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Review on Heat Transfer Enhancement using V-shaped Ribs

Khushal G. Sonawane[1*] and Uday S. Wankhede[2]

[1]Student, M. Tech., Heat Power Engineering,*
G. H. Raisoni College of Engineering, Nagpur, Maharashtra, India
Email: khushalsonawane7@gmail.com
[2]Professor, Department of Mechanical Engineering,
G. H. Raisoni College of Engineering, Nagpur, Maharashtra, India
Email: udaywankhede.ghrce@raisoni.net

Abstract:

The use of artificial roughness in different forms, shapes and sizes is an efficient way to improve the performance characteristics of heat exchangers and solar heaters. Different artificial roughness geometries such as ribs, baffles, delta winglets, rings, perforated blocks etc. are used for the purpose. Many researchers have carried out both numerical and experimental studies to determine the effect of these roughness geometries on performance of solar heaters and heat exchangers. Use of turbulators in the form of ribs can greatly improve the effectiveness of heat exchangers and solar air heater ducts. In the present study, emphasis has been given to works dealing with V-shaped ribs because according to the studies carried out by many researchers; these are known to be an economic tool in the field of heat transfer enhancement.

Keywords: Heat Transfer Enhancement, Passive techniques, V-shaped ribs.

Introduction

Ribs are popular passive heat transfer augmentation devices used in various cooling passages such as internal cooling channels of gas turbine blades, combustor walls, and guide vanes etc. Periodic ribs are often deployed on the surface of heat exchangers to improve the heat transfer rate. Attachment of periodic ribs to flow passages increases production of turbulent kinetic energy. The flow disturbance caused by rib arrays greatly increases the production of turbulent kinetic energy, which enhances turbulent heat transfer in the channels [20]. Artificial ribs attached to the surface cause extra flow resistances and hence there is always some pressure drop associated with it. The performance of heat exchanging surface depends on various geometrical parameters of the rib such as arrangement and configurations in terms of its height, width, cross-section etc.

Different types of rib roughness geometries used in various heat transfer passages are transverse rib, inclined ribs, combined inclined and transverse rib, V-shaped ribs, wedge shaped ribs, chamfered ribs, expanded metal mesh ribs or wire mesh, arc shaped ribs, W-shaped ribs, metal grit ribs, Z-shaped ribs, U-shaped ribs etc.

Heat Transfer Augmentation

Heat transfer in heat exchangers, flow channels, solar heaters etc. can be enhanced by using different methods. The process of improving the heat transfer performance of such systems is known as heat transfer enhancement or augmentation. In general, this means an increase in heat transfer coefficient. Heat transfer augmentation can be carried out using different techniques. These techniques are broadly classified into three different categories:

1. Active techniques
2. Passive techniques
3. Compound techniques

Active techniques of heat transfer augmentation require external power input to cause the desired flow modification and improvement in the rate of heat transfer. It finds limited applications since it requires external power input while passive techniques do not need any external power input.

Passive techniques are generally concerned with surface or geometrical modifications to the flow channel by incorporating inserts or additional devices. Heat transfer enhancement in case of passive techniques can be carried out by disturbing or altering the existing flow behaviour. When two or more of such techniques are employed simultaneously to obtain heat transfer enhancement that is greater than that produced by either of them when used individually, it is termed as compound enhancement.

Effect of various rib parameters

Effect of rib

Ribs are passive heat transfer augmentation devices placed on the cooling channel walls to increase convective heat transfer by providing additional heat transfer area. Presence of rib creates two flow separation regions- one on each side of the rib. Separation leads to generation of turbulence and hence the enhancement in heat transfer as well as in the friction losses takes place [22].

Effect of V shape

The V-shaping of the transverse rib generates secondary flows which results in considerably higher heat transfer performance. Due to the V-shaping, two flow cells on both sides of V are formed when compared with straight angled rib where only single flow cell is formed. This leads to maximum heat transfer augmentation in case of V-shaped ribs. V-shaped rib with apex facing downstream has a higher heat transfer as compared to that of with apex facing upstream [22].

Effect of discretization
Discretization of V-shaped rib is done by providing small symmetrical gap in both the legs of V [12]. The V-shaped ribs along with staggered rib pieces in between, further increase the number and area of heat transfer regions [22].

Effect of perforation
Creating the perforations in solid blocks enhances the heat transfer rate due to acceleration of flow in the form of jets through these perforations which subsequently strikes the heated surface and mix with main flow [19]. The presence of perforations not only increases heat transfer but also reduce pressure drop.

Literature Review

V-shaped Ribs

Ebrahim Momin et al. [1] presented the results of experimental investigations carried out in a rectangular solar air heater duct with V-shaped rib roughness at its surface. The absorber plate of duct is roughened by artificial roughness in the form of v-shaped rib at its underside to study heat transfer and fluid flow behaviors. The Reynolds number used for study lies in the range of 2500 to 18,000. Other parameters include angle of attack in the range 30 to 90^{o}, relative roughness height (e/Dh) of 0.02–0.034 and a fixed pitch of 10. It was observed that the thermo-hydraulic performance parameter becomes better by increasing the angle-of-attack for flow and relative roughness height and the optimum results occurs at 60° angle of attack (α). They found that the angle of attack of 60° corresponds to the higher values in case of both Nusselt number and the friction factor. They also observed that the V-shaped ribs are more advantageous than the inclined ribs for same operating conditions. Roughness elements on absorber plate used in this paper are showed in Figure-1.

