Enhanced Performance Solar Air Heater with Roughened Absorber Plates: A Review

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***Abstract* - The paper presents a review of the artificial roughness employed to enhance heat transfer in asymmetrically heated high aspect ratio rectangular cross-section ducts whose boundary conditions confirm to that of flat plate solar air heater. The review of various studies shows that optimum relative roughness pitch varies from about 6-10 depending on the type of roughness; lower values correspond to the chamfered rib roughness. The chamfered ribs are better than rectangular section ribs. The optimum inclination angle for different rib arrangements is reported to be 60º. Discrete or inclined ribs with gap are better than all other rib arrangements.**

Keywords* — *Artificial roughness; rib shape and pitch; rib arrangement; heat transfer enhancement.

I. INTRODUCTION

Flat plate collector is the heart of a solar heat collection system designed for operation in the low to medium temperature range (5º-50ºC above ambient temperature). It absorbs both beam and diffuse radiation, converts the absorbed radiation into heat and then transfers the heat to water or air flowing through the collector duct. The flat plate collector does not require tracking of the sun and little maintenance is required. A conventional flat plate solar air heater consists of a flat absorber plate, a transparent cover at the top and insulation at the bottom and on the sides. The air to be heated flows through the duct below the absorber plate.

As compared to a solar water heater, the thermal efficiency of the solar air heater is low because of a low value of convection heat transfer coefficient between the absorber plate and air flowing through the duct. This leads to a high operating temperature of the absorber plate, which results in a greater heat loss through the cover (termed as top loss) and hence in a low thermal efficiency of the air heater.

The top loss from the collector can be reduced by enhancing the heat transfer coefficient between the absorber plate surface and air flowing through the collector duct. The researchers have tried artificial rib-roughness in the form of projections on the underside (the air side) of the absorber plate to enhance the thermohydraulic performance of solar air heater with forced flow of air [1-19]. Since the artificial roughness on the heat-transferring surface creates turbulence near the wall or breaks the laminar sub-layer at the wall, it enhances the heat transfer coefficient with a minimum pumping power penalty. These researchers have used various rib shapes and have tried rib elements in various arrangements. Extensive experimental studies carried out by these researchers have shown that the geometry of the roughness (roughness shape, pitch, height, etc.) and their arrangement (orientation with respect to the flow direction) have a marked influence on the heat transfer and friction characteristics of the roughened surfaces, and on the energy collection (the thermal efficiency) of the solar air heaters. Most of these studies have been carried out for rectangular section ducts with one of the broad walls roughened and subjected to uniform electric heating while the remaining walls were insulated. These boundary conditions correspond closely to those found in flat plate solar air heaters.

The objective of the present paper is to present a parametric review of the studies carried out for the heat transfer enhancement in asymmetrically heated high aspect ratio rectangular ducts with special emphasis on the effect of the rib shapes, their arrangement with respect to flow and discretization of the ribs on the heat transfer and friction characteristic of such enhanced ducts and the performance of the solar air heater employing such roughness on the absorber plate.

II. EFFECT OF RIB SHAPE AND PITCH

The researchers have used various rib shapes: protruding wires [1-5], wedge shaped ribs [6], chamfered integral rib-roughness [7, 8], rib-grooved artificial roughness [12], chamfered rib-groove [13] and dimple-shaped projections [15] as shown in Fig. 1. In the case of the square, circular and rectangular cross-section ribs, the flow detaches at the ribs and reattaches at about 6-7 rib heights destroying the laminar sublayer completely in the reattachment region. The boundary layer redevelops after this region and hence its thickness is small. A recirculating region with frequent shading of vortices establishes in the wake of the ribs and is basically a region of low heat transfer coefficient. The near wall turbulence enhances the heat transfer coefficient with a minimum pumping power penalty. A typical flow pattern is shown in Fig. 2.

As compared to smooth surface, the presence of artificial roughness has been shown to increase the Nusselt number up to 3.24 times, while the friction factor up to 5.3 times by these researchers depending upon the relative roughness height (ratio of rib height to hydraulic diameter), shape and arrangement of the rib elements. However, the thermo-hydraulic performance (based on equal pumping power) of the roughened surface improves by 30-70% over the smooth surfaced duct [11].

