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Heat and fluid flow characteristics of roughened solar air heater ducts – A review

Anil Kumar[a,*], R.P. Saini[a], J.S. Saini[b]

[a] *Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand 247667, India*
[b] *Mechanical & Industrial Engineering Department, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand 247667, India*

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ABSTRACT

Artificial roughness in the form of repeated ribs is one of the effective way of improving the performance of a solar air heater ducts. Various studies have been carried out to determine the effect of different artificial roughness geometries on heat transfer and friction characteristics in solar air heater ducts. The objective of this paper is to review various studies, in which different artificial roughness elements are used to enhance the heat transfer coefficient with little penalty of friction factor. On the basis of correlations developed by various investigators for heat transfer coefficient and friction factor, an attempt has been made to compare the thermohydraulic performance of roughened solar air heater ducts. It has been found that lot of experimental and analytical studies reported in the literature.

1. Introduction

Energy is a basic ingredient needed to sustain life and development. Energy is needed in various forms to fulfill our daily requirements. Solar energy is available freely and a clean source of energy [1]. The simplest and the most efficient way to utilize solar energy is to convert it into thermal energy for heating applications by using solar collectors [2]. Solar air heaters, because of their inherent simplicity are cheap and most widely used for many applications at low and moderate temperatures.

Artificially roughened absorber plate is considered to be a good methodology to breaking the laminar sub-layer in order to reduce thermal resistance and to increase heat transfer coefficient. Regarding artificial roughness, many experimental investigations have been reported in literature by various authors. In this paper, an attempt has been made to categorize and review the reported roughness geometries used for creating artificial roughness. Correlations for heat transfer coefficient and friction factor developed by various investigators for solar air heater ducts having artificial roughness of different geometries were reviewed and presented in the paper.

2. Performance of flat plate solar collector

Thermal performance of flat plate solar collector was first investigated by Hottel and Woertz reported by Duffie and Beckman [2].

Bliss [3] introducing 'collector heat removal factor', F_R, defined as the ratio of actual useful energy gain to the useful energy gain if the whole collector absorbing surface were at the fluid inlet temperature (*Ti*).

$$q_u = \frac{Q_u}{A_c} = F_R[I(\tau\alpha) - U_L(T_i - T_a)] \quad (1)$$

where,

$$F_R = \frac{mC_p(T_o - T_i)}{A_c[I(\tau\alpha) - U_L(T_i - T_a)]} \quad (2)$$

Also

$$\eta_{th} = F_R\left[(\tau\alpha) - U_L\left(\frac{T_i - T_a}{I}\right)\right] \quad (3)$$

Eq. (3) is known as Hottel–Whillier–Bliss equation. Eq. (3) has been found to be approximately represented by a linear relationship as given below:

$$\eta_{th} = a - b\Delta T/I \quad (4)$$

where,

$$\begin{aligned} a &= F_R(\tau\alpha) \\ b &= F_R U_L \end{aligned} \quad (5)$$

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* Corresponding author. Tel.: +91 9557107829; fax: +91 1332274254.
E-mail address: anil_aheciit@yahoo.com (A. Kumar).

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Hence the above Eq. (4) shows that the plot between ηth and parameter $\Delta T/I$ can be approximated by a straight line as shown in Fig. 1. The intercept and slope of plot in the Fig. 1 gives the values of $F_R(\tau\alpha)$ and$F_R U_L$.

3. Artificial roughness

In order to attain higher heat transfer coefficient it is desirable that the flow at the heat transferring surface is made turbulent. However, energy for creating such turbulence has to come from the fan or blower and the excessive turbulence leads to excessive power requirement to make the air flow through the duct. It is therefore desirable that the turbulence must be created only in the region very close to the heat transferring surface i.e. in the laminar sub-layer only where the heat exchange takes place and the flow should not be unduly disturbed so as to avoid excessive friction losses. This can be done by keeping the height of the roughness element to be small in comparison with the duct dimensions.

Although there are several parameters that characterize the arrangement and shape of the roughness, the roughness element height (e) and pitch (P) are the most important. Theses parameters are usually specified in terms of dimensionless parameters, namely, relative roughness height (e/D), relative roughness pitch (P/e), angle of attack (α), relative gap position (d/W), relative gap width (g/e), groove position (g/P) and chamfer angle (ϕ) etc. The roughness elements can be two-dimensional ribs or three dimensional discrete elements, angled ribs, V-shaped continuous or broken ribs, Rib-groove, arc rib, Multi v-rib etc. Some important and the parameters that characterized the geometry and substantially influence the performance are given in Table 1.

4. Fluid flow and heat transfer characteristics of solar air heater duct with artificial roughness

Efforts for improving the heat transfer rate have been directed towards artificially destroying or disturbing the viscous sub-layer by providing the artificial roughness on heated surface. Many experimental investigations have been carried out to study the flow field and characteristics of heat transfer and friction factor of roughened tubes, annuli and ducts [4–8] and [9–33].