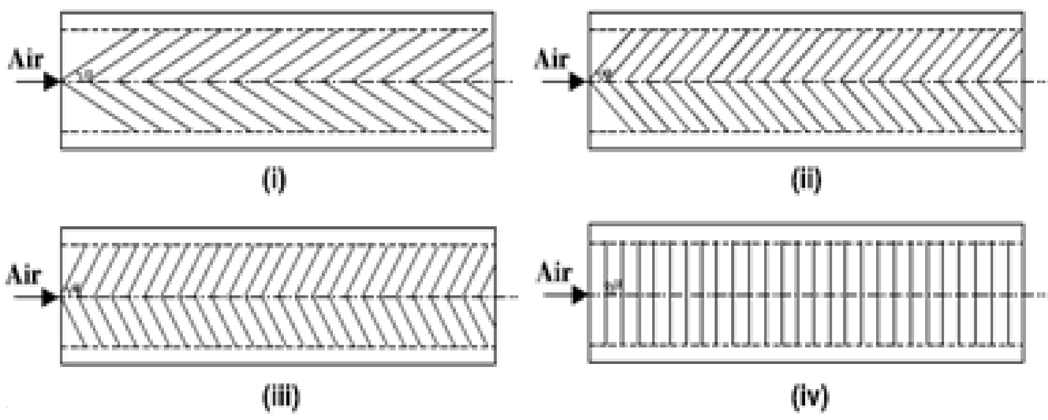


Figure 1: Roughness elements on absorber plate [1].

S.W. Chang et al. [2] experimentally examined the performances of heat transfer and pressure drop in rectangular channel with compound roughness of V-shaped ribs and deepened scales for both forward and backward flows. The HTE ratios with forward and backward flows inside the channel respectively for laminar flows are 9.5–13.6 and 9–12.3 and for turbulent flows lies between 6.8–6.3 and 5.7–4.3. It was found that the problem of decrease of HTE ratios as Re is increased for turbulent flow are almost diminished for a present channel fitted with compound rib roughness. Structural integrities of this compound HTE surface are satisfied with cooling applications to gas turbine blades. HTE impacts offered by this compound HTE roughness are accompanied by high pressure drop penalties. But they found that significant HTE effects offset the pressure drop penalties that considerably elevate the thermal performance factors in the test channel roughened by scales and V-ribs. They also derived Empirical correlations of Nu and C_f with Re as the determined variable for design applications.

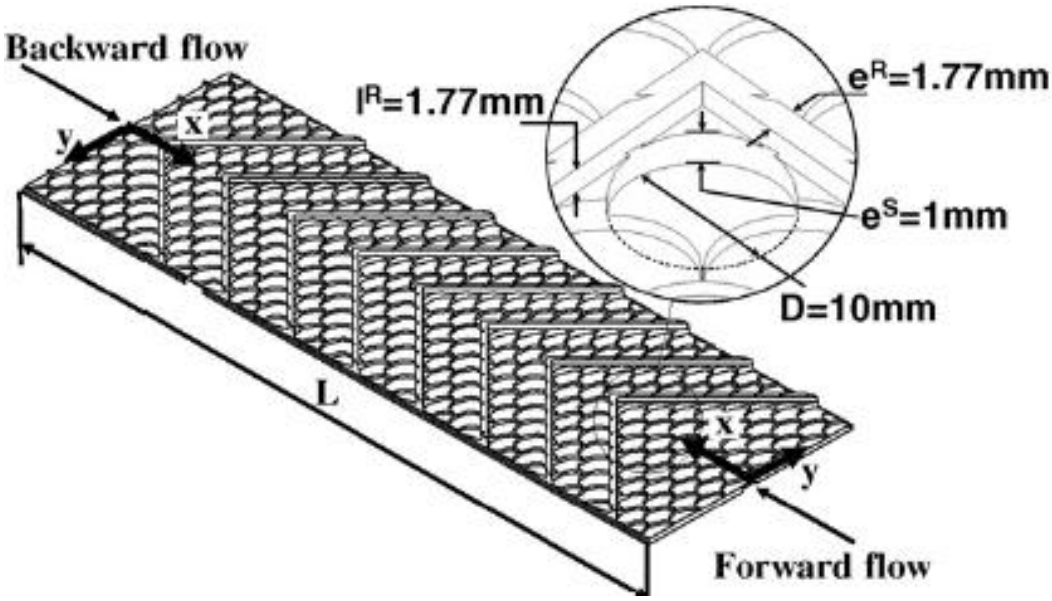


Figure 2: Compound HTE surface roughened by V ribs and scales [2].

Caliskan and Baskaya [3] experimentally studied the velocity field and turbulence effects on heat transfer characteristics for smooth surfaces and surfaces with V-shaped ribs with a Laser-Doppler Anemometry (LDA) system. Heat transfer results were showed using infrared thermal imaging from these surfaces under the action of impinging circular jet array. The velocity profiles were measured at Reynolds number of 10,000 and at for distance between the plate and the jet exit (H/d) equal to 3-12. For each H/d position, profiles were collected from x/d = 0 to 6 axial locations. The heat transfer entries were collected for three different values of Reynolds number. It was found that for the rib having V-shaped surface produces more turbulent kinetic energy as compared to that of smooth surfaces for low jet-to-plate spacings. The heat transfer results have also been compared with those of a smooth surface under the same flow conditions to determine the enhancement in the heat transfer coefficient from x/d = 0 to 3 locations. In these locations, the Nusselt numbers are higher for V-Shaped rib surfaces as compared to smooth surfaces. They found that the locations of the peaks and the minima are influenced by cross flow velocities which in turn depend on jet-to-plate spacing and V-Shape rib arrangements.

