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Heat Transfer and Friction Factor Characteristics in a Discrete Rib Roughened Channels – A Review

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Abstract – *Various Techniques have been used for heat transfer enhancement in several engineering applications. In recent years, the high cost of energy and material has resulted in an increased effort aimed at finding more efficient heat exchange technique. Providing an artificial roughness on a heat transferring surface is an effective passive heat transfer technique to enhance the rate of heat transfer to fluid flow. Several studies have been carried out to determine the effect of different roughness element geometries on heat transfer and friction in roughened duct. Various investigations appropriate to distinct roughness geometries shows that the enhancement in heat transfer is accompanied by considerable rise in pumping power and thus the thermo-hydraulic performance is an important parameter to decide the best suited rib geometry for effective heat transfer. It has concluded that many broken/discrete rib geometries make heat transfer better than the continuous ribs. The objective of this paper is to review various studies, in which different artificial discrete rib roughness elements are used to enhance the heat transfer rate with little penalty of friction. The effects of various rib parameters on heat transfer and fluid flow processes are also discussed so that it can be helpful for other researchers to propose a new design of rib geometry which may produce more heat transfer with best possible thermo-hydraulic performance.*

***Key Words*: Artificial Rib Roughness, Discrete rib, Heat transfer, friction factor.**

1. INTRODUCTION

Various experimental and numerical investigations have been carried out to study the effects of ribs on heat transfer in internal channels. To trip the boundary layers for promoting turbulence and thereby enhancing heat transfer, various kinds of turbulators (ribs) are usually provided on the surface/s of the passages. These ribs increase the heat transfer in the duct flows by increasing the heat transfer area and by disturbing the laminar sub layer.

The development of turbulence must be close to the laminar sub layer to evade extensive friction deprivation. Friction deprivation is possible by maintaining the roughness altitude within the permissible limit and not to exceed beyond the limit. The artificial roughness break laminar sub-layer but simultaneously friction factor is also increased. Therefore heat transfer rate and pumping power these are two major factors necessary before designing rib roughness geometry. Several investigators worked on continuous ribs that can be further modified by discretization which helps to further create turbulence to break boundary layer development.

2. RIB TURBULATED COOLING THEORY

The turbulence promoters enhance the heat transfer basically in two ways: they induce secondary flow to intensify the flow turbulence, and increase the surface area for convective heat transfer. The mechanistic model of the flow is shown in Figure 1. Flow separates at the leading edge of the rib and reattaches at the bottom wall downstream of the rib. A circulating region develops in front of the rib and a large recirculation zone (wake) formed behind the rib. After the reattachment the boundary layer redevelops.

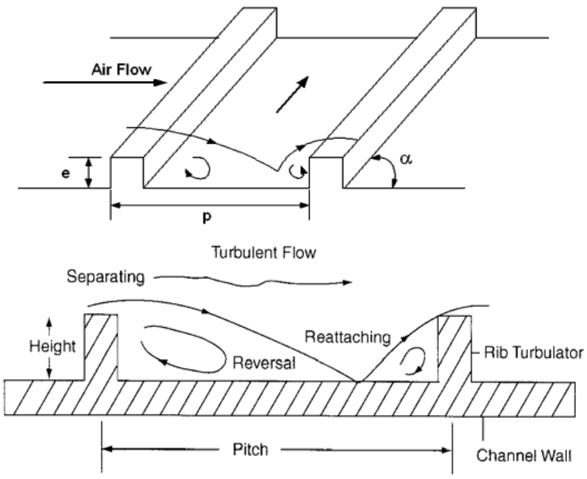


Figure-1 : Flow in a channel with rib turbulators

The heat transfer performance of the ribbed channel depends on the channel aspect ratio, the rib configurations, and the Reynolds number of the coolant flow. Many fundamental studies have been conducted to understand the coolant flow through a stationary ribbed channel [1, 2, 3].

3. DISCRETE/BROKEN RIBS

When ribs broken in to number of pieces (discrete ribs) and are arranged in a systematic manner, it will produce excessive enhancement in heat transfer, however, the friction factor also increases. The broken pieces can create more secondary flow cells and produce more local turbulence in the fluid flow to give rise to better heat transfer characteristic in comparison to continuous ribs.

