IJCRR
Vol 04 issue 21
Section: Technology
Category: Review
Received on: 04/09/12
Revised on: 19/09/12
Accepted on: 03/10/12

A REVIEW OF ARTIFICIAL ROUGHNESS V SHAPE GEOMETRY FOR ENHANCEMENT OF HEAT TRANSFER OF SOLAR AIR HEATER

Rajkumar Ahirwar, A. R. Jaurker

Department of Mechanical Engineering Jabalpur engineering college, Jabalpur

E-mail of Corresponding Author: raj_ahirwar2008@yahoo.co.in

ABSTRACT

The low value of convective heat transfer coefficient between the air and absorber plate is a major factor for low thermal efficiency of solar air heater. It can be enhanced by application of artificial roughness in solar air heaters. A serious of experimental work has been observed in literature shows that heat transfer rate increased by application of artificial roughness in the form of straight transverse ribs, inclined ribs, V shaped ribs either in full length or discrete, and combination of various ribs of different shapes. The results show that straight transverse ribs gives higher heat transfer rate than that of the smooth case in same flow and system parameters due to breaking of viscous sub layer and formation of turbulence. This paper covers a literature review of heat transfer enhancement by applying V shaped ribs in air flowing ducts. The results of V shapes ribbed ducts were compared with the smooth as well ribbed ducts on the same parameters. It is found that the angled ribs give higher heat transfer rate than transverse ribs, because of the secondary flow induced by the rib angle, in addition to breaking the laminar sub-layer and producing local wall turbulence. The results show that the V-shaped rib performs better than the angled ribs because of the development of two vortices cells compared to only one cell in the case of inclined ribs.

Keywords: Solar air heater, artificial roughness, Nusselt number, Friction factor.

INTRODUCTION

The knowledge of characteristics of solar radiation i.e. its intensity and variations with location and time is essential for the design of solar energy equipment. It is therefore, important to know about its creator i.e. the sun and its radiant energy. The sun is a sphere of intensely hot gaseous matter with diameter of 1.39×10^{6} km and is, about 1.5×10^{8} km away from the earth. In the central region, the temperature is estimated to vary from 8×10^{6} to 40×10^{6}K and the density is 80 to 100 times of water density. The surface of the sun is considered to be at an effective blackbody temperature of approximately 5762K. The power from the sun intercepted by the earth is approximately 1.8×10^{11}MW, which is many thousands of times larger than the present consumption rate on the earth of all commercial energy sources. Some of the important applications of solar energy are Solar cooking, Solar water heating. Solar space heating and cooling, solar crop drying, solar power generation In order to make the solar energy utilization economically viable, one of the important requirements is its efficient collection. Flat plate collector is the most important type of solar collector because it is simple design, cheap in construction, easy in operation and little maintenance cost. It is designed for a variety of applications in which temperature ranging from ambient to 100ºC. The principle usually followed is to expose a dark surface to solar radiation so that radiation is absorbed. Apart of the absorbed radiation is then transferred to fluid like air or water. But its application is limited by low value of heat transfer rate between plate and air.

Heat Transfer Enhancement Technique: Artificial Roughness

The artificial roughness has been used extensively for the enhancement of forced convection heat transfer coefficient in solar air heaters. It has been found that the artificial roughness applied on heat transferring surface breaks the viscous sub-layer to reduce thermal resistance close to the surface. The application of artificial roughness in the duct of a conventional solar air heater has been shown as an efficient method of enhancement of thermal efficiency of solar air heater. For basic type of roughness geometry, the key dimensionless variables are as follows:

i) Relative roughness height (e/D) defined as the ratio of roughness height to hydraulic diameter of duct.
ii) Relative roughness pitch (p/e) defined as the ratio of the distance of two successive roughness elements to the height of the roughness.
iii) Angle of attack (α) defined as angle of roughness elements with respect to the flow direction.

For a specific roughness type, a family of geometrically similar roughness is possible simply by changing e/D, maintaining constant p/e and α, thus, the designer is faced with choosing among thousands of possible specific roughness geometries and sizes. The rib geometry to define the dimensional and non-dimensional parameters.