Luai AL-Hadhrami et al. [4] carried out an experimental study to obtain heat transfer data for a two-pass rectangular channel with smooth and ribbed surfaces for two channel orientations. The V-shaped ribs were placed on the leading and trailing surfaces. They carried out a comprehensive study to cover five different arrangements of 45° V-shaped ribs and a comparison with 45° V-shaped crossed rib case. In addition to this, the effect of the channel orientation with respect to the axis of rotation was investigated for two positions β=90° and β=135°. They obtained the heat transfer data for the Reynolds number and rotation number ranges were 5,000–40,000, and 0.0–0.21, respectively. The effect of rotation showed an increase in the Nusselt number ratio in the first pass trailing surface and second pass leading surface, while the opposite situation can be observed in the first pass leading surface and second pass trailing surface. A better heat transfer augmentation was observed in case of 45° V-shape rib arrangement as compared to crossed and inverted 45°V-shaped rib arrangements. Also a higher rotation effect was observed for 90° channel orientation than that of 135° channel orientation.

Lesley M. Wright et al. [5] studied frictional loss and heat transfer distribution in a rotating channel for which the aspect ratio was 4:1. Investigations were carried out on V-shaped, discrete V-shaped, angled, discrete angled ribs as well as the newly proposed W-shaped and discrete W-shaped ribs as shown in Figure-3. Systematic investigations were carried out with six different rib configurations in both nonrotating and rotating channels to check their thermal performances. The Ribs were attached on both leading as well as trailing channel surfaces in all six cases with an orientation of rib 45° to the main stream of flow. The orientation of channel was made 135° with respect to the direction of rotation. For both rotating and nonrotating channel the W-shaped and discrete W-shaped ribs showed the superior heat transfer performance with higher pressure drop penalties. However, the lowest pressure drop was observed in case of discrete V-shaped and discrete angled ribs. Angled rib configuration showed the worst performance among all six rib configurations studied. By taking basis of heat transfer enhancement and pressure drop penalty in both rotating and non-rotating channels, it was found that the best overall thermal performance were showed by V-shaped and discrete W shaped ribs.

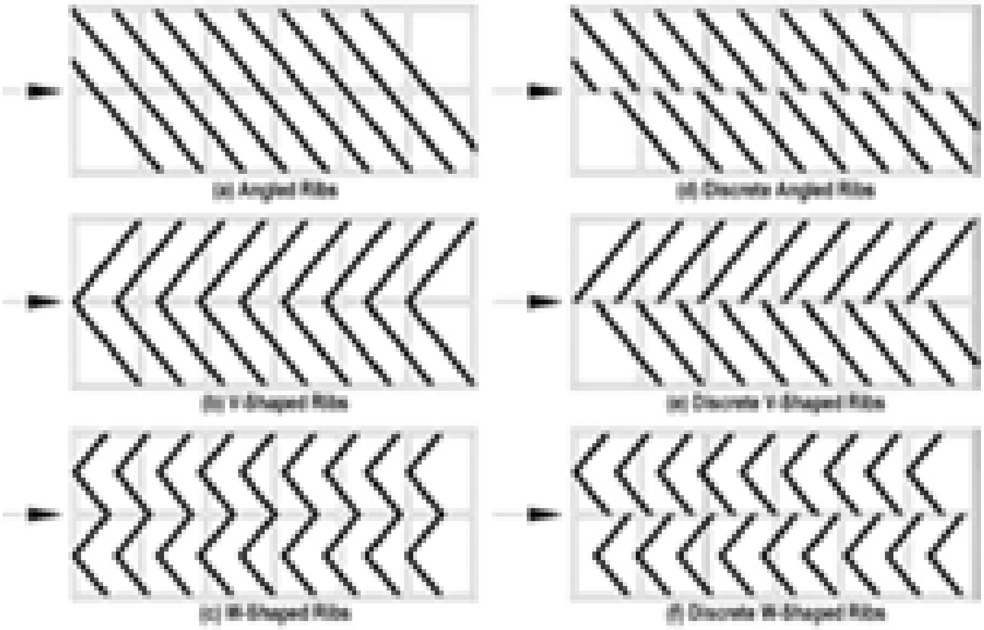


Figure 3: Top view of the six rib configurations [5].