3.1 Transverse Discrete ribs

Lau et al. [4, 5] investigated the heat transfer and friction factor characteristics of fully developed flow in a square duct with transverse and inclined discrete ribs. They reported that a five-piece discrete rib with 90° angle of attack shows 10-15% higher heat transfer coefficient as compared to the 90° continuous ribs, whereas inclined discrete ribs give 10-20% higher heat transfer than that of the 90° discrete ribs.

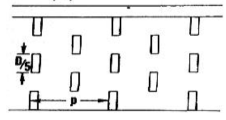
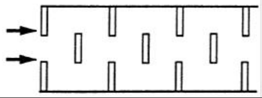
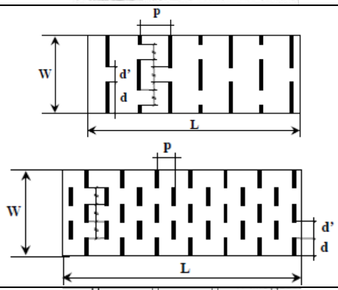
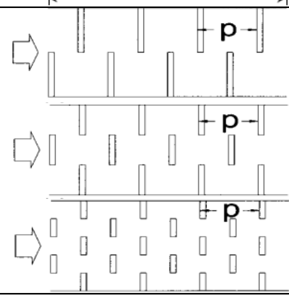
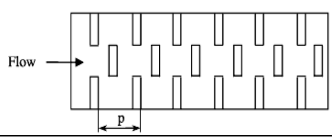
Han and Zhang [6] carried out experiments to study the heat transfer and pressure drop characteristics of a roughened square channel with various angled and V-shaped broken rib arrangement. The rib attack angle was 45° and 60° and Reynolds number was varied from 15000 to 90000. They concluded that broken ribs create heat transfer enhancement level of 2.5 to 4 while the enhancement created by the continuous ribs is only 2 to 3.The broken pieces can create more secondary flow cells and produce more local turbulence in the fluid flow to give rise to better heat transfer characteristic.

Tanda [7] investigated the heat transfer enhancement for one wall-ribbed rectangular channel of AR = 5:1 with continuous ribs, 90° broken using liquid crystal thermography. He found that the enhancement in heat transfer for 90° broken ribs is around 1.8 times than the continuous ribs.

Cho, Wu and Kwon [8] investigated angled and discrete angled ribs using mass transfer. They concluded that the heat transfer performance of the discrete ribs is similar to that of the angled ribs in a rectangular channel with an aspect ratio of 2.04:1.

Sahu and Bhagoria [9] investigated the effect of 90° broken ribs on thermal performance of a solar air heater for fixed roughness height (e) value of 1.5 mm, duct aspect ratio (W/H) value of 8, pitch (p) in the range of 10–30 mm and Reynolds number (Re) range of 3000–12,000. Roughened absorber plate increased the heat transfer coefficient by 1.25 to 1.4 times as compared to smooth one under similar operating conditions. Corresponding to roughness pitch (p) value of 20 mm, maximum value of Nusselt number was obtained that decreased on the either side of this roughness pitch (p) value. Based on the experimental investigation, the thermal efficiency of roughened solar air heater was found to be in the range of 51–83.5% depending upon the flow conditions.

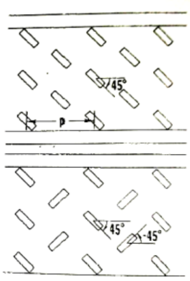
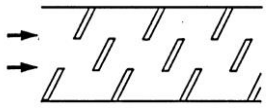
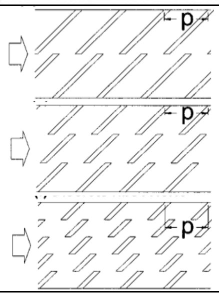
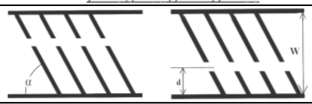
Table- 1: Discrete Ribs investigated by different researchers

Investigators	Type of Discrete transverse Ribs
Lau et al. [4]	
Han and Zhang [6]	
Tanda [7]	
Cho [8]	
Sahu & Bhagoria [9]	

3.2 Inclined Discrete ribs

Hu et al. [10] investigated the effect of inclined discrete rib with and without groove and reported that discrete rib arrangement without groove shows better performance than that of the discrete rib with groove.If gaps are provided in ribs, it accelerates the flow through the gap which increases the local turbulence and thus increases the heat-transfer coefficient. It was observed that due to gap in inclined rib the secondary flow along the rib joins the main flow through gap accelerating the flow field behind the rib, which energizes the retarded boundary layer flow along the surface and enhance the heat transfer rates [10].

