Solar Energy 171 (2018) 258–270

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Simulation and experimental investigation of fluid flow in porous and non-porous solar air heaters

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ARTICLE INFO

Keywords:
Packed bed
Heat transfer
Friction factor
Solar energy
Fluid flow
Colburn factor

ABSTRACT

The porous absorber in the solar air heater gives considerable temperature increment which is shown by computational fluid dynamic simulation and verified experimentally. Experimental analysis on porous (wire screen) and non-porous solar air heaters were carried out to study the heat transfer and friction factor characteristics. The analysis encompasses the investigation on effect of mass flow rate on air temperature increment, thermal efficiency and pressure drop across the test section. The heat transfer parameter is established in terms of Colburn (J_h) factor for porous bed solar air heaters. The effect of friction factor on different geometries for a range of operating Reynolds number (194–591) is presented. Two wire screen matrix (WSM) solar air heater WSM-I and WSM-II were investigated which has different diameter, pitch and porosity. Thermal efficiency increased on introducing the packed wire-screen matrix diagonally in the air flow path. The increase in thermal efficiency for WSM-I and WSM-II were found to be 5–17% and 5–20% respectively with the mass flow rate ranging from 0.01 kg/s to 0.055 kg/s. The collector heat removal factor was found to be 0.95 ± 0.021 for wire mesh absorber and 0.72 ± 0.0073 for conventional type. The pressure drop across the length of the duct was studied to be in the range of 15 ± 0.28 Pa to 17 ± 0.28 Pa and 7 ± 0.16 Pa to 11 ± 0.28 Pa for WSM-I and WSM-II respectively and for conventional type it was between 5 ± 0.20 Pa and 10 ± 0.28 Pa.

1. Introduction

The half of the global energy consumption accounts for heat production. Despite this huge energy consumption, the heating sector receives less attention. The source for heat is generally derived from fossil fuel reserves and biomass and the demand for fossil fuels and their adverse impact on environment gave rise to the development of alternate energies. Solar energy is a naturally available resource that is free of cost. Proper design and implementation of technology will help in utilizing the freely available energy to a maximum extent. Solar thermal collector is a kind of technological advancement in deriving the sun's energy for fluid heating application. Solar flat plate collectors are mainly used for low and medium temperature applications. Solar air heater is a simple flat plate collector that has an air passage between the absorber plate and back plate. Due to the low heat capacity of air, the efficiency of the system is less as compared to water heating system. Modification of different components of flat plate air heater may help succeeding higher efficiency. The mode of air flow also plays an important role in reducing heat loss. Double pass (El-khawajah et al., 2011), double pass with external recycle (Ho et al., 2013; Singh and Dhiman, 2014; Yeh and Ho, 2011), n-pass solar air heater (Mahdi and Baharna, 1991) are some of the studied designs. The modification in the design includes absorber plate modification and glazing modification. Absorber plate modification includes dimpled shape roughness element (Sethi and Thakur, 2012), W-shaped rib roughness (Lanjewar et al., 2011), broken arc ribs (Hans et al., 2017), V-down rib (Singh et al., 2012; Karwa and Chitoshiya, 2013), corrugated absorber (Chouchury and Garg, 1991), multiple V ribs (Hans et al., 2010). Providing one or more glazing as a top cover reduces the long wave radiation from escaping to the surrounding (Dhiman et al., 2011). Porous absorber is of another type that allows the fluid to pass through the absorber, so that the fluid comes more in contact with the high temperature absorber and the heat transfer rate enhances. Porous medium can be created in the air flow duct to increase the heat transfer area by using aluminum cans (Ozgen et al., 2009), cylindrical glass honeycombs (Buchberg and Edwards, 1976), square celled honeycomb (Ghoneim, 2005), etc. Packing the duct with wire mesh or matrix material is another kind, in which few simulation studies were reported (El-Sebaii et al., 2007; Ramadan et al., 2007; Rajarajeswari and Sreekumar, 2016).

The optimization of geometrical parameters of wire mesh and operating mass flow rate are the main challenges of porous bed solar air heaters. The optimization of geometrical parameters of wire mesh and

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https://doi.org/10.1016/j.solener.2018.06.079
Received 11 April 2018; Received in revised form 5 June 2018; Accepted 20 June 2018