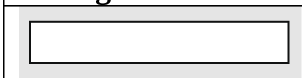
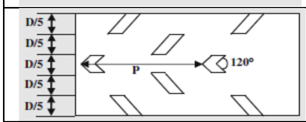
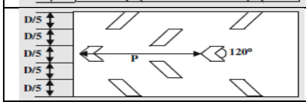
T.-M. Liou et al. [6] compared the heat transfer augmentation levels of 12 different shaped longitudinal vortex generators in a square channel using transient liquid crystal thermography. Laser-Doppler velocimeter and pressure transducer was used for measuring flow patterns and friction factors respectively. Based on hydraulic diameter of channel and bulk mean velocity, Reynolds number was selected to be 1.2×10^4. The pitch-to-height ratio and height-to-hydraulic diameter ratio of vortex generator were 10 and 0.12, respectively. The fluid dynamic mechanisms and wall confinement relevant to heat transfer enhancement were documented for three-selected vortex generator models. In addition to this, they addressed the differences in fluid flow and heat transfer characteristics between a single vortex generator and a vortex generator array for the delta wing I and 45° V (with tips facing upstream) models which provide better thermal performance among the 12 configurations examined. They found that the heat transfer advancement through the wall of duct was affected by strength and directions of secondary flows with respect to heat transfer wall are the most important fluid-dynamic factors.

V-broken ribs

Giovanni Tanda [7] presented local and average heat transfer coefficients in a rib-roughened rectangular channel of aspect ratio 5. Investigations were carried out for different configurations of rib which includes sequences of V-shaped broken, transverse continuous and transverse broken ribs to increase turbulence and improve heat transfer by convection. A rectangular channel having repeated ribs on the surface heated with uniform heat flux was used to study the mechanism of heat transfer. The V-shaped with an angle of 45 or 60^{o} were deployed relative to the direction of flow and the ribs having rectangular or square sections were deployed transverse to the main direction of flow. The effect of both continuous and broken ribs was also taken into consideration. Local heat transfer coefficients were obtained at various Reynolds numbers, within the turbulent flow regime. The detailed distributions of the heat transfer coefficient in rib-roughened channels were studied by using Liquid crystal thermography.

SriHarsha et al. [8] carried out a study on double walled channel having square cross section with 60° V broken ribs and 90° continuous attached rib (Table-1). The effect of rib height to the hydraulic diameter ratio on distribution local heat transfer coefficient was the objective of study. They also presented the rib detachment effects in case of broken rib to study their heat transfer distribution within duct. An increase in heat transfer was observed in the channel in case of continuous 90° attached rib which increases with increase in rib height-to-hydraulic diameter ratio (e/D). But it was observed that, a pressure drop penalty is also associated with it across the test section of channel. During the experimentation it was observed that as compared to 90° continuous attached ribs, 60° V broken ribs showed better enhancements and also caused lesser pressure drop. The effect of increase in rib height in case of broken ribs was found to have adverse effect on heat transfer. The heat transfer characteristics degraded with increase in the rib height in both attached and detached broken ribbed cases.

Table 1: Details of 90° continuous attached and 60° V-broken rib configurations [8].

Configuration	P/e	e/D	Description
	10	0.15, 0.20 and 0.25	90° Continuous attached rib
	10	0.0625, 0.10 and 0.15	60°V Attached broken rib
	10	0.10 and 0.15	60°V Detached

Pei-Xue Jiang et al. [9] studied convection heat transfer in a channel with 90° ribs and V-shaped ribs both numerically and experimentally. Six different rib arrangements were analyzed by them having continuous and interrupted rib layouts. As compared to the smooth wall duct without rib, both V-shaped rib and 90° ribs showed enhancement in convective heat transfer. But V- shaped has better thermal/ hydraulic performance than 90°ribs.The numerical simulations were also carried out by them using the SST k-ω turbulence model for checking the thermal and hydraulic performance for six rib arrangements. The results indicated that the 45° V-shaped continuous ribs had the best thermal/hydraulic performance. Comparison of continuous and interrupted ribs showed that the heat transfer with the V-shaped interrupted ribs was lower than that of V-shaped continuous ribs, while the 90° ribs had the opposite result.

Multiple V-shaped ribs

Hyung Hee Cho et al. [10] investigated the local heat/mass transfer characteristics and friction losses for 60° continuous V-shaped rib and 45° multiple V-shaped rib configurations with varying aspect ratios and Reynolds numbers (Figure-4). The test section was fitted with square ribs on the surface in parallel manner. They used naphthalene sublimation method to measure the local heat/mass transfer coefficients. It was observed that, for 60° continuous V-shaped rib configurations, the heat/mass transfer coefficients showed the maximum values at the center region, and decreased gradually along the angled ribs due to the two pairs of large-scale counter-rotating secondary flows generated in the channel. However, for the multiple V-shaped rib configuration with 45° attack angle, asymmetric secondary flow patterns were generated due to its geometric features, resulting in uniform heat/mass transfer distributions. They found that the effect of aspect ratio was in good agreement for 60° continuous V-shaped rib configurations, while weak for multiple 45° V-shaped rib configuration.