Optimum relative roughness pitch (*p*/*e*) for circular and rectangular section ribs is reported to be 10 by most of the researchers. The same has been reported to be about 6-8 for the chamfered, wedge and chamfered rib-grooved surfaces [6-8, 12, 13].

The performance of chamfered or rib-grooved surface is superior to that of circular, square or rectangular section ribs [7, 12, 13]. Positively chamfered ribs with 15° chamfer angle and 18° chamfer angle in case of chamfered and grooved have been shown to provide optimum performance [7, 13] while the optimum angle for the wedge shaped ribs is 10° [6]. Negatively chamfered ribs are poor in performance [7]. Chamfered and wedge shaped ribs provide better performance mainly because of the reduced recirculation zone behind the ribs [6, 7]. Integral ribs provide additional heat transfer enhancement due to the fin effect [7].

Gupta et al. [2], Singh et al. [18] and Karwa and co-authors [8, 16, 19] carried out studies on solar air heaters with transverse wire as roughness, chamfered or discrete rib roughness and have shown thermal efficiency enhancement of the order of 10-40% over the smooth duct solar air heaters. It has been shown that, at the low flow rates of air per unit area of the absorber plate, the ribs with greater relative roughness height are beneficial [16, 19].

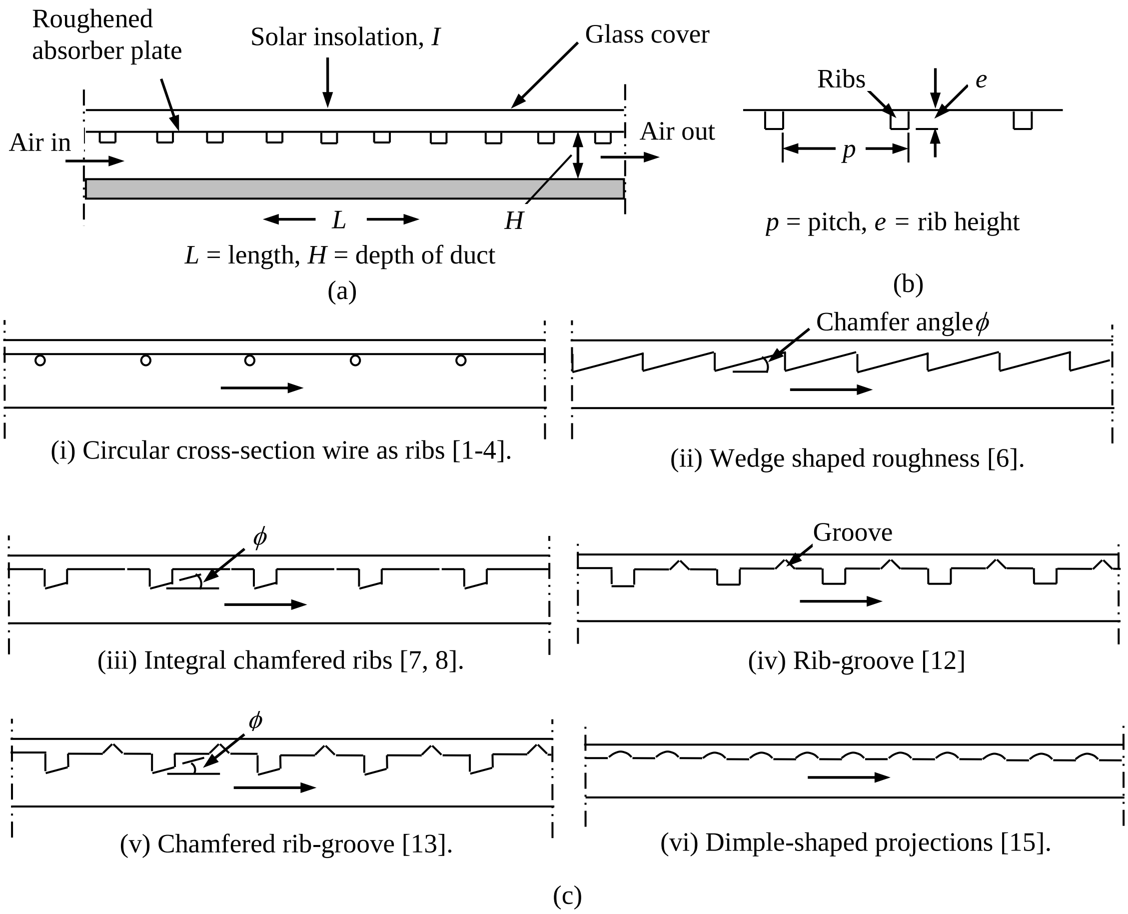


Fig. 1 (a) Solar air heater with roughened absorber plate, (b) Rib geometry (c) rib shapes.

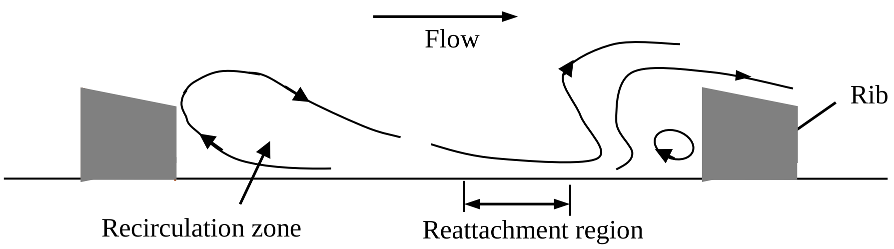


Fig. 2 Flow pattern for 15° chamfered ribs [20].

III. EFFECT OF RIB ARRANGEMENT

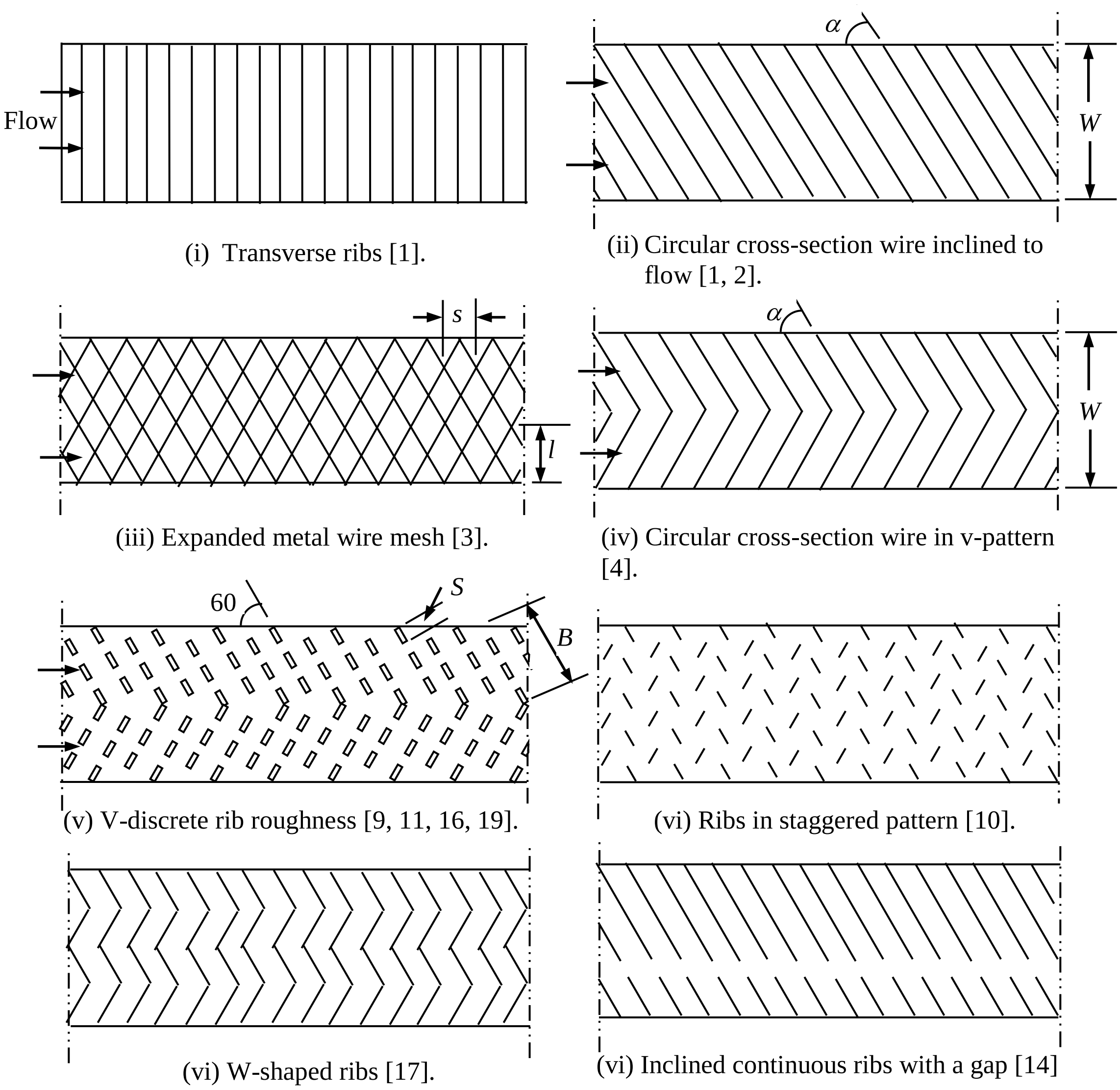
Researchers have tried rib elements in various arrangements: inclined continuous ribs [1, 2], expanded metal wire mesh [3], inclined continuous ribs with a gap [14], circular cross-section wires arranged in v-shape [4], discrete rectangular section ribs in v-pattern [5, 9, 16, 18, 19], ribs in staggered pattern [10], and ribs in w-pattern [17] as shown in Fig. 3.