Table- 2 : Inclined Discrete Ribs investigated by different researchers

Investigators	Type of Discrete inclined Ribs
Lau et al. [4]	
Han and Zhang [6]	
Cho [8]	
Cho et al. [11] Aharwal et al. [12] Chaube et al. [13]	

Cho et al. [11] examined the effect of angle of attack and number of discrete ribs in a square duct and observed that the gap region between the inclined discrete ribs accelerates the flow and enhances the local turbulence near the gap which will results in an increase in overall heat transfer. They also reported that the inclined rib arrangement with a downstream gap position shows higher enhancement in heat transfer compared to that of continuous inclined rib arrangement.

Aharwal et al. [12] experimentally studied the effect of width and position of gap in inclined split-ribs having square cross section on heat transfer and friction characteristics of a rectangular duct. The duct had an aspect ratio (W/H) of 5.84, relative roughness pitch (p/e) of 10, relative roughness height (e/D) of 0.0377, angle of attack (α) of 60^o, relative gap width (g/e) range of 0.5–2 and relative gap position (d/W) varied from 0.1667 to 0.667 for Reynolds number (Re) range of 3000– 18,000. For the split-rib and continuous rib roughened ducts, the enhancement in heat transfer was reported to be in the range of 1.71–2.59 and 1.48–2.26 times respectively over smooth duct under similar operating conditions.

Chaube et al. [13] investigated the influence of a gap provided in integral inclined ribs on heat transfer and friction factor enhancement. The Reynolds was varied between 5000 to 40000. The rib pitch-to-height ratio (p/e) was 10, the rib height-to-hydraulic diameter ratio (e/D) was 0.060 and rib attack angle (α) varies in the range of 300 to 900. The relative gap position (d/W) and relative gap width (g/e) is varied in the range of 1/5 –2/3 and 0.5–2.0 respectively. Presence of inclined ribs with a gap yields about 4-fold enhancements in Nusselt number and about 8-fold increase in the friction factor compared with smooth duct and about 1.3 times and 1.4 times higher than the case of continuous ribs.

3.3 High performance Discrete ribs

In the majority of cooling channels, discrete ribs were shown to outperform the continuous angled or V-shaped ribs [8, 14]. Han and Zhang [6] observed that 60^0 broken 'V' ribs offered higher heat transfer augmentation (4.5 times the smooth wall situation) and performed better than the continuous ribs. The 60^0 V-shaped broken rib arrangements give better performance than 45^o V-shaped broken rib arrangements. The experiments were conducted on two wall-ribbed channels for Reynolds number ranging from 15,000 to 90,000. The rib height to hydraulic diameter ratio (e/D) for all the cases was 0.0625 and the pitch to rib height ratio (P/e) was 10.