Dipprey and Sabersky [2] applied the law of walls similarity as obtained by Nikuradse [1] to develop a heat and momentum transfer analogy relation, which is commonly known as heat transfer function ($G(e^+)$) for flow in sand grain roughened tubes. The experimental investigation with the rough tubes containing close-packed, granular type of surface with roughness height to diameter ratio ranging from 0.0024 to 0.049 for Reynolds numbers varying from 60000 to 500000. They correlated their experimental heat transfer data by using heat transfer function and found that in fully rough flow, the heat transfer function, $G(e^+)$ was function of two variables i.e. roughness Reynolds number and Prandtl number. The correlation developed was as follows:

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

The important observations of the investigation are:

i) For a wide range of Reynolds and Prandtl numbers, an improvement by a factor of 2 to 3 in the Stanton number can be obtained by substituting rough tubes for smooth tubes.
ii) There is a limit for any combination of Reynolds number and Prandtl number beyond which the enhancement of heat transfer coefficient becomes very small as compared to the increase in friction losses.
iii) At higher Prandtl number, large improvement in Stanton number due to roughening can be achieved with little or no decrease in the value of Stanton number to friction factor ratio.

Sheriff and Gumley [3] reported considerable data for repeated rib roughness for Reynolds number about 10^5-10^6, with a small ratio of rib height to hydraulic diameter between 10^{-2} and10^{-3} in an annular flow geometry in which the inner annular surface is rough and outer surface is smooth, to simulate the geometry of fuel bundles in advanced gas-cooled nuclear reactor. Dalle Donne and Meyer [5] proposed the various modifications in the original methods to transform the rough surface data taken with annular geometry to a form useful for a simple channel.

Fig.1 Webb et al. [4] and Prasad and Saini, [8] shows the flow patterns downstream of a rib as the rib height and pitch are changed. Separation occurs at the rib, forming a widening free shear layer which reattaches 6-8 rib heights downstream from the separation point. A reverse flow boundary layer originates at the reattachment point and grows in thickness in the upstream region. The boundary layer tends toward redevelopment downstream from the reattachment point. The wall shear stress is zero at the reattachment point and increases from zero in the reverse flow and reattachment regions. Maximum heat transfer has been found to occur in the vicinity of a reattachment point. It is reasonable to expect that a similar effect can be produced by decreasing the relative roughness pitch (p/e) for fixed relative roughness height (e/D) or by increasing the relative roughness height for fixed relative roughness pitch. For relative roughness pitch considerably lower than about 8, the reattachment will not occur at all resulting in the decrease of heat transfer enhancement. However, an increase in pitch beyond about 10 also results in decreasing the enhancement. It can therefore be concluded that there occurs an optimum combination of pitch and height that will result in maximum enhancement.

Han et al. [6] conducted extensive experiments to simulate turbine air foil cooling passages. Developed a general correlation based on the law of the wall similarity and the application of the heat-momentum analogy developed by Dipprey and Sabersky [2] for friction loss and heat transfer to account for rib shape, spacing and angle of attack. In the experimental program, sixteen different geometries were tested for relative roughness pitch of 5, 7.5,10, 15, and 20, relative roughness height of 0.032,0.042, 0.056, 0.076, and 0.102 angle of attack of 20°, 45°, 75° and 90°, and Reynolds number from 3000 to 30000.The main conclusions of the investigation are as follows:

i) For small value of relative roughness pitch (p/e = 5), the flow which separates on each rib does not reattach before it reaches the succeeding rib while a relative roughness pitch value of about 10, the flow reattaches close to the next rib. For large rib spacing the reattachment point is reached and a boundary layer begins to grow before the succeeding rib is encountered, reducing both the average shear stress and heat transfer.
ii) The maximum value of both the heat transfer coefficient and the friction factor occur at relative roughness pitch (p/e) of 10, and ribs at 45° angle of attack resulting in superior heat transfer performance at given friction power when compared to ribs at a 90° angle of attack or when compared to sand-grain roughness.

Han et al [7] investigated the effect of the rib pitch to height and rib height to equivalent hydraulic diameter ratio on friction factor and heat transfer coefficient with Reynolds number varied from 7000 to 90,000, relative roughness pitch varied from 10 to 40; while relative roughness height varied from 0.021 to 0.063. He found that the maximum values of friction factor and the Stanton number occur at a relative roughness pitch of 10. Both the average friction factor and Stanton number increase with increasing relative roughness height.