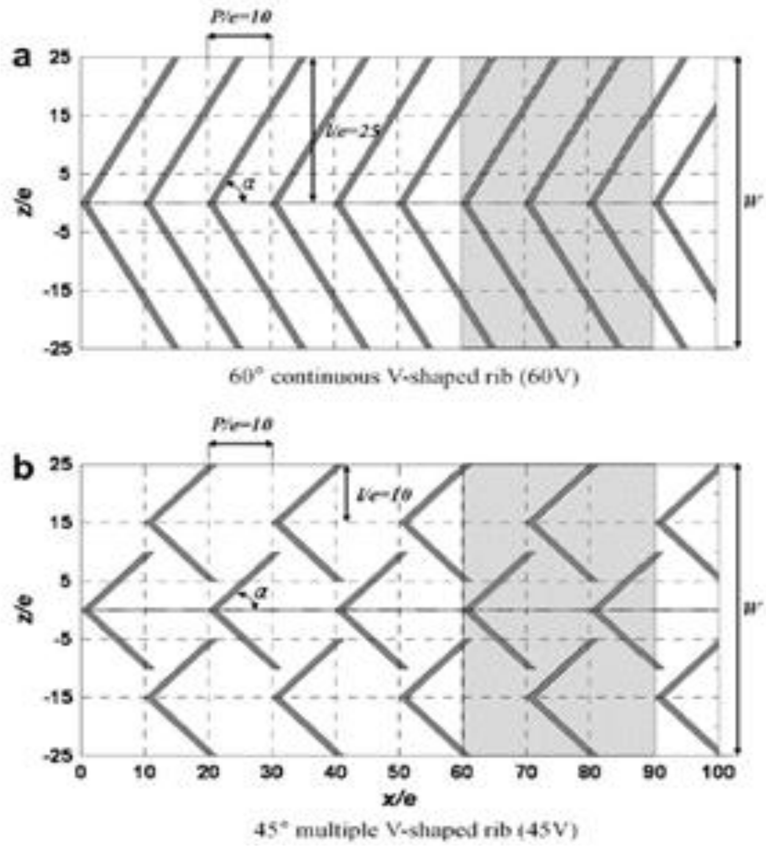


Figure 4: Schematic of 45° and 60° multiple V-shaped Rib configurations [10].

V.S. Hans et al. [11] did an experimental investigation to study the effect of multiple V-rib roughness on heat transfer coefficient and friction factor in an artificially roughened solar air heater duct. The measurements were done for Reynolds number (Re) from 2,000 to 20,000, relative roughness pitch (P/e) range of 6–12, relative roughness height (e/D) values of 0.019–0.043, attack angle (α) in the range of 30–75° and relative roughness width (W/w) range of 1–10. An extensive experimentation has been done by them to collect the data on fluid flow and heat transfer characteristics of a rectangular duct roughened with multiple V-ribs. They found that with increase in relative roughness width value to 2, the number of leading ends and secondary flow cells doubles resulting in considerable enhancement in heat transfer and the maximum heat transfer enhancement occurs for a relative roughness width (W/w) value of 6 while friction factor attains maximum value for relative roughness width (W/w) value of 10. They observed that the Nusselt number and friction factor attain maxima corresponding to angle of attack (α) value of 60°. They also observed that maximum enhancement of Nusselt number and friction factor corresponding to relative roughness pitch (P/e) value of 8 while Nusselt number and friction factor increase monotonically with increase in the value of relative roughness height (e/D).

Discrete V-down ribs

Sukhmeet Singh et al. [12] used discrete V-down rib roughness on absorber plate of solar air heater for predicting the exergetic efficiency of it. The effect of Reynolds number and rib-roughness parameters on exergetic efficiency was examined by them. For Reynolds number range normally used in solar air heaters i.e. for Reynolds number less than 18,000 ,the exergy based criterion suggests the use of solar air heater ducts roughened by discrete V-down rib. For the Reynolds number greater than 18,000, the smooth conventional flat-plate solar air heater is suitable. The various rib roughness parameters are considered in the range of Relative roughness pitch (P/e) 4-12, Relative gap position (d/w) 0.20-0.80, Angle of attack (α) 30-75°, Relative gap width (g/e) 0.5-2.0, Relative roughness height (e/Dh) 0.015-0.043. They found that a set of rib roughness parameters namely relative gap position of 0.65, relative roughness pitch of 8, angle of attack of 60°, relative gap width of 1.0 and relative roughness height of 0.043 yield maximum exergetic efficiency for $\Delta T/I > 0.0175$ Km^2/W.

Sukhmeet Singh et al. [13] carried out investigations for studying heat transfer and fluid flow characteristics with periodically fitted v-down rib in a rectangular duct (Figure-5). The experiment is carried out to determine the flow and heat characteristics of discrete V-down rib-roughened rectangular duct. The discretization was done by making small symmetrical gaps in both the sides of V- down rib. They varied Reynolds number (Re) from 3000-15000 with relative gap width (g/e), relative gap position (d/w), relative roughness height (e/Dh) relative roughness pitch (P/e) and angle of attack (α) in the range of 0.5-2.0, 0.20-0.80, 0.015-0.043,4-12 and 30°-75° respectively. The effect of these roughness parameters on Nusselt number (Nu) and friction factor (f) has been determined and the results obtained were compared with that of smooth duct. They also developed correlations for Nu and f as function of Re and discrete V-down rib parameters based on the obtained experimental results.