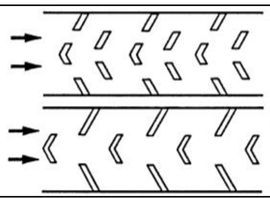
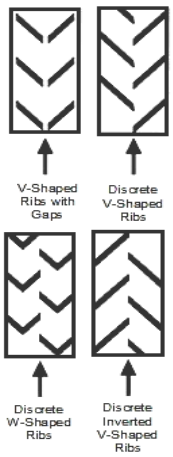
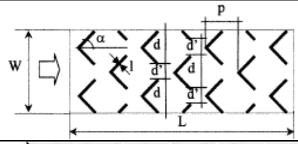
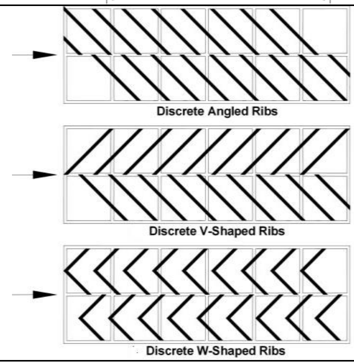
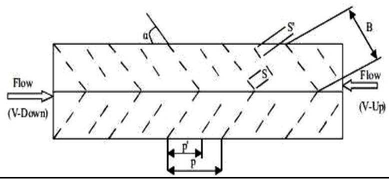
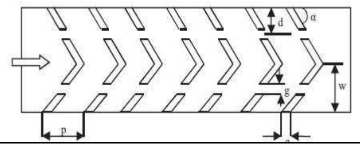
Tanda [7] presented the studies on detailed heat transfer distributions for continuous, discrete and V-broken ribs. They concluded that the features of the inter rib heat transfer distributions are strongly related to the rib shape and the arrangement. The augmentation levels of the transverse broken ribs were reported to be around 2.4 to 3.2 times higher than the smooth channel. Lau et al. [16] investigated V- shaped ribs angled at 45°, 60°, 90°, 120° and 135° for a P/e ratio of 10.The results indicated that the V-shaped ribs at (α = 46° and 60°) produced a 38%-46% and 47%-66% increase in thermal performance when compared to the 90° full rib. Similarly, when the following ribs were reversed, the heat transfer performance was enhanced by 26%-32% and 39%-48% respectively. This enhancement in thermal performance was accompanied by a 55%-79% increase in the pressure drop for various V-shaped configurations in comparison to the 90° rib. The reversed V-shaped ribs was found to result in poor heat transfer performance. It was also found that doubling the P/e ratio lowers the heat transfer augmentation and friction.

Taslim, Li, and Kercher [17] studied various configurations of angled and V-shaped ribs using a liquid crystal technique. They also concluded that V-shaped ribs result in the greatest heat transfer enhancement while having the greatest pressure loss. Ekkad and Han [18] also used a liquid crystal technique to obtain detailed heat transfer distributions in a two-pass channel with parallel (angled), V-shaped, and broken V-shaped (discrete V-shaped) ribs. They concluded that the parallel, V-shaped, and broken V-shaped ribs produce similar heat transfer enhancement in the first pass, with the broken V-shaped ribs giving slightly higher enhancement.

Rhee et al. [19] investigated rectangular channels (AR=3:1, 5:1, and 6.82:1) and studied the thermal performance of V-shaped and discrete V-shaped ribs. Based on their configurations, they concluded the thermal performance of the two configurations was comparable and the thermal performance of discrete V – shaped ribs is more as compared to continuous V-shaped ribs.

Taslim et al. [20] experimentally investigated the heat transfer and friction in channel roughened with angled, V-shaped and discrete ribs on two opposite walls for Reynolds number raging from 5,000 to 30,000. The results showed that the 90° transverse ribs produced the lowest heat transfer performance. The 45° angled V-shaped ribs produced the highest heat transfer performance in comparison to other rib configurations. For V-shaped ribs facing downstream of flow, the one with lowest blockage ratio had better heat removal rate. The discrete ribs also produced better performance in comparison to the transverse ribs.

Table- 3 : V and W shaped Discrete Ribs investigated by different researchers

Investigators	**Type of high performance Discrete Ribs**
Han and Zhang [6]	
Han and Wright [15]	
Tanda [7]	
Wright et al. [21]	
Muluwork et al. [23]	
Singh et al [24]	

Wright et al. [21] performed the experiments on 4:1 rectangular channel with angled, V shaped and W shaped (double V shaped) ribs and showed that the discrete V-shaped and discrete W-shaped ribs have the best thermal performance in both rotating and non rotating channels. For the non rotating and rotating rectangular channels, the W-shaped and discrete W - shaped ribs yield the best heat transfer enhancement. This comes at the cost of the greatest pressure drop. Also the performance of the V-shaped ribs is better than the performance of the angled ribs. Furthermore, the performance of the discrete angled ribs is comparable to that of the V-shaped ribs in both non rotating and rotating channels.

Prabhu et al. [22] concluded that the average heat transfer in a square channel with 60° V-broken ribs is comparatively higher than that of 90° continuous attached ribs. The local heat transfer distributions in the channel with 60° V - broken ribs indicate the formation of vortices which result in the better mixing of the fluid and hence higher are the augmentations. The effect of increase in rib height in case of broken ribs is found to have adverse effect on the heat transfer. The heat transfer characteristics are observed to degrade and this can be attributed to the loss of the effect 'V' shape of the rib due to the increased height.