Han and Park [9] investigated the combined effect of the rib angle of attack and the channel aspect ratio on local heat transfer distributions. The results show that angled or inclined ribs give higher heat transfer rate than the transverse ribs, and narrow aspect ratio ducts perform better than wide aspect ratio ducts. The angled ribs give higher heat transfer rate than transverse ribs, because of the secondary flow induced by the rib angle, in addition to breaking the laminar sub-layer and producing local wall turbulence.

V-Shaped Roughness geometries used in solar air heaters

Effect of V-shaping of rib

The possibility of further enhancing the wall heat transfer by the use of v-shaped ribs helps in the formation of two leading ends (where heat transfer rate is high) and a single trailing end (where heat transfer is low) resulting in much large area of heat transfer. V-shaped ribs form two secondary flow cells as compared to one in case of a straight angled rib resulting in higher overall heat transfer coefficient in case of v-shaped rib as shown in Fig.2. V-shaped rib with apex facing downstream has higher heat transfer as compared to that of with apex facing upstream.

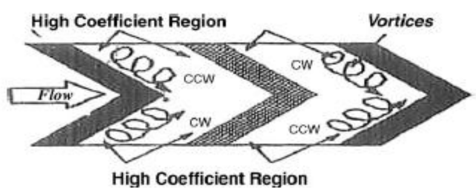

Fig.2. Effect of v-shaping rib. [10]

Inclined and V- shaped rib

Han et al. [10] and Han and Zhang [11] Investigated the effect of the angle of orientation on the local heat transfer distribution and pressure drop in a square channel with two opposite ribbed walls having in line ribs for range of Re =15000 to 90000, e/D = 0.0625 and p/e =10. The rib configuration includes 90° ribs, 60° and 45° parallel ribs, 60° and 45° crossed ribs 60° and 45° V- shaped ribs, and 60° and 45° Λ-shaped ribs as shown in Fig.3.The results show that the V-shaped rib performs better than the angled ribs because of the development of two vortices cells compared to only one cell in the case of inclined ribs.

Han JC, Zhang YM. [12]. Investigated the effect of parallel and V-shaped broken rib orientation on the local heat transfer distribution and pressure drop in a square channel with two opposite ribbed walls and found that 60° staggered discrete V-shaped ribs provide higher heat transfer than parallel discrete ribs.

Xiufang Geo et al. [14].Carried out investigation of the thermal and hydraulic performance of three rib roughened rectangular ducts. The aspects ratio of the duct 1 to 8 and the ribs were arranged staggered on the two walls. Three rib configuration were tested parallel rib and V-shaped ribs pointing upstream or downstream of the flow direction. For all parameters range Re= 1000 to 6000, e/d_h=0.06, p/e =10, α=60°. It is as compared to results in parallel rib to v-shaped rib in better performance.

V-shaped rib

Momin et al. [15].Carried out experimentally investigated the effect of geometrical parameters of V-shaped ribs on heat transfer and fluid flow characteristics in rectangular duct of solar air heater. The investigated geometry was as shown in Fig.4. For this geometry it was observed that the rate of increase of Nusselt number with an increase in Reynolds number is lower than the rate of increase of friction factor. The maximum enhancement of Nusselt number and friction factor as result of providing artificial roughness had been found as 2.30 and 2.83 times to smooth surface respectively for α=60°. It was also found that for e/d_h of 0.034 and 60° the V-shaped ribs enhance the value of Nusselt number by 1.14 and 2.30 times over inclined ribs and smooth plate respectively. It was concluded that V Shaped ribs gave better heat transfer performance than the inclined ribs for similar operating conditions.

V-shaped discrete ribs

Muluwork et al. [13].Compared the thermal performance of staggered discrete v-apex up and down ribs with corresponding transverse staggered discrete ribs is shown in fig.5. 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 (α) 60° and 70°, respectively. Correlations for Nusselt number and friction factor were developed.

Sukhmeet Singh et al. [18]. The heat and fluid flow characteristics of rectangular duct having its one broad wall heated and roughened with periodic ‘discrete V-down rib. The effect of roughness parameters on Nusselt number (Nu) and friction factor (f) has been determined and the results obtained were compared with those of smooth duct. The maximum increase in Nu and f over that of smooth duct was 3.04 and 3.11 folds respectively. The rib parameters corresponding to maximum increase in Nu and f were d/w = 0.65, g/e =1.0, P/e = 8.0, α = 60˚ and e/D_h= 0.043.