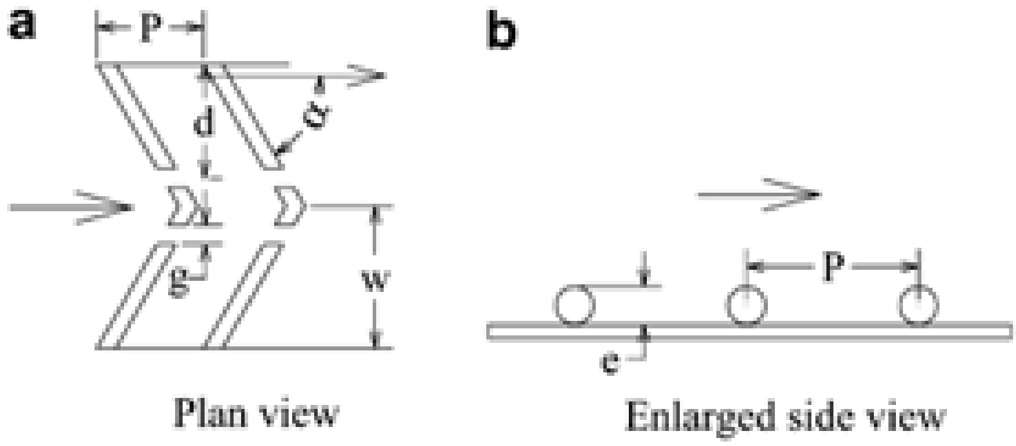


Figure5: Discrete V-down rib arrangement [13].

Sukhmeet Singh et al. [14] investigated the thermo-hydraulic performance of rectangular ducts roughened with V-down rib having gap equal to rib height for variation of flow-attack-angle. The tests were carried out for five rib roughened plates having flow-attack-angle (α) from 30° to 75°. It was observed that both friction factor and Nusselt number of the roughened duct are strong function of flow-attack-angle and their maximum values are obtained for the flow-attack-angle of 60°. The symmetrical gap in both legs of V which is equal to the height of rib based on equal pumping power results in improved thermo-hydraulic performance parameter. The rib roughness parameters of continuous V-down rib are then compared with the results that were obtained with rib of 60° flow-attack-angle.

Rajendra Karwa and Girish Chitoshiya [15] studied experimentally the thermo-hydraulic performance of a solar air heater with 60° V-down discrete rib roughness on the airflow side of the absorber plate along with that for a smooth duct air heater. An enhancement in the thermal efficiency of 12.5-20% has been found depending on the flow rate due to artificial roughness on air flow side of the absorber plate; higher enhancement is at the lower flow rate. The collected experimental data was used to verify the mathematical model, so that data can also be used for designing and predicting the performance of smooth as well as rib roughened air heaters under variable operating conditions. The mathematical model was developed which presents the results of detailed thermo-hydraulic performance of discretized V-down rib roughness in solar air heater ducts and effect of different varying parameters on the performance of ducts has also been studied.

Multi v-shaped ribs with gap

Anil Kumar et al. [16] did experiments on solar air heater duct with rectangular cross-section roughened with Multi v-shaped rib with gap in its both the limbs to study the effect their geometrical parameters on heat transfer performance and flow characteristics of fluid flowing through it (Figure-6). The thermo-hydraulic performance of the system was checked by varying the values of Nusselt number and Nusselt number ratio as function roughness parameters which includes relative gap width and relative gap distance. They found that Nusselt number and Nusselt number ratio increase with increase in the relative gap width up to about 1.0, beyond which it decreases with increase in the relative gap width. It is observed that the friction factor and friction factor ratio increases with the values of relative gap width up to about 1.0.It has been observed that up to the value of 1.0 of relative gap width, Friction factor and Friction factor ratio increases and their optimum values are occurs at the value of 0.69 of the relative gap distance. From the experimental results obtained they found that the relative gap width of 1.0 and a relative gap distance of 0.69 results in a highest values of thermo-hydraulic performance parameter.

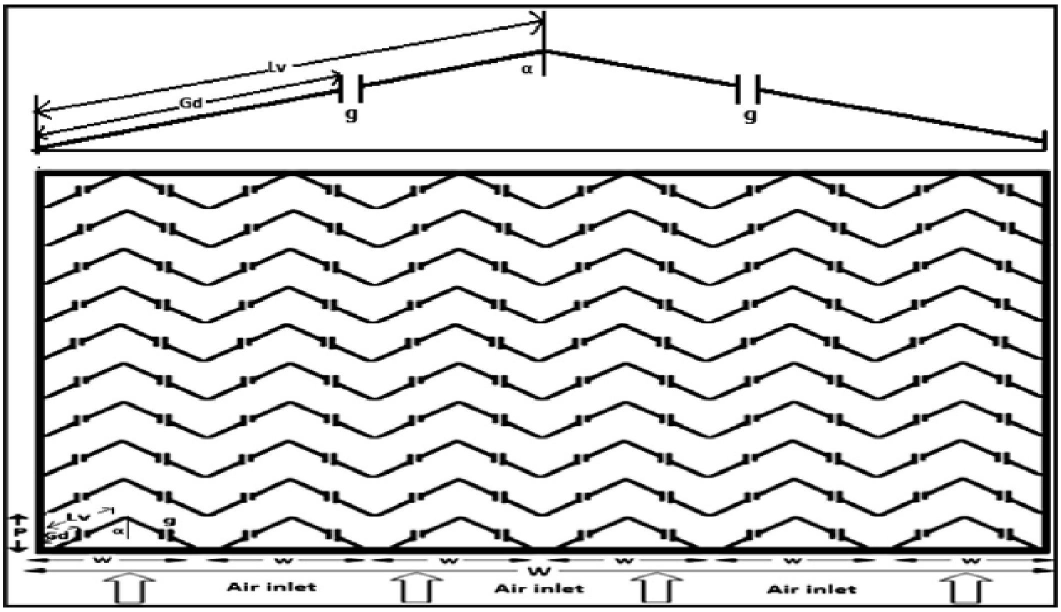


Figure 6: Multi v-shaped rib with gap [16].