Muluwork et al. [23] compared the thermal performance of staggered discrete v-apex up and down ribs with corresponding transverse staggered discrete ribs. They studied the effect of relative roughness length ratio (B/S), relative roughness segment ratio (S'/S), relative roughness staggering ratio (p'/p) and angle of attack (α) on the heat transfer and friction factor. It was observed that the Nusselt number increased with the increase in relative roughness length ratio (B/S). Nusselt number for v-down discrete ribs was found to be higher than the corresponding v-up and transverse discrete roughened surfaces. Nusselt number increased with increase in relative roughness staggering ratio (p'/p) and attained a maximum value for relative roughness staggering ratio (p'/p) value of 0.6. Heat transfer and friction factor attained maximum values for angle of attack (a) 60^o and 70^o, respectively. Correlations for Nusselt number and friction factor were developed.

Singh et al. [24] perform on discrete V-down ribs. Experiment was carried for Reynolds number 3000-15,000 with relative gap width (g/e) and relative gap position (d/w) in range of 0.5-2.0 and 0.20-0.80 respectively, relative roughness height as 0.015-0.045, relative roughness pitch as 4-12, angle of attack 30-75. Maximum increase in Nusselt number and friction factor over smooth duct was 3.04 and 3.11 times respectively. Rib parameter corresponding to increase in Nusselt number and friction factor were d/w=0.65, g/e=1.0, p/e=10, angle of attack 60^o and e/D=0.043.

Figure-2 shows the comparison of Nusselt number ratio between continuous and discrete ribs. It is clearly depicts from the figure that the heat transfer enhancement for discrete ribs is much more as compared to the corresponding continuous ribs. A parametric comparison of different V-shaped ribs investigated by different researchers is presented in Table-4.

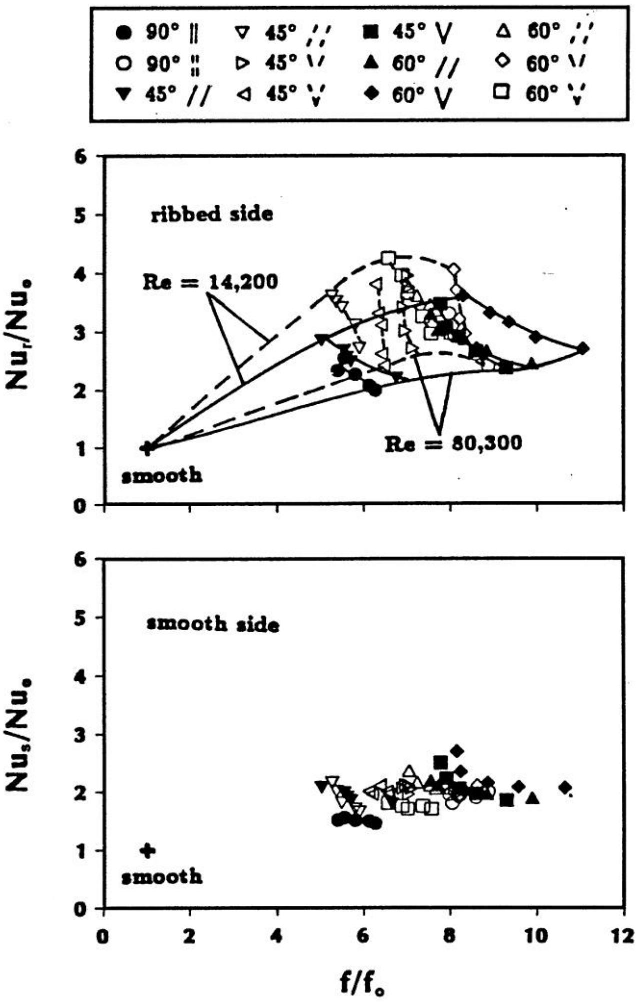


Figure-2 : Comparison of heat-transfer between broken and continuous ribs [6].