Karwa et al.[16]. Carried out a comparative experimental study of Augmented heat transfer and friction in a rectangular duct with rectangular cross-section ribs arranged in v-continuous and v discrete pattern for duct aspect ratio range of 7.19–7.75, p/e=10, e/D_h = 0.0467–0.050 and Re= 2800–15,000. The enhancement in the Stanton number over the smooth duct was reported to be in range of 102–137%, 110–147%, 93–134% and 102–142% for transverse inclined, v-up continuous, v-down continuous, v-up discrete and v-down discrete rib arrangement, respectively. The friction factor ratios corresponding to these arrangements were found as 3.02–3.42, 3.40–3.92, 3.32–3.65, 2.35–2.47 and 2.46–2.58, respectively. The performance of v-down ribs was observed to be better than that of v-up ribs.

3.5 Broken for transverse and V-shaped ribs

Tanda G. [17]. Investigations using Liquid Crystal Thermography to obtain detailed distributions of heat transfer coefficient in rib-roughened channels. The roughness geometries induced by transverse continuous, transverse broken and V-shaped broken ribs were deployed on a heated surface as shown in fig.6. The highest value of enhanced Nusselt number was reported for the transverse broken ribs having relative roughness pitch value of 4. Large increase in friction factor was induced by ribs as compared to the smooth channel.

Spacing for V-shape ribs

Nawaf Y. Alkhamis et al. [19].Carried out investigation in heat transfer coefficients and friction factors are measured in a 45 deg v-shaped rib roughened square duct at high Reynolds numbers, pertaining to internal passages of land based gas turbine engines. Re in this study range from 30,000 to 400, 000, which is much higher than prior studies of V-shaped rib roughened channels. The dimensions of the channel are selected to ensure that the flow is in the incompressible regime .Blockage ratio ranges from 0.1 to 0.18 and the spacing ratio P/e ranges from 5 to 10.Reported heat transfer coefficients are regionally averaged, measured by isothermal copper plates. Results show that the heat transfer enhancement decreases with increasing Reynolds number. The friction factor is found to be independent of the Re. The thermal performance decreases when the Re increases. 45° V-shaped ribs show a higher thermal performance than corresponding 45° angled ribs, consistent with the trend established in literature. Correlations for the Nusselt number and the friction factor as function of Re, e/D, and P/e are developed. Also developed are correlations for R and G as a function of the roughness Reynolds number (e^+).Reducing the spacing ratio (p/e) increases the number of ribs in the test section. A larger number of ribs imply a larger secondary swirl, greater turbulence, and more area for heat transfer. Conversely, a large spacing results in a thicker boundary layer between two ribs before it is tripped by the next rib, decreasing heat transfer (fig.7.)

Table.1: Figur in Rib Geometries

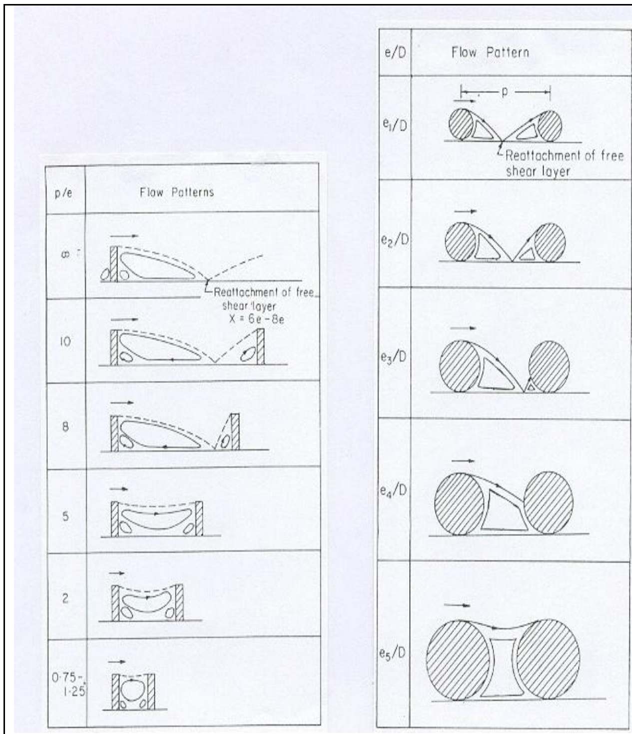

Fig.1: Effect of rib height and pitch on flow [8]