Anil Kumar et al. [17] had done experimental investigations for heat transfer and friction characteristics with Multi v-shaped ribs with gap roughness in a rectangular duct. The effect of various roughness parameters such as relative gap width (g/e), relative gap distance (Gd/Lv), relative roughness width (W/w), relative roughness height (e/D), relative roughness pitch (P/e), and angle of attack (α) on the performance of rectangular duct with Multi v rib roughness has been studied. According to the range of parameters investigated by them, it was found that as compared to smooth duct the presence of artificial roughness yields Nusselt number up to 6.74 times whereas friction factor raises up to 6.37 times. The enhancement of Nusselt number and friction factor values is more in case of Multi v-shaped rib with gap than that of continuous Multi v-shaped rib. The correlations for Nu and f have been developed by them based on the obtained the experimental results as function of roughness parameters of Multi v-shaped with gap rib.

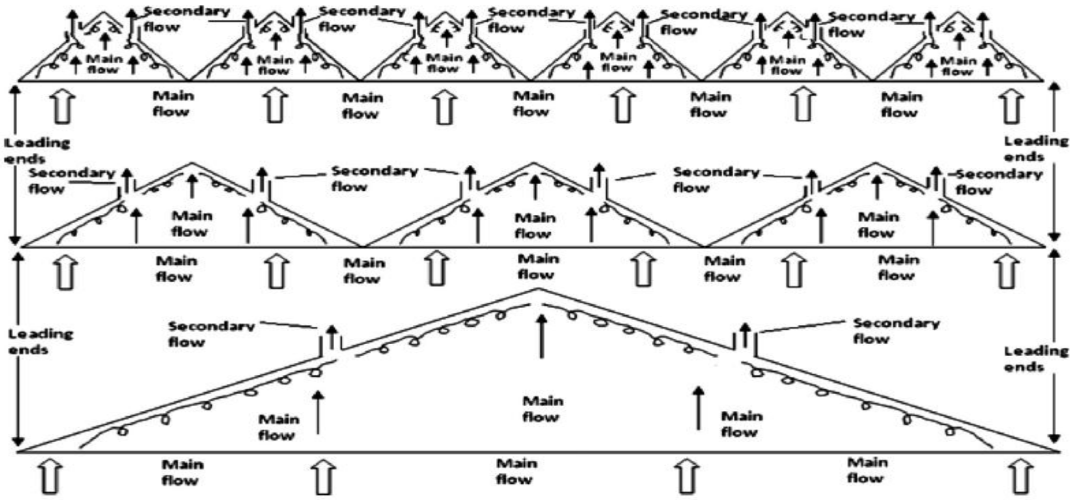


Figure 7: Flow pattern of secondary flow for Multi v-shaped rib with gap [17].

V-shaped perforated blockages

Tabish Alam et al. [18] experimentally evaluated the heat transfer and friction characteristics of V-shaped blockages with various perforation shapes fitted to one broad wall of rectangular duct. (Figure-8(a)) On the basis of experimental results, the shape of the perforation has been optimized. In order to define shapes of perforation, a new parameter known as circularity (ψ) of perforation has been defined. Measurements were carried out to study the effect of circularity of perforation holes, open area ratio, angle of attack, relative blockage height, and relative pitch ratio on friction factor and Nusselt number. The experiments were carried out for Reynolds number ranging from 2,000 to 20,000.Non-circular perforation holes resulted in relatively higher heat transfer when compared with same open area ratio circular holes and an optimum non-circular shape was obtained for the circularity (ψ) of 0.69. The maximum enhancement is found corresponding to the angle of attack of 60^{o}. They also developed the correlations for Nusselt number as well as friction factor in terms of Reynolds number and geometrical parameters of V blockages. These correlations were then used for predicting the friction factor and Nusselt number values with considerably good accuracy.

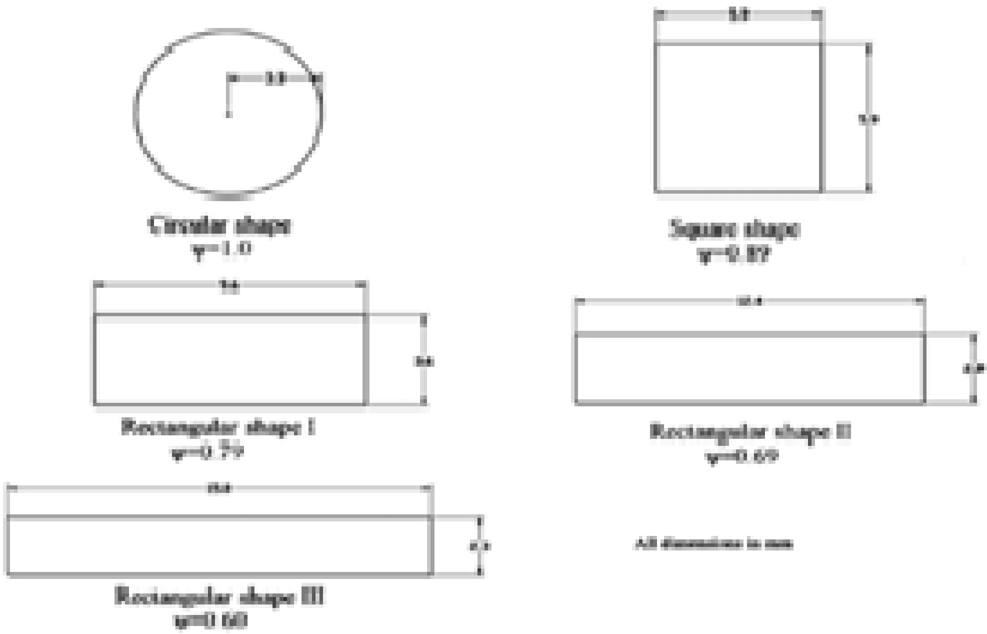


Figure 8(a): Five different shapes of Perforation [18].

