Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 132 (2016) 591–605

SOLAR ENERGY

www.elsevier.com/locate/solener

Investigations on thermal performance characteristics of wire screen packed bed solar air heater

Vimal Ku. Chouksey *, S.P. Sharma

Department of Mechanical Engineering, N.I.T. Jamshedpur, Jharkhand, India

Received 29 July 2015; received in revised form 10 March 2016; accepted 18 March 2016
Available online 12 April 2016

Communicated by: Associate Editor I. Farkas

Abstract

This paper presents the theoretical investigations of thermal performance characteristics of solar air heater having its duct packed with blackened wire screen matrices. The heat transfer equations for two dimensional fully developed fluid flow under quasi-steady state conditions have been developed in order to analyze the thermal efficiency and temperature rise and to study the effect of system and operating parameters. Finite difference solution algorithm has been developed for obtaining numerical solutions of the governing equations for energy transfer. A computer programme is developed in C++ language to estimate the temperature rise of the entering air for evaluation of thermal efficiency by solving the governing equations numerically using relevant correlations for heat transfer coefficient for packed bed systems. Results of temperature distributions and other performance parameters obtained from analysis have been compared with available experimental results. The percentage deviation between the experimental and the analytical values of the dimensionless air temperatures of air and thermal efficiency have been found to be in the range of 7.18 to -9.83 and 7.20 to -9.65 respectively. This establishes the validity of proposed analytical model for the investigation of thermal performance characteristics of packed bed solar air heaters.

Keywords: Solar energy; Packed-bed; Solar air heater; Plane collector

1. Introduction

Flat plate collectors are extensively used in low temperatures solar energy technology and have attracted the attention of large number of investigators. Several designs of solar air heaters have been developed over the years in order to improve their performance. There has been significant interest in packed-bed absorbers for air heating collector because of some distinct advantages over that of flat plate collectors. Packed-bed matrix absorbs solar radiation ‘in depth’ and has high ratio of heat transfer area to volume and high heat transfer capability, resulting in relatively low absorber temperature. This will decrease the heat losses from absorber to ambient air and hence result in an increase in the efficiency of the collectors. Absorber having a bed packed with slit-and-expanded aluminum foils matrix (Shoemaker, 1961; Chiou, 1965), iron turnings (Cheema and Mannan, 1979), crushed glass (Collier, 1979), hollow spheres (Swartman and Ogunlade, 1966), iron chips, aluminum chips and pebbles (Mishra and Sharma, 1981), wire mesh screens (Sharma et al., 1991; Beckmann, 1968; Ahmad et al., 1996) have been reported. These studies indicate that such air heaters have superior performance as compared to that of plane collector. A packed-bed solar air heater having its bed packed with

* Corresponding author. Tel.: +91 7870527386.
E-mail address: vimalkumarchouksey@gmail.com (V.Ku. Chouksey).

http://dx.doi.org/10.1016/j.solener.2016.03.040
0038-092X/

Nomenclature

A_c collector plate area (m^2)
A_p surface area of packing material (m^2)
A_f frontal area of collector bed (m^2)
A_v surface area per unit volume (m^{-1})
c_p specific heat of air ($J\,kg^{-1}\,K^{-1}$)
D depth of the channel (m)
D_e equivalent diameter of packing material $\left(=\frac{6V_p}{A_p}\right)$ (m)
d wire diameter of screen (m)
G mass flow rate per unit collector area ($kg\,s^{-1}\,m^{-2}$)
G_0 average mass velocity in matrix based on free flow area ($=m/pA_{fr}$) ($kg\,s^{-1}\,m^{-2}$)
h_c convective heat transfer ($W\,m^{-2}\,K^{-1}$)
h_{rs} radiative heat transfer coefficient from solid surface to solid surface ($W\,m^{-2}\,K^{-1}$)
h_{rv} radiative heat transfer coefficient from void to void ($W\,m^{-2}\,K^{-1}$)
h_v volumetric heat transfer coefficient ($W\,m^{-3}\,K^{-1}$)
h_w wall heat transfer coefficient for glass cover ($W\,m^{-2}\,K^{-1}$)
I intensity of solar radiation (Wm^{-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 intesity of solar radiation at depth y from top surface of the bed ($W\,m^{-2}$)
k_e effective thermal conductivity of packed bed ($W\,m^{-1}\,K^{-1}$)
k_g, k_s thermal conductivity of air, bed material respectively ($W\,m^{-1}\,K^{-1}$)
k_e^0 stagnant bed thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L length of the channel (m)
l_v effective thickness of fluid film in void (m)
m mass flow rate of air ($kg\,s^{-1}$)
n refractive index of packing
Nu Nusselt number
p porosity of the bed
p_l longitudinal pitch (mm)
p_t transverse pitch (mm)
Pr Prandtl number ($=\mu c_p/k_g$)
q_u useful heat gain (W)
Q_r radiative heat fluxe ($W\,m^{-2}$)
r_c reflectivity of cover glass
r_H hydraulic radius $\left[=\frac{V_p}{A_p}\left(\frac{p}{1-p}\right)\right]$ (m)
R radiosity at the top surface of upper glass cover ($W\,m^{-2}$)
R_I radiosity at the bottom surface of lower glass cover ($W\,m^{-2}$)
R_2 radiosity at the bottom plate ($W\,m^{-2}$)
R_y radiosity at a distance y from top surface ($W\,m^{-2}$)
$\Re$ Reynolds number ($=4r_H G_0/\mu$)
Re_m modified Reynolds number $\left(=\frac{Re(1-Fp)}{Fp}\right)$
St Stanton number ($=h_c/G_0 c_p$)
T_a, T_b, T_g, T_p, T_c temperatures of surrounding, bed, air, packed material and cover glass respectively (°C)
T_i, T_o inlet and outlet temperature of air respectively (°C)
ΔT air temperature rise (°C)
$\bar{u}$ flow velocity in duct (ms^{-1})
U_L overall loss coefficient ($W\,m^{-2}\,K^{-1}$)
V_p volume of packing material (m^3)
x distance in horizontal direction from inlet (m)
$\bar{x}$ dimensionless distance ($=x/L$)
$\Delta\bar{x}$ non-dimensional elemental thickness in x-direction
y distance in vertical direction from top surface (m)
$\bar{y}$ dimensionless depth ($=y/D$)
W width of the channel

Greek symbols
α absorptivity of wire screen matrices
α_c absorptivity of cover glass
τ optical depth
τ_0 optical depth at $y=D$ ($=\beta D$)
$\Delta\tau$ non-dimensional elemental thickness in y-direction
ρ density of air ($kg\,m^{-3}$)
σ Steafan–Boltzmann constant
β extinction coefficient of matrix (m^{-1})
ε emissivity of solid surface
ε_w emissivity of bottom plate
φ angle factor i.e. the ratio of effective thickness of fluid film in the void in relation to thermal conduction to equivalent diameter of packing material ($=l_v/D_e$)
μ dynamic viscosity of fluid ($Ns\,m^{-2}$)

optically semi-transparent material was proposed and heat collection and storage characteristics were investigated theoretically and experimentally by Hastani et al. (1985). It was observed from the analysis of experimental data that solar air heaters in which optically semi-transparent materials like glass beads or glass tubes were used for heat collection and storage material had higher efficiency of energy collection in comparison to a usual flat plate