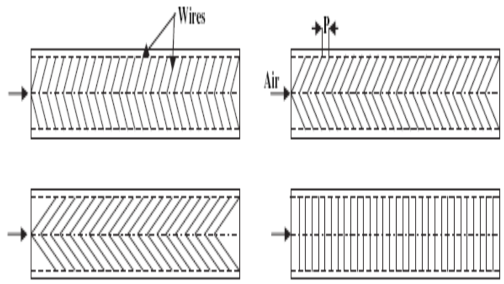

Fig.4: roughness element of absorber plate [15]

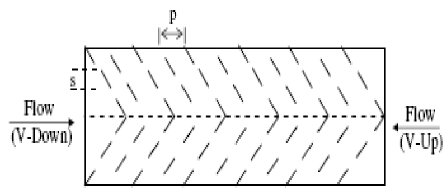

Fig.5: Discrete v-shape ribs [13]

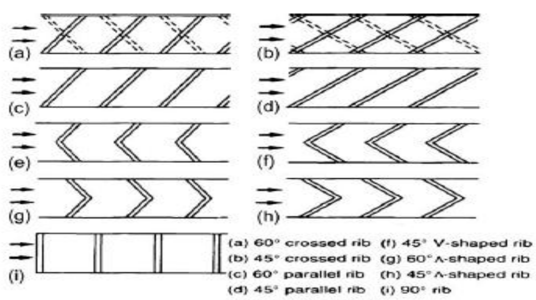

Fig.3: Top view of rib configuration [10]

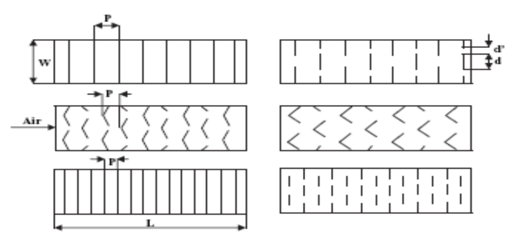

Fig.6: Roughness geometris in traverse and v-shaped broken ribs[17]

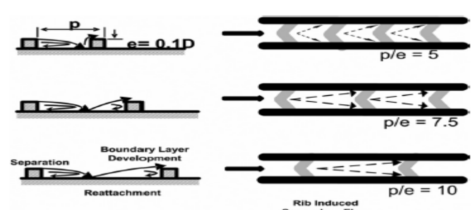

Fig.7: flow over v-shaped ribs indicating the effect of spacing for rib height [19]

Table 2. Heat transfer coefficient and Friction factor correlations for V-shaped roughness geometries.

