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Fluid flow and heat transfer analysis for heat transfer enhancement in three sided artificially roughened solar air heater

B.N. Prasad *, Arun K. Behura, L. Prasad

Mechanical Engineering Department, N.I.T., Jamshedpur 831014, India

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Abstract

Analytical results are available in plenty for heat transfer and friction factor for artificially roughened solar air heaters. Provision of artificial roughness of various geometries and orientations on the absorber plate in solar air heaters have remained limited to only one side (top side) of the solar air heater duct which results in higher values of heat transfer and associated pressure drop. The present paper deals with the analysis with respect to fluid flow and heat transfer in a novel solar air heater having artificial roughness on three sides (the two side walls and the top side) of the rectangular solar air heater duct, with three sides glass covers. Equations for friction factor and heat transfer parameter have been developed. The analytical values of friction factor and heat transfer parameter have been found to be 2–40% more and 20–75% more than those of the respective values of (Prasad and Saini, 1988) for the same range of the values of operating parameters p/e, e/D and Re and fixed values of *W* and *B*. The present novel type of solar air heater would be superior to those of only one side artificially roughened solar air heaters with respect to heat transfer.

Keywords: Relative roughness pitch (p/e); Relative roughness height (e/D); Flow Reynolds number (Re); Average Nusselt number ($\overline{\mathrm{Nu}_r}$)

1. Introduction

Different geometries of artificial roughness have been widely used to enhance heat transfer in solar air heaters. (Prasad and Mullick, 1983), used small diameter wires on the top absorber plate to enhance heat transfer in a solar air heater. Based on the approach considered by (Han, 1984), analysis for the effect of artificial roughness was made by (Prasad and Saini, 1988), for heat transfer and friction factor in a solar air heater provided with artificial roughness of small diameter wires on the top surface, having relative roughness pitch of 10, 15, 20 and relative roughness height of 0.020, 0.027 and 0.033 to predict for a correlation for the average Nusselt number written under as:

$$\overline{\mathrm{Nu}} = \frac{\bar{f}/2}{1 + \left(\sqrt{\bar{f}/2}\right)\left[4.5(e^{+})^{0.28}\mathrm{Pr}^{0.57} - 0.95\left(\frac{p}{e}\right)^{0.53}\right]}\mathrm{Re}\,\mathrm{Pr} \tag{1}$$

Analysis for the optimal thermohydraulic performance of the top side artificially roughened solar air heater was made by (Prasad and Saini, 1991), covering a wide range of the values of relative roughness pitch, (p/e), relative roughness height, (e/D) and flow Reynolds number (Re), to arrive at the conclusion that the value of the parameter, roughness Reynolds number, $e^{+} \approx 24$, gives the optimal value of thermohydraulic performance (i.e., maximum heat transfer for the minimum pumping power). (Gupta et al.,

* Corresponding author. Tel.: +91 9431344731.
E-mail address: bnprasad.nit@gmail.com (B.N. Prasad).