The optimum inclination angle for v-continuous or discrete rib pattern is reported to be 60° [3, 4, 9]. In the case of the expanded metal wire mess also, the optimum performance is reported for the 60° inclination of the elements of the mess to the flow direction [3] though the pitch in this case is variable.

Karwa [9] has presented the following flow structure in the case of inclined or v-discrete rib pattern.

The additional heat transfer enhancement observed for the inclined or the v-pattern ribs over the transverse ribs has been attributed to the secondary flow of the air induced by the rib inclination. Thus, the heated air moves along the plate surface to the side wall in the case of the inclined ribs and towards both of the side walls in the case of v-up pattern of ribs. This exposes the absorber plate to a relatively lower temperature air of the axial or primary flow over the ribs. In the case of the v-down pattern, there are two contradictory effects. The secondary flow is towards the central axis where it interacts with the axial flow creating additional turbulence leading to the increase in the heat transfer rate while the rise in the temperature of the axial flow, just above the ribs in the central region, reduces the heat transfer rate.

In the case of discrete ribs, the secondary flow mixes with the primary flow after a short distance movement leading to greater turbulence. 60° v-down discrete ribs and inclined ribs with gap are shown to be the best of all the rib arrangements [9, 11, 14]. The discrete and staggered ribs provide greater turbulence and mixing at the surface.



α = Rib angle with flow, s/l, S/B = .Relative roughness length

Fig. 3 Rib arrangements.

IV. CONCLUSIONS

The review of various studies shows that

(i) Optimum relative roughness pitch for circular and rectangular section ribs is 10 while the same has been reported to be about 6-8 for the wedge, chamfered and rib-grooved surfaces.

(ii) Positively chamfered ribs with 15^o - 18^o chamfer angle have been shown to provide optimum performance while the optimum angle for the wedge shaped ribs is 10^o. Negatively chamfered ribs are poor in performance.

(iii) Integral ribs provide additional heat transfer enhancement due to the fin effect.

(iv) The optimum inclination angle for v-continuous or discrete rib pattern is reported to be 60^o. 60^o v-down discrete ribs are the best of the all rib arrangements. Discrete and staggered ribs provide greater turbulence at the surface.

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