Authors	Roughness geometry	Parameters	Correlations	
			Heat transfer	Friction factor
J C Han et al. [11]	Parallel , Crossed , v-shaped ribs	Re = 15000–90,000 e/D_h = 0.0625 p/e = 10; α = 90˚ rib , 45˚ & 60˚ // , 45˚ & 60˚ X, 45˚ & 60˚ V, and 45˚ & 60° ^	Nu/Nu_0 =(hd/k) / (0.023 $Re^{0.8}$ $Pr^{o.4}$	f/fo = f/ (0.046 $Re^{-0.2}$) f= Δpe /[4(L/D) (G^2 / 2ρgc)]
Muluwork et al. [12]	V-shaped rib	Re = 2000-15500 e/D_h= 0.02; B/S = 3-9; α = 60°	Nu_r = $0.00534Re^{1.2991}(p/s)^{1.3496}$	f= $0.7117Re^{-2.991}(P/S)^{0.063}$
Xiufang Geo et al. [9].	V-down Discrte rib	Re = 1000-6000 p/e = 10 e/D_h = 0.06 α = 60°	Nu =$0.023Re^{0.8}\,pr^{0.4}$	f =$0.0791Re^{-0.025}$
Abdul-Malik Ebrahim Momin et al. [8]	V-shaped rib	Re = 2500–18000 e/D_h = 0.02–0.034 α = 30°–75° P/e = 10	Nu= 0.067 x $(Re)^{0.888}$ x $(e/D_h)^{0.424}$ x $(\alpha/60)^{-0.077}$ x exp [-0.82 x (ln (α/60))2]	f= 6.266 x $(Re)^{-0.425}$ x $(e/D_h)^{0.565}$ x $(\alpha/60)^{-o.o93}$ x exp [-0.719 x (ln α/60)2]
Karwa R et al. [18]	Transvarse, Inclind, v-continous, v-discrete ribs	Re = 2800-15000 p/e = 10 e/D_h = 0.0467-0.05 α = 60° & 90°	G = {(f/2st) -}√(2/f)+R	R = √(2/f) +2.5ln($2e/D_h$)+3.75 e^+ √(f/2)Re(e/D_h)
Tanda [20]	Transvarse continous, Transvarse broken, V-shaped broken ribs	Re = 5000-50000 p/e = 4,8,13.3 e/D= 0.09,,0.15 α = 45°,60°,90°	$Nu_o = 0.023Re^{0.8}\,pr^{0.4}$ $Re_o = (21.74fRe3)^{0.351}$	f = $0.046Re^{-0.2}$
Sukhmeet Singh et al. [13, 14]	v-discrete ribs	Re = 3000-15000 (e/D_h) = 0.015-0.043 (P/e) = 4-12 α = 30° - 75° (d/w) = 0.2 -0.8 (g/e)= 0.5 - 2.0	Nu = $2.36x10^{-3}$ $Re^{0.90}(p/e)^{3.50}$ $(\alpha/60)^{-0.023}$ $(d/w)^{-0.043}$ $(g/e)^{-0.014}$ x $(e/D_h)^{0.47}$ exp(0.84 (ln $p/e)^2$)exp (-0.72(ln $\alpha/60)^2$ x exp (-0.05(ln $d/w)^2$ exp (-0.15(ln $g/e)^2$	f= $4.13x10^{-2}$ $Re^{-0.126}$ $(p/e)^{2.74}(\alpha/60)^{0.058}$ $(g/e)^{0.031}$ x $(e/D_h)^{0.70}$ exp (-0.685(ln $p/e)^2$) exp(-0.93(ln $\alpha/60)^2$) x exp (-0.058(ln $d/w)^2$ exp (-0.21(ln $g/e)^2$)
Nawaf Y et al. [22]	V-down discrte	Re = 30000-400000 p/e = 5 to 10 e/D_h= 0.1 to 0.18 α = 45°	Nu = $1.05(p/e)^{-0.1}\,pr^{0.4}$ $Re^{0.61}$ $(e/D)^{0.0225}$ g = $1.3(p/e)^{-0.05}(e/D)^{-0.08}$ $(e^+)^{0.39}$	f = 1.76 $(p/e)^{-0.29}$ $(e/D)^{-0.39}$ R= 2.59 $(p/e)^{-0.29}$ $(e/D)^{-0.13}$

CONCLUSION

It can be concluded from the presents review that lots of work has been carried out to the effect of artificial roughness of the concept of performance enhancement of roughened ducts has been discussed. Correlations for heat transfer cofficient and friction factor by various researchers devloved for solar air heater ducts having artificial roughness of different geometries were presents in the papar(Table 2).

1. Straight transverse rib roughness enhance the heat transfer coefficient by sepration and generation of vertices on the upsream and

downstream of rib and reattachment of flow the inter rib.

2. Incliend to movement of vorticees along the rib and formation of secondary flow cell which is result in higher heat transfer rate as compared to transverse rib.
3. V-shaping of a long angled rib helps in the formation of two secondary flow cells as compared to one in case of an angled rib resulting in still higher heat transfer rate.
4. It has been found to enhance the heat transfer incliend with gap rib to be breaking the secondary flow and produceing higher level of turbulence in the fluid downstream of the rib. A similar the discrete in both the limb v-shape rib further enhance heat transfer by same effect.

ACKNOWLEDGEMENT

Authors acknowledge the immense help received from the scholars whose articles are cited and included in references of this manuscript. The authors are also grateful to authors / editors /publishers of all those articles, journals and books from where the literature for this article has been reviewed and discussed.

