Renewable Energy 62 (2014) 689–715

Contents lists available at ScienceDirect

Renewable Energy

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

Review

Use of turbulators for heat transfer augmentation in an air duct – A review

Tabish Alam [a,*], R.P. Saini [a], J.S. Saini [b]

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

ARTICLE INFO

Article history:
Received 5 November 2012
Accepted 19 August 2013
Available online 19 September 2013

Keywords:
Air solar heater
Heat exchanger
Perforated blocks/baffles
Turbulators
Delta winglet

ABSTRACT

Energy and material saving considerations, as well as economic incentives, have led toward making effort for producing more efficient heat exchange equipment such as solar air heaters, heat exchangers. In order to enhance the heat transfer rate to flowing air in the duct of solar air heater and heat exchangers various turbulence generators viz. ribs, baffles and delta winglets are considered as an effective technique. Investigators reported on various turbulators in literature for studying heat transfer and friction characteristics in a duct of solar air heaters and heat exchangers. An attempt has been made in this paper to carry out an extensive literature review of various turbulators investigated for enhancing heat transfer and friction in solar air heaters and heat exchangers. The correlations developed for heat transfer and friction factor in solar air heaters and heat exchangers by various investigators have been presented and reviewed.

1. Introduction

Energy which is available in various forms plays a vital role in sustenance of life. In recent years, energy consumption rate has increased manifold with the growth of world population, urbanization and industrialization. Continuous use of fossil fuels or conventional energy resources would eventually lead to the exhaustion. Due to the world's depleting fossil fuel reserves, non-conventional energy resources have started playing a prominent role now a days. Solar radiation, one of the renewable energy sources is available as a green and inexhaustible source of energy. They can be utilized as thermal energy for heating purposes. Solar air heaters are one of the applications considered very important and widely used for drying of crops and space heating. Due to its simplicity in nature at low and moderate temperatures, it is very popular for low temperature applications. Thermal performance of solar heaters is an area of concern for researches worldwide. One of the methods of improving the performance is by increasing the heat transfer coefficient between the absorber plate and air. Various methods of enhancing the heat transfer rate of solar air heaters have been studied and applied. Many investigators used artificial roughness of different shapes and sizes for increasing the heat transfer rate and thereby improving the performance of the solar air heater. In this paper, an attempt has been made to review the different artificial roughness geometries, turbulators viz. ribs, perforated baffles/block/ribs, obstacles and delta winglets.

2. Methodology of artificial roughness geometry used in solar air heater

The existence of a laminar sub-layer between the absorber plate and the flowing air is the main cause of high thermal resistance for heat. Artificial geometry creates turbulence in the laminar sub-layer due to flow separation and reattachment between the two repeated ribs, which enhances the heat transfer rate between the absorber plate and the flowing air of a solar air heater. Recirculation flow further enhances the convective heat transfer. Flow from the core to surface depletes the thickness of the boundary layer and the secondary flow from the surface to the core promotes mixing. Pressure drop could also be minimized to keep the height of the roughness element small or using perforated ribs.

Although there are several parameters that characterize the arrangement and shape of the roughness, ribs height (e) and pitches (p) are the most common. Apart from these parameters some dimensionless parameters, namely relative roughness pitch (p/e), relative roughness height (e/D), angle of attack (α), relative gap position (g/p), chamfered angle (Φ) and perforation area ratio (β) etc. have considerable effect on roughness. Roughness elements

* Corresponding author. Tel.: +91 9411007747; fax: +91 1332 273517.
E-mail address: tabish.iitr@gmail.com (T. Alam).