Table-4 : Parametric comparison of V-shaped ribbed channel reference

Reference	Configuration	Aspect ratio	*e/H*	*P/e*	*α*	*Re*
Wright et al. [21]	Angled/ Discrete angled V Shaped /Discrete V Shaped	5.08 X 1.27 = 4:1	0.16/ 1.27 = 0.125	1.60/ 0.16 = 10	45^0	10,000-40,000
Cho et al. [11]	Angled/ Discrete angled	10.16 X 5.08 = 2 :1	0.50/ 5.08 = 0.098	5/ 0.5 = 10	45^0	10,000-30,000
Rhee et al. [19]	V Shaped	15 X 5 = 3:1	0.30/ 5 = 0.06	3/ 0.3 = 10	60^0	10,000-40,000
		15 X 3 = 5:1	0.30/ 3 = 0.10	3/ 0.3 = 10	60^0	10,000
	Discrete V Shaped	15 X 5 = 3:1	0.30/ 5 = 0.06	3/ 0.3 = 10	45^0	
		15 X 3 = 5:1	0.30/ 3 = 0.10	3/ 0.3 = 10	45^0	
Prabhu et al. [22]	90^0 continuous /60^0 V broken	4 X 4 = 1:1	0.15,0.20, 0.25	10	90^0 60^0	10,000-30,000

4. CONCLUSIONS

Advanced gas turbines operating at extremely high temperatures, it is necessary to implement various cooling methods, so the turbine blades and vanes survive in the path of the hot gases. Simply passing coolant air through the airfoils does not provide adequate cooling; therefore, turbulence promoters (ribs) are cast in internal passage of turbine blades for further enhance the heat . Rib turbulated cooling by discrete ribs gives highest thermal performance amongst other profiles. By reviewing the available literature it seems that further improvements will be possible by combining the V shaped ribs with grooves. A very few literature is available for high reynold's no. Also very limited work has been done for high rotation nos. and density ratios. Further work can be carried at high reynods nos. with high rotation nos. to find out the effect of rotation, Coriolis and centrifugal forces on turbulence and transport.

More studies are needed with high performance turbulators and with or without film cooling holes under realistic coolant flow, thermal and rotating conditions. The use of advanced shaped ribs (broken and with gap) have to be explored for more heat transfer from the blade surface. Optimization of gape size and position on V and W profile can be one of the field for further research. Highly accurate and highly detailed local heat transfer data is needed to aid engineers in their design of blades for advanced gas turbines.

5. REFERENCES

[1] J. C. Han, S. Dutta, and S. V. Ekkad, Gas Turbine Heat Transfer and Cooling Technology, Taylor & Francis, Inc., New York, 2001.

[2] J. C. Han, L. R. Glicksman, and W. M. Rohsenow, "An Investigation of Heat Transfer and Friction for Rib-Roughened Surfaces," Int. Journal of Heat and Mass Transfer, 21, 1978, pp. 1143-1156.

[3] J.C. Han, Y.M. Zhang, C.P. Lee, "Augmented heat transfer in square channels with parallel, crossed and V-shaped angled ribs", Journal of Heat Transfer, 113, 1991, pp. 590–596.

[4] Lau, S. C., McMillin, R. D., and Han, J. C., "Turbulent heat transfer and friction in a square channel with discrete rib turbulators," Journal of Turbomachinery, Vol. 113, 1991, pp. 360-366.

[5] Lau, S. C., McMillin, R. D., and Han, J. C., "Heat Transfer characteristics of turbulent flow in a square channel with angled discrete ribs," ASME Journal of Turbomachinery, Vol. 113, 1991, pp. 367-374.

[6] Han, J. C., and Zhang, Y. M., "High Performance Heat Transfer Ducts With Parallel Broken and V-Shaped Broken Ribs," Int. J. Heat Mass Transfer, 35, No. 2, 1992, pp. 513–523.

[7] G. Tanda, "Heat transfer in rectangular channel with transverse and V-shaped broken ribs", Int. Journal of Heat and Mass Transfer, 47, 2004, pp. 229–243.

[8] Cho, H. H., Wu, S. J., and Kwon, H. J., "Local Heat/Mass Transfer Measurements in a Rectangular Duct With Discrete Ribs," ASME Journal of Turbomachinary, 122, 2000, pp. 579–586.

