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Optimization of thermo hydraulic performance in three sides artificially roughened solar air heaters

B.N. Prasad *, Ashwini Kumar, K.D.P. Singh

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

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Abstract

Providing artificial roughness on the air flow side is an effective technique to enhance rate of heat transfer in solar air heaters, which results in associated higher value of friction factor, and more power required. A novel solar air heater duct with three artificially roughened sides has been analyzed (Prasad et al., 2014), for more increase in heat transfer than that in only one side roughened solar air heaters. Artificially roughened solar air heaters have been analyzed (Prasad and Saini, 1991) and investigated (Verma and Prasad, 2000), for optimal thermo hydraulic performance. The present analysis deals with optimization of thermo hydraulic performance in three sides artificially roughened solar air heaters, and arrives at the conclusion that the equation given by $e^+_{opt} = e/D\sqrt{\frac{\bar{f}_r}{2}}Re = 23$, always corresponds to the optimal thermo hydraulic performance, when every set of the values of the roughness and flow parameters p/e, e/D and Re, separately or combined, results in the optimal thermo hydraulic performance. Optimal thermo hydraulic performance of such solar air heater is both quantitatively and qualitatively better than one side roughened solar air heaters.

Keywords: Relative roughness pitch (p/e); Relative roughness height (e/D); Stanton number roughness parameter (B^{-1}); Efficiency roughness parameter (C^{-1}); Efficiency parameter (L^{-1}); Roughness Reynolds number (e^+)

1. Introduction

Fully developed turbulent flow heat transfer and friction factor for artificially roughened ducts, annuli and tubes have been widely studied by Nunner (1958), Webb et al. (1971), Han (1984), Lewis (1975a,b), Sheriff and Gumley (1966), Dipprey and Sabersky (1963), Kolar (1964), Owen and Thomson (1963), Dalle Donne and Meyer (1977), Edwards and Sheriff (1961) and Webb and Eckert (1972). Use of artificial roughness to enhance heat transfer in flat plate solar air heater for low temperature energy technology have attracted the attention of researchers in a wide range. A number of solar air heaters have been designed and developed over the years to refine their thermal enactment. The thermal efficiency of solar air heaters is usually low due to low value of heat transfer coefficient between absorber plate and flowing air, which raises the absorber plate temperature, leading to higher heat losses. For the enhancement of heat transfer coefficient, extensive information is available in literature. Prasad and saini (1988) analyzed for heat transfer enhancement for fully developed turbulent flow in a solar air heater duct with small diameter wires on the absorber plate. Gupta et al. (1997) used continuous ribs at an inclination of 60° to the air flow direction. Karwa et al. (1999) used chamfered rib roughness on the absorber plate and found that at low flow rate, higher relative roughness height yields a better performance.

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

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Nomenclature

B	solar air heater duct height, m
B^{-1}	Stanton number roughness parameter, $B^{-1} = G_H - P_{r_t} R_M$
C^{-1}	efficiency roughness parameter, $c^{-1} = 2.5 \ln(e^+) + 5.5 - R_M$
D	hydraulic diameter of solar air heater duct, m
e	roughness height, m
e/D	relative roughness height
e^+	roughness Reynolds number, $e^+ = e/D\sqrt{\frac{\bar{f}_r}{2}}Re$ (Present case)
e^+	roughness Reynolds number, $e^+ = e/D\sqrt{\frac{\bar{f}}{2}}Re$ (Prasad and Saini, 1991)
e^+_{opt}	optimum value of e^+
f_S	friction factor in smooth solar air heater
f_r	friction factor in roughened solar air heater
$\bar{f}$	average friction factor (Prasad and Saini, 1988)
$\bar{f}_r$	average friction factor (Prasad et al., 2014)
G_H	heat transfer roughness function, $G_H = 4.5(e^+)^{0.28} (P_r)^{0.57}$
h^+	roughness Reynolds number (Lewis, 1975a,b) $= e^+$
L	collector length
L^{-1}	efficiency parameter, $L^{-1} = C^{-1} - B^{-1}$
p	pitch of roughness element, m
p/e	relative roughness pitch
P_r	Prandtl number
P_{r_t}	turbulent Prandtl number
Re	Reynolds number
R_M	momentum transfer roughness function, $R_M = 0.95(p/e)^{0.53}$
S_{t_s}	Stanton number for smooth solar air heater
$\overline{S_t}$	average Stanton number (Prasad and Saini, 1988)
$\overline{S}_{tr}$	average Stanton number (Prasad et al., 2014)
W	width of solar air heater
η	efficiency parameter, defined by Eqs. (7)–(9)

The recent works of Prasad (2013) and Prasad et al. (2014) for fully developed turbulent flow in artificially roughened solar air heater for heat transfer and friction factor are available. Three sides artificially roughened solar air heater duct (Prasad et al., 2014), with a large aspect ratio ($W \gg B$) is a novel one, where correlations predict the effect of roughness and flow parameters (p/e, e/D, Re) on heat transfer for fully developed turbulent flow, and results are found to be even better than one side roughened solar air heaters. As the enhancement of heat transfer coefficient is attempted by providing artificially roughness, it always goes with an increment of pressure drop and the requirement of pumping power is increased. So, there is a need to optimize the system parameters to maximize heat transfer while keeping friction losses as low as possible.

Analysis for the optimal thermo hydraulic performance of rough surfaces (circular tube with ribs) to heat exchanger design was made by Webb et al. (1971), covering a wide range of the values of heat transfer surface area, overall heat conductance and flow friction power to obtain the conclusion that the value of parameter, roughness Reynolds number, $e^+ = 20$, gives the optimal thermo hydraulic performance. For optimal thermo hydraulic performance of circular tube roughened with ribs, Lewis (1975a,b) introduced new efficiency parameters (L^{-1}, B^{-1}, C^{-1}, G_H and R_M) and arrived at the conclusion that the value of the roughness Reynolds number $h^+ = e^+ = 20$, corresponds to the optimal thermo hydraulic condition. Sheriff and Gumley (1966) has studied for annulus with wire type roughness and found the value of roughness Reynolds number, $e^+ = 35$, for the optimal thermo hydraulic condition. Optimal thermo hydraulic performance analysis in one side artificially roughened solar air heater of Prasad and Saini (1991) has constituted a particular set of values of roughness and flow parameters to give the value of roughness Reynolds number, $e^+ = 24$, for optimal thermo hydraulic condition. Optimal thermo hydraulic performance of solar air heaters has been investigated (Verma and Prasad, 2000), for the maximum heat transfer and minimum pressure drop to arrive at the conclusion that the value of $e^+ = 24$, corresponds to the optimal thermo hydraulic performance. In addition, a number of investigators have shown their interest and have worked on different roughness geometries. Mittall and Varshney (2005) has worked on optimal thermo hydraulic performance of wire mesh packed solar heater. Second law optimization of solar air heater having chamfered rib groove as a roughness element has been analyzed by Layek et al. (2007). Karmare and Tikeka (2008) has optimized the thermo hydraulic performance of solar air heater integrated with metal rib as roughness element. CFD based thermo hydraulic performance (Yadav and Bhagoria, 2014) has been found out to be 2.11 at e/D equal to 0.042 and p/e equal to 7.14 for equilateral triangular rib section, using *ANSYS FLUENT* at $Re = 15{,}000$.

Based on the fluid flow and heat transfer analysis (Prasad et al., 2014), the present work deals with the thermo hydraulic optimization of three sides artificially roughened solar air heater to get the maximum heat transfer for the minimum pumping power (friction factor).