Nomenclature

A	effective heat transfer area (m^2)
A_f	frontal area (m^2)
A_p	absorber area (m^2)
C_p	specific heat capacity of air (J/kg K)
C_z	inertial resistance (m^{-1})
d_w	wire diameter (m)
D	thickness of porous bed
D_e	equivalent diameter (m)
f	coefficient of friction
F_R	collector heat removal factor
F'	collector efficiency factor
G_o	mass velocity of air (kg s^{-1} m^{-2})
h_c	convective heat transfer coefficient from Absorber to fluid (W/m^2 K)
$h_{c'}$	convective heat transfer coefficient from back plate to fluid (W/m^2 K)
h_r	radiative heat transfer coefficient from Absorber to back plate (W/m^2 K)
I	intensity of solar radiation (W/m^2)
J_h	Colburn factor
L	length of collector (m)
$\dot{m}$	mass flow rate (kg/s)
n	number of wire mesh layers
P	porosity of wire mesh
p_t	pitch of wire mesh (m)
Pr	prandtl number
Q_u	useful heat gain (W)
r_h	hydraulic radius (m)
S	input solar radiation (W/m^2)
St_p	stanton number
T_p	absorber temperature (K)
T_a	ambient temperature (K)
T_f	fluid temperature (K)
T_b	temperature of back plate (K)
T_i	inlet fluid temperature (K)
U_t	top loss coefficient (W/m^2 K)
U_b	bottom loss coefficient (W/m^2 K)
U_l	overall heat loss coefficient (W/m^2 K)
v	air velocity (m/s)

Greek symbols

η_{th}	thermal efficiency (%)
τ	transmissivity
α	absorptivity
β	viscous resistance
ΔP	pressure drop (N/m^2)
ρ	density of air (kg/m^3)
υ	kinematic viscosity (m^2/s)

mass flow rate is essential in order to develop standards for porous bed solar air heater. Solar air heaters play an important role in agricultural product drying (Aravindh, 2015; Rajarajeswari, 2016; Rajarajeswari et al., 2016; Sreekumar et al., 2008; Aravindh and Sreekumar, 2014; Aravindh and Sreekumar, 2014; Rajarajeswari and Sreekumar, 2014), industrial process heating and space heating. Testing of porous bed solar air heaters on a commercial scale would help improving the thermal systems of industries. This work helps the readers to get an idea on the selection of wire mesh geometry and mass flow rate for designing solar air heaters.

In this paper, the behavior of fluid through the wire mesh absorber was simulated using CFD method and analyzed for particular porosity. The radiation model used for simulating temperature of fluid has not been reported in any other work before and also the work related to simulation of porous bed solar air heaters are very few. The turbulent model selected was validated with the experimental data. Experiments were carried on with different porosity of wire mesh. The experimental study involves testing of porous bed solar air heater in a commercial scale of 2 m^2 area. The porous medium is made up of two types of wire screen matrices with different material and geometric parameters. The air mass flow rate for the study was chosen from low to high values (from 0.01 kg/s to 0.055 kg/s). The air heaters are studied for a wide range of mass flow rates under outdoor conditions and the optimized flow rate for high thermal performance and low pressure drop was witnessed.

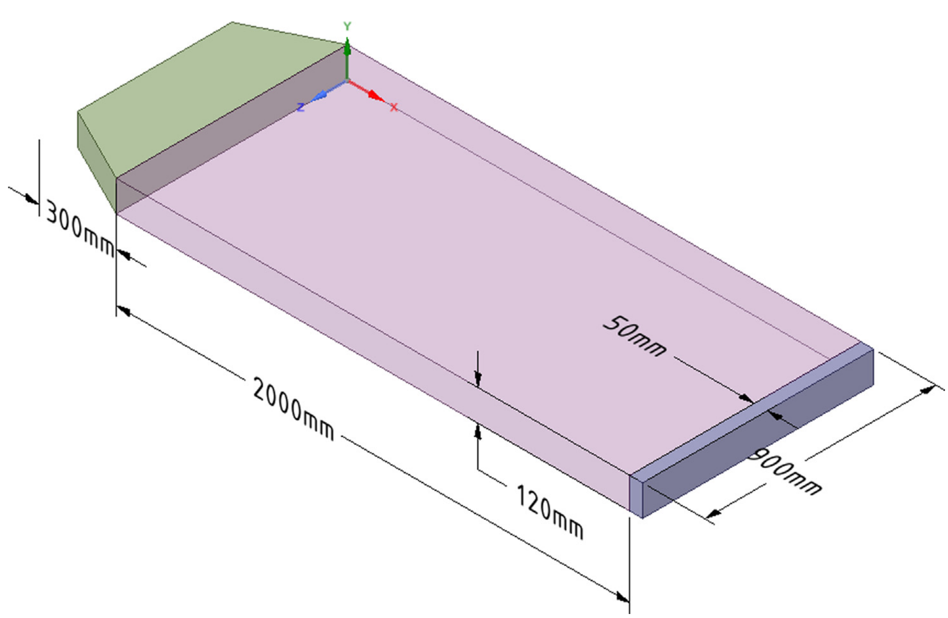

Fig. 1. Geometry of solar air heater.