[9] Sahu M. M, Bhagoria J. L., "Augmentation of heat transfer coefficient by using 90o broken transverse ribs on absorber plate of solar air heater", Renewable Energy, 30, 2005, pp. 2057–2063.

[10]Hu, Z., and Shen, J., "Heat transfer enhancement in a converging passage with discrete ribs," International Journal of Heat and Mass Transfer, Vol. 39 (8), 1996, pp. 1719-1727.

[11]Cho, H. H., Kim, Y. Y., Rhee, D. H., Lee, S.Y., and Wu, S. J., "The effect of gap position in discrete ribs on local heat/mass transfer in a square duct," J. of Enhanced Heat Transfer, Vol.10 (3), 2003, pp.287-300.

[12]Aharwal K. R., Gandhi B. K, Saini J. S., "Experimental investigation on heat transfer enhancement due to a gap in an inclined continuous rib arrangement in a rectangular duct of solar air heater", Renewable Energy, 33, 2008, pp. 585–596.

[13]Chaube, A., Gupta, S. and Verma, P., "Heat Transfer and Friction Factor Enhancement in a Square Channel Having Integral Inclined Discrete Ribs on Two Opposite Walls," Journal of Mechanical Science and Technology, 28 (5), 2014, pp. 1927-1937.

[14]Karwa R., "Experimental studies of augmented heat transfer and friction in asymmetrically heated rectangular ducts with ribs on the heated wall in transverse, inclined, V-continuous and V-discrete pattern", Int. Communications of Heat and Mass Transfer, Vol. 30, 2003, pp. 241-250.

[15]Han, J. C., and Wright, L. M., "Enhanced internal cooling of turbine blades and vanes," In The Gas turbine Handbook, U.S. National Energy Technology Laboratory, Morgantown, W V, section 4-2-2-2, 2007, pp. 321-352.

[16]Lau, S. C., Kukreja, R. T. and McMillin, R. D., "Effects of V-Shaped Rib Arrays on Turbulent Heat Transfer and Friction of Fully Developed Flow in a Square

Channel,'' Internatinal Journal of Heat Mass Transfer, 34 [7],1991, pp. 1605–1616.

[17]Taslim, M. E., Li, T., and Kercher, D. M., ''Experimental Heat Transfer and Friction in Channels Roughened With Angled, V-Shaped, and Discrete Ribs on Two Opposite Walls,'' Int. J. of Turbomachinary, 118, 1996, pp. 20–28.

[18]Ekkad, S. V., and Han, J. C., ''Detailed Heat Transfer Distribution in Two-Pass Square Channels With Rib Turbulators,'' Int. J. Heat Mass Transfer, 40, No. 11, 1997, pp. 2525–2537.

[19]Rhee, D. H., Lee, D. H., Cho, H. H., and Moon, H. K., ''Effects of Duct Aspect Ratios on Heat/Mass Transfer With Discrete V-Shaped Ribs,'' ASME Paper no. GT2003-38622, 2003.

[20]Taslim, M. E., Li, T., Kercher, T. M., "Experimental Heat Transfer and Friction in Channel Roughened with Angled, V-Shaped and Discrete Ribs on Two Opposite Walls," J. of Turbomachinery, Vol. 118, 1996, pp. 20-28.

[21]Wright, L.M., Fu, W. L., and Han, J.C., "Thermal Performance of Angled, V-Shaped, and W-Shaped Rib Turbulators in Rotating Rectangular Cooling Channels (AR=4:1), International Journal of Turbomachinery, 126, Oct. 2004, pp. 604-614.

[22]Prabhu S.V., Sri Harsha V., Vedula R.P.," Influence of rib height on the local heat transfer distribution and pressure drop in a square channel with 90^0 continuous and 60^0 V-broken ribs" Journal of Applied Thermal Engineering, 29, 2009, pp. 2444–2459.

[23]Muluwork K.B.,"Investigations on fluid flow and heat transfer in roughened absorber solar heaters", Ph.D. Dissertation, 2000; IIT, Roorkee-247667,India.

[24] Singh S., Chander S., Saini J. S., "Heat transfer and friction factor correlations of solar air heater ducts artificially roughened with discrete V- downrib", Energy, 36, 2011, pp. 5053-5064.