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Experimental and numerical investigation of forced convective heat transfer in solar air heater with thin ribs

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ABSTRACT

Ribs on the underside of the absorber plate of solar air heater enhance the convective heat transfer rate of the air flowing through it. Several experimental and numerical investigations, with different rib geometry and flow conditions, have been carried out. This paper is one such effort of experimental and numerical investigations of solar air heater. It presents the effect of rib arrangements on the heat transfer and frictional loss characteristics of a rib roughened solar air heater. The geometrical and flow conditions of the present work circumscribe with aspect ratio (W/H) of 10 for the duct, blockage ratio (e/H) is 0.1, relative roughness height (e/D_h) of 0.055, relative roughness pitch (P/e) of 10, angle of attack (α) of 90° and Reynolds number (*Re*) from 4000 to 16000. Two thin transverse continuous and two truncated ribs are used for one pitch length. Four different rib arrangements are considered for the heat transfer, friction factor and thermo hydraulic performance parameter (THPP) investigations. A three dimensional (3D) numerical simulation is carried out with the commercial CFD code ANSYS FLUENT ver. 16.2 and RNG k–ε turbulence model. The enhanced wall treatment as wall function is used, keeping the Y+ criteria < 1. The numerical results are in good agreement with the experimental results. Three important outcomes are observed in the present investigation. Rib arrangement 1, with mid ribs placed at 3.3% and 6.67% truncation from the sidewalls gives the highest heat transfer enhancement. Arrangement 3, with mid ribs placed at 5% truncation from the side walls gives the best overall THPP results and arrangement 4, with two transverse continuous ribs in between the truncated ribs shows the highest average friction factor.

1. Introduction

Solar air heaters (SAHs) are devices for converting the solar energy to thermal energy. Solar air heater is a simple type of heat exchanger in the form of rectangular duct. This device can be fabricated with woods, which is available in plenty. It has various applications like space heating for residential and commercial purpose, drying of laundry, agricultural crops (i.e. tea, corn, and coffee) and seasoning of wood. However, the poor thermal conductivity (k) of air leads to a lesser heat transfer between the fluid and the absorber plate, which in turn makes it less efficient. In order to enhance the performance, a passive technique of introducing ribs on the absorber plate is the most common practice. These ribs create turbulence inside the duct, which significantly increases the heat transfer rate, in addition to the frictional losses, which require high pumping power. Therefore, to avoid higher pumping power needs, turbulence is created only near to the absorber plate in the laminar sub layer zone. Lots of research is going on experimentally as well as numerically, to predict the performance of a solar air heater with rib turbulators on the absorber plate. The investigations on experimental work of various researchers have been discussed and summarized in review articles by Kumar et al. (2012), Yadav and Thapak (2014), Sharma and Kalamkar (2015). The numerical studies are in lesser numbers and few researchers have summarized it in their review articles like Yadav and Bhagoria (2013a), Sharma and Kalamkar (2016). These reviews reveal that the heat transfer and fluid flow characteristics depend on the geometrical parameters like the relative roughness pitch (P/e), relative roughness height (e/D_h), angle of attack (α) along with Reynolds number (*Re*) and duct aspect ratio (W/H), associated with ribbed solar air heater duct. The experimental work consumes time and effort. However, numerical or computational fluid dynamics (CFD) techniques have emerged as a strong tool for simulating such devices. The increasing computation power of the machines has reduced the time, cost and labour involved in getting the simulations of such system both quantitatively and qualitatively. Numerical techniques use different algorithms to solve and analyze the problems of the thermo-fluid system. CFD has been used in the

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Nomenclature

A	absorber plate area, mm^2
A_t	orifice throat area, mm^2
C_p	specific heat of air, J/kg/K
C_d	coefficient of discharge of orifice meter
D	dimensional
D_h	hydraulic diameter of the duct, mm
e	rib height, m
h	heat transfer coefficient, W/m^2 K
H	height of duct, mm
k	thermal conductivity of air, W/m/K
L_1	entry length of duct, mm
L_2	test section length, mm
L_3	exit section length, mm
$\dot{m}$	mass flow rate of air, kg/s
P	rib pitch, mm
ΔP_o	pressure drop across test section, Pa
ΔP_t	pressure drop across orifice, Pa
T_o	outlet temperature, K
T_{pm}	mean plate temperature, K
T_i	inlet temperature of air, K
T_f	mean air temperature inside duct, K
THPP	thermo-hydraulic performance parameter
V	velocity of air in duct, m/s
W	width of duct, mm

Dimensionless parameters

e/H	blockage ratio
e/D_h	relative roughness height
f	friction factor
f_0	friction factor for smooth plate
f_r	friction factor for roughened plate
Nu	Nusselt Number
Nu_0	Nusselt number for smooth plate
Nu_r	Nusselt number for roughened plate
P/e	relative roughness pitch
Pr	Prandtl number
Re	Reynolds number
W/H	duct aspect ratio
Y^+	non dimensional wall co-ordinate

Greek symbols

α	rib angle of attack, °
ρ	density, kg/m^3
ε	dissipation rate, m^2/s^3
μ	dynamic viscosity, Ns/m^2
ν	kinematic viscosity, Ns/m^2
μ_t	turbulent viscosity, Ns/m^2
β	orifice to pipe diameter ratio
Γ	molecular thermal diffusivity
Γ_t	turbulent thermal diffusivity

analysis, optimization of rib roughened solar air heater, and it becomes a popular tool nowadays.