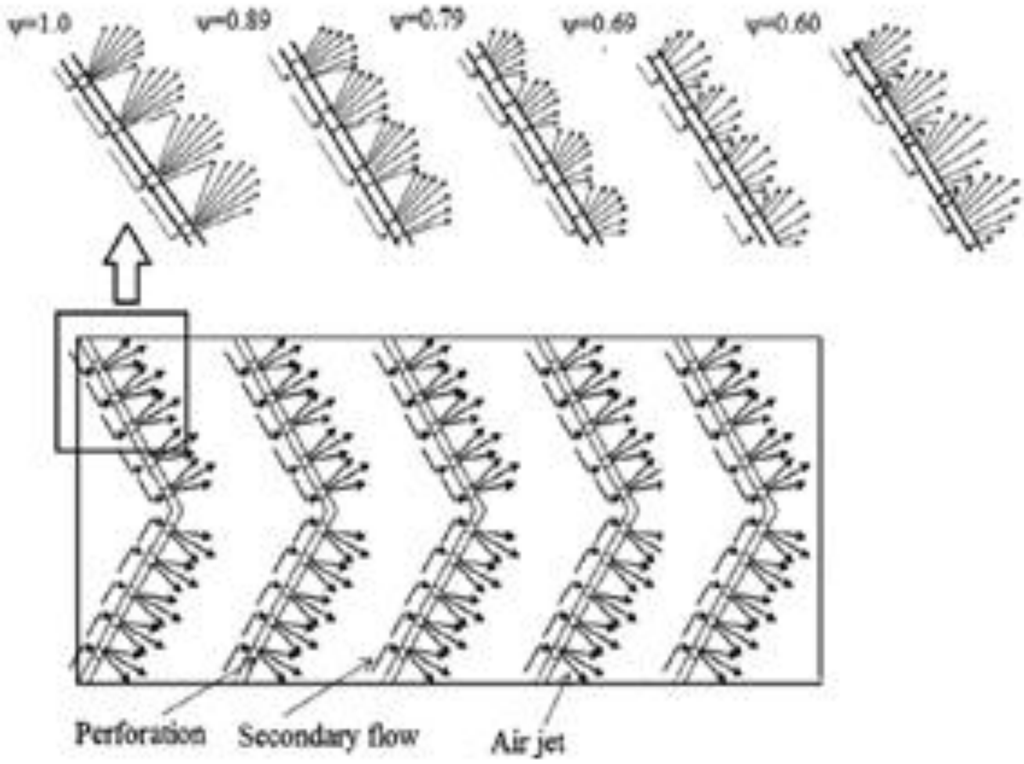


Figure 8(b): Movement of secondary flow and interaction of neighboring jets for different circularity [18].

Tabish Alam et al. [19] performed experimentations on rectangular duct with V-shaped perforated blockages. The effect of their geometrical parameters was also considered to study heat transfer and flow characteristics. The geometrical parameters namely, relative blockage height, relative pitch ratio and open area ratio at a fixed angle of attack are taken into consideration. The effect of V-shaped perforated blockages has been investigated for Reynolds number range of 2,000 to 20,000. V-shaped blockages with perforations yields in maximum enhancement of Nusselt number 6.76 and friction factor 28.84 times to that of smooth duct. Thermo-hydraulic performance of V-shaped perforated blockages is also compared to that of V-shaped solid blockages for same geometrical parameters. Approximately, 50% improvement in thermo-hydraulic performance is achieved by using V-shaped perforated blockages over solid blockages.

Conclusion

This review paper focused on V-Shaped rib roughness geometries that have been used by many researchers for the enhancement of heat transfer. An attempt has been made in this paper to carry out a literature review of V- shaped rib turbulators used to investigate the augmentation in heat transfer. Many investigators carried out number of experimental and numerical studies for better understanding of heat transfer enhancement and friction characteristics due to turbulence generated by the presence of V-shaped roughness on the heat exchanging surface. The review of both experimental as well as numerical analyses carried out by various researchers is presented in this paper.

The V-shaping of transverse ribs results in considerably higher heat transfer due to generation of secondary flows. Maximal heat transfer intensification is observed at 60° in most of the studies. The presence of perforations enhances the heat transfer rate due to acceleration of flow in the form of jets through these perforations since more area is available for heat transfer due to perforations made in solid blockages. Based on the literature, it is observed that Multi v-rib with a gap gives better performance in comparison to others roughness geometries. The enhancement is a strong function of gap distance and size. Multi v-rib with gap roughness has also showed better thermo-hydraulic performance in comparison with inclined rib with gap, V-rib, broken inclined rib and Multi v-rib without gap.

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