REFERENCES

1. Nikuradse, J, (1950). Laws of flow in rough pipes. NACA, Technical Memorandum 1292. November 1950.
2. Dippery DF, Sabersky RH, (1963). Heat and momentum transfer in smooth and rough tubes at various Prandtl number. Int J Heat Mass Transfer 6:329–53.
3. Sheriff, N., Gumley, P. (1966). Heat transfer and friction properties of surfaces with discrete roughness. International Journal of Heat and Mass Transfer, 9:1297–1320.
4. Webb, R.L., Eckert, E.R.G., Goldstein, R.J., (1971). Heat transfer and friction in tubes with repeated-rib roughness. International Journal of Heat and Mass Transfer, 14: 601–617.
5. Donne, D., Meyer, L,(1977). Turbulent convective heat transfer from rough surfaces with two dimensional rectangular ribs. International Journal of Heat and Mass Transfer, 20:582–620.
6. Han, J.C, Glicksman, L.R., Rohsenow, W.M., (1978). An investigation of heat transfer and friction for rib-roughened surfaces. International Journal of Heat and Mass Transfer 21:1143–1156.
7. Han, J.C, (1984). Heat transfer and friction in channels with two opposite rib-roughened walls. ASME Journal of Heat Transfer 106:774–781.
8. Prasad BN, Saini JS,(1988). Effect of artificial roughness on heat transfer and friction factor in a solar air heater. Solar Energy; 41:555-60.
9. Han, J.C., Ou, S., Park, J.S., Lei, C.K. (1989). Augmented heat transfer in rectangular channels with narrow aspect ratios with rib tabulators. International Journal of Heat and Mass Transfer 32: 1619–1630.
10. Han, J.C., Zhang, Y.M., Lee, C.P., 1991. Augmented heat transfer in square channels with parallel, crossed, and V-shaped angled ribs. ASME Journal of Heat Transfer 113:590–596.
11. Han, J.C., Zhang, Y.M., 1992. High performance heat transfer ducts with parallel, broken and V-shaped broken ribs. International Journal of Heat and Mass Transfer 35 (2), 513–523.
12. Han JC, Zhang YM, Lee CP,(1994).Influence of surface heat flux ratio on heat transfer augmentation in square channel with parallel, crossed and V-shaped angled ribs. ASME J Turbo machinery 114:872–80.
13. K.B. Muluwork, Saini JS, Solanki SC, (1998) Studies on discrete rib roughened solar air heaters. In Proceedings of National Solar Energy Convention, Roorkee. pp. 75–84.
14. Xiufang Geo, Bengt Sunden,(2001).Heat transfer and pressure drop measurements in rib- roughened rectangular ducts.

Experimental Thermal and Fluid science 24:25-34.
15. Abdul-Malik Ebrahim Momin, J.S. Saini, S.C. Solanki, (2002).Heat transfer and friction in solar air heater duct with V-shaped rib roughness on absorber plate, International Journal of Heat and Mass Transfer 45: 3383–3396.
16. Karwa R. (2003). 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. International Journal Heat Mass Transfer.30:241–50
17. Tanda G. (2004). Heat transfer in rectangular channels with transverse and V-shaped broken ribs. International Journal Heat Mass Transfer, 4:229–43.
18. Sukhmeet Singh, Subhash Chander, J.S. Saini, (2011).Heat transfer and friction factor correlations of solar air heater ducts artificially roughened with discrete V-down ribs, Energy36: 5053-5064.
19. Nawaf Y, Alkhamis, Akhilesh P.Rallabandi, Je-Chin Han, (2011).Heat Transfer and Pressure drop Correlations for square channels with V-shaped ribs at high Reynolds numbers. ASME, Journal Heat Mass Transfer, 133:111901-8.
20. Varun, R.P. Saini, S.K. Singal, (2007). A review on roughness geometry used in solar air heaters. Solar Energy 81:1340–1350.
21. S.P.Sukhatme solar energy. Tata Mc Graw Hill.

Nomenclature

B	half length of v-rib element (m)
D, D_h	equivalent or hydraulic diameter of duct (m)
d	gap position from upstream side of rib (m)
e	height of roughness element (m)
g	gap width for rib (m)
H	depth of air duct (m)
h	convective heat transfer coefficient (w/m^{2}k)
P	roughness pitch (m)
S	length of main segment of rib element (m)
W	width of air duct (m)
w	width of rib (m)

Dimensionless Parameters

B/S	relative roughness length ratio
d/w	relative gap position
e/D_h, e/D	relative roughness height
e^+	roughness Reynolds number
f,f_r	friction factor of roughed duct
f_o, f_s	friction factor of smooth duct
G	momentum heat transfer function
g/e	relative gap position
Nu,Nu_r	nusselt number of roughed duct
Nu_s	nusselt number of smooth duct
Pr	Prandtl number
p/e	relative roughness pitch
P'/P	relative staggering ratio
R	friction roughness function
Re	Reynolds number
Re_o	Reynolds number for reference channel

Greek symbol

α	angle of attack (º)