0960-1481/$ – see front matter
http://dx.doi.org/10.1016/j.renene.2013.08.024

Nomenclature

A_s	surface area of absorber plate (m^2)
D_e, D_h	equivalent or hydraulic dia of duct (m)
e	rib height (m)
e^+	roughness Reynolds number
f	friction factor for roughened duct
f_s	friction factor for smooth duct
g	groove position (m)
h	heat transfer coefficient (W/m^2 K)
H	depth of duct (m)
k	conductivity of air (W/m K)
Nu	Nusselt number for roughened duct
Nu_s	Nusselt number for smooth duct
p	pitch (m)
p'	staggering pitch (m)
Re	Reynolds number
S	length of main segment of rib (m)
S'	length of staggered pitch (m)
W	width of duct (m)
Dimensionless Symbols	
B/S	relative roughness length ratio
e/D_h or e/D	relative roughness height
g/e	relative gap width
G_d/L_v	relative gap position
g/p	relative groove position
l/e	relative long way length
p/e	relative pitch
p/H	baffles pitch ratio
P'/p	relative roughness staggering ratio
P_l/e	relative longitudinal pitch
P_t/b	relative transverse pitch
s/e	relative short way length
S'/S	relative roughness segment ratio
W/H	aspect ratio
W/w	relative roughness width
Greek symbols	
α	angle of attack (°)
β	open area ratio
ϕ	chamfered/wedge angle (°)
ρ	density (kg/m^3)
μ	dynamic viscosity (N s/m)
ν	kinematic viscosity (m^s/s)

can be 2-dimensional or 3-dimensional, continuous, discrete, transverse, crossed, angled, W-shaped, V-shaped, multi V-shaped and rib grooved. Although circular ribs are the most commonly used geometry, square ribs, chamfered, baffles and grooved sections have also been investigated in order to find out most efficient arrangement for solar thermal energy utilization system.

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

The artificial roughness has beneficial effects on heat transfer. Different types of artificial roughness have been evaluated and examined by various investigators in order to enhance the heat transfer. Fluid flow and heat transfer characteristics are a very complex phenomenon in terms of development of analytical models. Nikuradse [1] analyzed the velocity distribution and friction factor roughened by sand blasting. He covered a wide range of Reynolds number ($Re = \rho VL/\mu$), from 600 to 10^6 and relative roughness heights from 0.001 to 0.033 in his studies. The three flow regions are shown in Fig. 1.

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

For all values of relative roughness height (e/D), friction factor does not change; the value coincides with those for smooth pipe. The measured pressure data in hydraulic smooth flow regime were correlated in the form of Re (e^+) as follows

$$Re(e^+) = 5.5 + 2.5\ln(e^+) \tag{1}$$

(ii) Transitionally rough flow

In this zone, the friction factor increases with increase in roughness Reynolds number (e^+). In this zone, the friction factor is affected by the Reynolds number and the relative roughness height.

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

In fully rough region, the roughness function remains constant. It does no change with roughness Reynolds number.

Dippery and Sabersky [2] also developed a correlation for heat transfer in terms of a heat transfer function $G(e^+)$ for roughened circular pipes which is presented as follows:

$$G(e^+) = \left[\frac{f}{2St} - 1\right]\sqrt{\frac{f}{2}} + R(e^+) \tag{2}$$

Poitras et al. [3] reported the effect of variation of the distance between the ribs (placed perpendicular to the flow) on the structure of channel flow by numerical simulation and experimental flow visualization with surface mounted ribs for the Reynolds number ranging from 400 to 1000. The length of the recirculation zone downstream of the second rib varies as a function of the distance of separation of the ribs.

4. Effects of parameters on heat transfer coefficient and frictional factor

The effect of different roughness parameters such as relative roughness height (e/D), relative roughness pitch (p/e), angle of attack (α) on heat transfer coefficient and friction factor as investigated by various investigators is given below.

4.1. Relative roughness height

Prasad and Saini [4] show the flow pattern as a function of relative ribs height as shown in Fig. 3. They collected the data for Nusselt number and frictional factor and plotted then for different relative roughness height as a function of the Reynolds number as shown in Fig. 2. Nusselt number and friction factor both increases with increase of relative roughness height. But the rate of increase of the average friction factor increases whereas the rate of increase of the average Nusselt number decreases with the increase of the relative roughness height. Values of relative roughness height have been shown in Table 1 for maximum value of heat transfer coefficients.