasatani et al. [8]. The experiments were conducted by modeling the radiative heat source for which eight infrared lamps (100 V–125 W) were used. The lamps were arranged in two rows obtaining uniform flux above the glass cover. The collector used had the test section of size 1 m × 0.1 m × 0.3 m. The solution of energy balance equation developed for bed showed that the solar air heater with packed bed has higher efficiency of energy collection in comparison with that for a conventional flat plate collector.

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Nomenclature

A_c	collector plate area, m^2
A_f	frontal area of collector bed, m^2
a_v	heat transfer area per unit volume of bed
C	conversion factor
C_p	specific heat of air, J/kg K
D	depth of bed, m
D_e	equivalent diameter of particle ($=6/a_v$), m
d_w	wire diameter of screen, m
f_p	friction factor in packed bed
G	air mass flow rate per unit collector area, kg/(s m^2)
G_o	mass velocity of air, kg/(s m^2)
h_c	convection heat transfer coefficient between air and matrices, W/(m^2 K)
h_v	volumetric heat transfer coefficient, W/(m^3 K)
h_w	wind heat transfer coefficient, W/(m^2 K)
I	intensity of solar radiation, W/m^2
I_1	irradiation at the inner surface of lower glass cover, W/m^2
I_2	irradiation at the bottom plate of packed bed collector, W/m^2
I_y	intensity of solar radiation at depth y from top surface of the bed, W/m^2
J_h	Colburn J-factor ($=S_t P_r^{2/3}$)
K_a	thermal conductivity of air, W/(m K)
K_{eff}	effective thermal conductivity of packed bed, W/(m K)
L	length of collector bed, m
m	mass flow rate of air, kg/s
n	number of screens in a matrix
P	porosity
P_m	mechanical power, W
P_r	Prandtl number
p_t	pitch of wire mesh, m
ΔP	pressure drop in the duct, N/m^2
q_u	useful heat gain, W
Q	volume flow rate, m^3/s
Q_r	radiative heat flux at a distance y, W/m^2
r_c	reflectivity of glass cover
r_h	hydraulic radius ($=Pd_w/4(1-P)$), m
R_{tg}	radiosity at the top surface of upper glass cover, W/m^2
R_{bg}	radiosity at the bottom surface of lower glass cover, W/m^2
R_{bp}	radiosity at the bottom plate, W/m^2
R_y	radiosity at a distance y from top surface, W/m^2
R_{ep}	packed bed Reynolds number ($=2G_oD_e/3(1-P)\mu$)
r_c	reflectivity of glass cover
r_h	hydraulic radius ($=Pd_w/4(1-P)$), m
S_t	Stanton number ($=h_c/(C_pG_o)$)
t_a	ambient temperature, °C
t_b	bed temperature, °C
t_g	air temperature, °C
t_i	air inlet temperature, °C
t_o	air outlet temperature, °C
t_p	temperature of packing material, °C
U_t	top loss coefficient, W/(m^2 K)
v	velocity of air in the duct, m/s
x	distance in horizontal direction from inlet, m
y	distance in vertical direction from top surface, m
η_{eff}	effective efficiency
η_{th}	thermal efficiency
η_{thp}	thermal efficiency predicted
η_{the}	thermal efficiency experimental
η_{hp}	effective efficiency of high porosity matrix
η_{lp}	effective efficiency of low porosity matrix

Greek symbols

ε_p	emissivity of back plate
μ	dynamic viscosity of fluid, N s/m^2
ρ	density of air, kg/m^3
τ'	transmissivity of cover glass
τ_o	optical depth at $y = D$ ($=\vartheta D$)
$(\tau)_{eff}$	effective transmittance for double glass cover system
ϑ	extinction coefficient, m^{-1}

An experimental investigation of the thermal performance of double glass double pass solar air heater with packed bed (DGDPSAHPB) has been carried by EI-Sebaii et al. [9] to study the effect of mass flow rate and porosity on the air outlet temperature, thermal output power, pressure drop and thermo hydraulic efficiency. Study reveals that the heat transfer is enhanced by using gravel instead of lime stone as a packed bed above the absorber plate and the annual averages of the outlet temperature and thermo hydraulic efficiency of the DGDPSAHPB are about 16.5% and 28.5% higher than those of double glass, double pass solar air heater. A theoretical and experimental investigation of double glass double pass solar heater with packed bed (DGDPSAHPB) above the heater absorber plate has been carried by Ramadan et al. [10]. The lime stone and gravels were used as packed bed materials and effect of mass flow rate of air and porosity of packed bed material was studied and it was found that for increasing the outlet temperature of the flowing air after sunset, it is advisable to use higher masses and low porosities. The thermo-hydraulic efficiency is found to increase with increasing mass flow rate until the flow rate of 0.05 kg/s beyond which the increase in efficiency becomes insignificant and operating range of mass flow rate is set to 0.05 kg/s or less in order to have low pressure drop across the system.

The thermal performances of single and double pass solar air heaters with steel wire mesh layers instead of a flat absorber plate were investigated experimentally by Aldabbagh et al. [11]. The results indicate that the efficiency increases with increasing the mass flow rate within the range of 0.012–0.038 kg/s. For the same range of flow rate, efficiency of double pass is 34–45% higher than single pass and the maximum efficiency attained in single and double pass is 45.93% and 83.65% respectively for the flow rate of 0.038 kg/s. Karthikeyan et al. [12] performed parametric studies on the performance of a packed bed storage unit filled with phase change material (PCM) encapsulated spherical containers, suitable for low temperature solar air heating applications. A parametric analysis was carried out using the validated enthalpy based numerical model that considers the thermal gradient inside the PCM container. The results of simulation analysis showed that the size of the PCM ball, fluid inlet temperature and the mass flow rate of the heat transfer fluid (HTF) influenced respectively the heat transfer area in the packed bed, temperature difference between the HTF and PCM and the surface convective heat transfer coefficient between the HTF and PCM balls.

Sopian et al. [13] conducted experimental studies on the double pass solar collector with and without porous media. The double-pass solar collector with porous media in the lower channel