Several researchers have used ribs of various shapes on the underside of absorber plate in solar air heaters. Karmare and Tikekar (2007, 2009) studied with metal grit as the roughness element. They reported an enhancement of 187% and 213%, respectively, in Nu_r & f_r. They observed thermal efficiency increment of 10–35% and in f_r of 80–250% for the second investigation. Gupta et al. (2008) studied with 90° continuous, 90°-saw tooth profile and 60° broken ribs in a square channel. They obtained higher heat transfer for 60° inclined ribs. Layek et al. (2009) investigated with transverse chamfered and V shape groove in combination. They obtained the maximum enhancement in Nu_r at 18°-chamfered angle. Kumar et al. (2009) investigated with discrete W-shaped ribs and obtained the maximum Nu_r and f_r of 2.16 and 2.75, respectively, for α of 60°. Aharwal et al. (2008) investigated solar air heater with integral repeated discrete ribs, for the gap width and gap position of the rib turbulators. They obtained maximum enhancement in Nu_r and f_r of 2.83 and 3.60, respectively. Karwa and Chauhan (2010) in their investigation with 60° V down discrete ribs concluded that mass flow rate of air less than 0.04 kg s^{-1} m^2 gave significant heat transfer enhancement. Hans et al. (2010) investigated the solar air heater with multiple V shaped ribs on the absorber plate. They reported the enhancement of Nu_r and f_r by 5 and 6 times than the smooth plate. Singh et al. (2011) concluded with discrete V down ribs that the maximum Nu_r and f_r of 3.04 and 3.11, respectively, at P/e = 8.

Several investigations were focussed on the transverse rib also. Prasad and Mullick (1983) used protruded wires and found an improved plate efficiency factor of 0.63–0.72. The overall improvement of 14% is reported in the investigation, for a Re number of 40,000. Prasad and Saini (1988) investigated with protruded wire in solar air heater. They reported an increment of average Nu_r number by 2.38 times over the smooth duct for e/D_h of 0.033 and P/e of 10. Gupta et al. (1993) investigated with thin transverse wire for a transitionally rough region. They reported a slight fall in Stanton number (St) value beyond Re of 12,000, and further the maximum value shifts towards a lower value of Re with decrease in e/D_h. Karwa et al. (1999) performed investigation with chamfered ribs on the absorber plate with different values of aspect ratio W/H (4.8–12), P/e (4.5–8.5) and chamfered angle of (−15° to 18°) for the Re ranging from 3000 –20,000. They reported that the heat transfer and friction factor, both maximizing at 15° of chamfering. Verma and Prasad (2000) using small-diameter wires as the roughness elements obtained the optimal thermo hydraulic performance of 71% at the roughness Reynolds number (e^+) of 24. Bhagoria et al. (2002) investigated with transverse wedge shaped ribs and reported an enhancement of Nusselt number and friction factor by 2.4 and 5.3 times, respectively, as compared to the smooth duct. Karwa (2003) investigated with the transverse, inclined and V shape ribs and concluded that the V shape downstream and discrete ribs showed the best heat transfer performance. Tanda (2004) investigated the rectangular channel with rectangular, square transverse and V shape rib with an angle of 45° and 60°. He concluded that the transverse broken ribs with P/e = 4 and 8 give the highest heat transfer enhancement under the same mass flow rate condition and pumping power. Sahu and Bhagoria (2005) investigated with transverse broken ribs. They found an increment of 83.5% in the thermal efficiency at P = 20 for the flow condition. Gupta et al. (2008) studied heat transfer enhancement in the square channel with 90° continuous, 90°-saw tooth profile and 60° broken ribs. They concluded that 60° inclined ribs gave higher heat transfer enhancement. Layek et al. (2009) reported that the maximum enhancement of Nu_r is obtained at 18° chamfer, for the transverse chamfered and V shape groove.

Several authors have performed the numerical investigations (CFD) on thermo hydraulic performance assessment of solar air heaters, however, lesser in numbers. With the increase in computational capability of the computers, such investigations are getting more popular among the researchers. 2D simulations are quite popular due to low computational power and time requirement. Chaube et al. (2008) performed 2D simulation with different