Nikuradse [4] studied the effect of roughness on friction factor and velocity distribution in pipes roughened by sand blasting. A wide range of values of relative roughness heights from 0.001 to 0.033 and Reynolds number from 600 to 10^6 has been covered in his study. The three flow regions shown in Fig. 2 are as under:

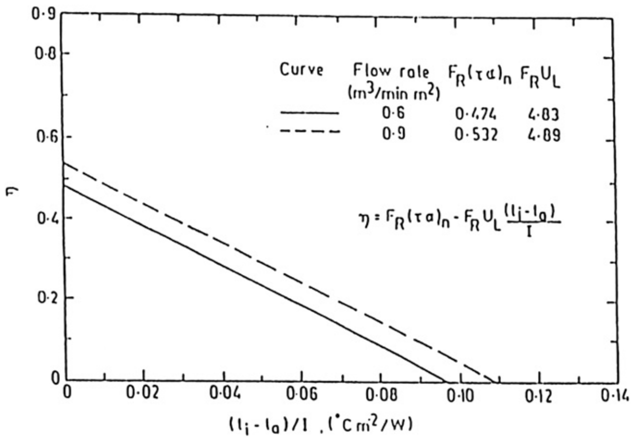

Fig. 1. Efficiency plot of a typical solar air collector at different flow rates.

Table 1
Different types artificial roughness geometries and important parameters.

Sr. no.	Investigators	Rib geometry	Parameters
1.	Prasad and Saini [8]	Transverse continuous rib	P/e, e/D
2.	Sahu and Bhagoria [9]	Transverse broken rib	P/e, e/D, α
3.	Gupta et al. [11]	Inclined continuous rib	e/D, α
4.	Aharwal et al. [13]	Inclined rib with gap	P/e, e/D, α, d/W, g/e
5.	Varun et al. [15]	Combination of inclined and transverse rib	P/e, e/D
6.	Momin et al. [18]	V-shaped rib	P/e, e/D, α
7.	Singh et al. [19]	Discrete v-rib	d/W, g/e, P/e, e/D, α
8.	Bhagoria et al. [20]	Wedge shaped rib	P/e, e/D, ϕ
9.	Jaurker et al. [21]	Rib-groove	P/e, e/D, g/p
10.	Karwa et al. [22]	Chamfered rib	P/e, e/D, ϕ
11.	Saini and Saini [23]	Expanded metal mesh	e/D, S/e, L/e, α
12.	Saini and Verma [24]	Dimpled shaped rib	P/e, e/D
13.	Saini and Saini [25]	Arc shaped rib	e/D, α
14.	Karmare and Tikekar [26]	Metal grit rib	P/e, e/D, l/s
15.	Lanjeware et al. [28]	W-shaped rib	P/e, e/D, α
16.	Kumar et al. [29]	Discrete w-shaped rib	P/e, e/D, α
17.	Bopche and Tandale [30]	U-shaped rib	P/e, e/D, α
18.	Hans et al. [31]	Multi v-shaped rib	P/e, e/D, α, W/w

(i) Hydraulically smooth flow ($0 < e^+ < 5$)

In this flow the roughness has no effect on the friction factor and for all values of relative roughness height (e/D), the values coincides with those for a smooth pipe. The measured pressure loss data in this regime were correlated by Nikuradse [4] in the form of $R\,(e^+)$ as under,

$$R\left(e^+\right) = 5.5 + 2.5\ \ln\left(e^+\right) \tag{6}$$

(ii) Transitionally rough flow ($5 \le e^+ \le 70$)

In transition zone, the influence of roughness becomes noticeable to a greater degree; the friction factor increases with increase in roughness Reynolds number (e^+). This zone is particularly characterized by the fact that the friction factor depends on the Reynolds number as well as on the relative roughness height.

(iii) Fully rough region ($e^+ > 70$)

In this region, the roughness function was found to be independent of the roughness Reynolds number and it attains

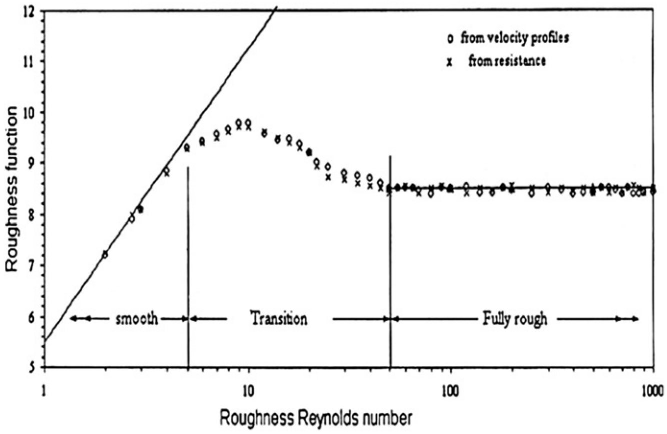

Fig. 2. Variation of momentum transfer roughness function with roughness Reynolds number.