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Nomenclature

A_c	collector area, m^2
B	solar air heater duct height, m
D	hydraulic diameter of solar air heater duct, m
e	artificial roughness height, m
e^+	roughness Reynolds number $= e/D\sqrt{\left(\frac{\bar{f_r}}{2}\right)}\mathrm{Re}$ (Present case)
e^+	roughness Reynolds number $= e/D\sqrt{\left(\frac{\bar{f}}{2}\right)}\mathrm{Re}$ (Referred cases)
e/D	relative roughness height
F'	plate efficiency factor
$\bar{f}$	average friction factor $= (f_s + f_r)/2$, in roughened collector (Referred cases)
f_s	friction factor in four sided smooth duct
f_r	friction factor in four sided rough duct
$\bar{f_r}$	average friction factor in three sided rough duct (Present case)
H	solar air heater duct height, m (Referred cases)
h	convective heat transfer coefficient, W/m^2 K
L	collector length, m
Nu_r, $\overline{\mathrm{Nu}}$	Nusselt number for top side roughened duct (Referred cases)
$\overline{\mathrm{Nu}_r}$	average Nusselt number for three sided roughened duct (Present case)
$\mathrm{Nu_s}$	Nusselt number for four sided smooth duct
p	roughness pitch, m
p/e	relative roughness pitch
Pr	Prandlt number
Re	Reynolds number
$\overline{\mathrm{St}_r}$	average Stanton number for three sided roughened duct (Present case)
$\overline{\mathrm{St}}$	Stanton number for top side roughened duct (Referred cases)
St_r	Stanton number in a four sided rough duct
W	solar air heater duct width, m
U_L	overall heat transfer coefficient, W/m^2 K
v_s	fluid flow velocity in four sided smooth duct, m/s
v_r	fluid flow velocity in four sided rough duct, m/s
$\overline{v_r}$	fluid flow velocity in three sided rough and one side smooth duct, m/s
τ	wall shear stress, N m^{-2}
τ_r	wall shear stress in four sided rough duct, N m^{-2}
τ_s	wall shear stress in four sided smooth duct, N m^{-2}
$\bar{\tau}$	average wall shear stress in three sided rough and one sided smooth duct, N m^{-2}
ρ	fluid density, Kg/m^3

Subscripts

s	four sided smooth duct
r	four sided rough duct
$1s$	one sided smooth duct
$3r$	three sided rough duct

1993) used transverse wire roughness on the top surface in a solar air heater to investigate for the effect of solar air heater duct aspect ratio and relative roughness height for a relative roughness pitch of 10 and flow Reynolds number of 3000–18,000 to arrive at the following correlations:

For $e^+ < 35$,

$$\mathrm{Nu}_r = 0.000824\left(\frac{e}{D}\right)^{-0.178}\left(\frac{W}{H}\right)^{0.288}(\mathrm{Re})^{1.62} \tag{2}$$

For $e^+ \geqslant 35$,

$$\mathrm{Nu}_r = 0.00307\left(\frac{e}{D}\right)^{0.469}\left(\frac{W}{H}\right)^{0.245}(\mathrm{Re})^{0.812} \tag{3}$$

(Saini and Saini, 1997), dealt with the effect of expanded wire mesh geometry parameter of relative long way length of mesh, relative short way length of mesh and relative roughness height of mesh on heat transfer. (Karwa et al., 1999), developed heat transfer coefficient and friction factor correlations in rib-roughened solar air heater duct for transitional flow. (Verma and Prasad, 2000), developed correlations for heat transfer in a top side artificially roughened solar air heater for fully developed turbulent flow as under:

$$\mathrm{Nu}_r = 0.08596\left(\frac{\mathrm{p}}{\mathrm{e}}\right)^{-0.054}\left(\frac{e}{D}\right)^{0.072}(Re)^{0.728}, \quad \text{for } e^+ \leqslant 24 \tag{4}$$

$$\mathrm{Nu}_r = 0.02954\left(\frac{\mathrm{p}}{\mathrm{e}}\right)^{-0.016}\left(\frac{e}{D}\right)^{0.021}(\mathrm{Re})^{0.802}, \quad \text{for } e^+ > 24 \tag{5}$$

Studies conducted by (Bhagoria et al., 2002; Karwa, 2003; Sahu and Bhagoria, 2005; Jaurker et al., 2006; Varun et al., 2008; Saini and Verma, 2008; Saini and Saini, 2008; Layek et al., 2009; Hans et al., 2010; and Lanjewar et al., 2012), represent various roughness geometries of transverse or inclined wedge shaped rib, rib-grooved, dimple-shaped, arc-shaped wire, compound turbulation, multiple v-ribs, metal grit ribs and w-shaped, dealing with the analysis and investigation for heat transfer enhancement in solar air heaters. The review article of (Varun et al., 2007), deals with the various types of roughness geometries used in solar air heaters and that of (Hans et al., 2009), deals with the performance of artificially roughened solar air heaters. (Patil et al., 2012), have also reviewed the types of roughness geometries and