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Assessment of Performance Characteristic of Solar Air Heater with Assorted Geometries - A Review

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Abstract
Artificial roughness is an efficient way for increasing the heat transfer rate in solar air heater with the corresponding improvement in its thermal performance. A viscous sub-layer is responsible for the low heat transfer coefficient between absorber plate and flowing air. Repeated ribs in form of artificial roughness are an effective way to increase the heat transfer rate and improving the performance of solar air heater. Artificial roughness of the absorber plate is much economical and effective way to improve the thermal performance of solar air heater. Several investigators have done various investigations to improve heat transfer coefficient with little penalty of friction factor. They have also developed different correlation for heat transfer coefficient and friction factor. The correlations developed for heat transfer and friction factor by various investigators have been reviewed and presented.
Keywords: Solar air heater, Absorber plate, Artificial roughness, Review

I. INTRODUCTION

In current scenario everyone turn towards the non-conventional energy because it is abundant in nature. For the better economic process and industrial growth it is necessary to turn towards solar energy. Efficiency of solar air heater is generally low due to low heat transfer capability as compare to solar water heaters. So it is necessary to enhance heat transfer coefficient for increasing the efficiency of solar air heater. It may be possible to use two criterions for improving the heat transfer coefficient. First to increase the surface area of the material with the help of corrugated surfaces or extended surfaces called fins. The second method is to increase the heat transfer coefficient with the help of artificial turbulence at the heat-transferring surface. This turbulence can be achieved by applying artificial roughness on the underside of absorber plate. Various investigators have worked on several designs for enhancing the heat transfer coefficient with minimum penalty of friction.

II. ARTIFICIAL ROUGHNESS

Roughness converts the laminar sub layer into local turbulence at heat transferring surface. Several investigators have investigated on different roughness geometry in order to enhance the heat transfer rate with minimum friction losses. For reducing the friction losses it is necessary to reduce roughness height as compare to duct dimension. The roughness element height (e) and pitch (p) are the important parameters that stabilize the arrangement and shape of the roughness. The parameter of artificial roughness can be expressed in terms of dimensionless parameters like relative roughness height (e/D), relative gap width, chamfer angle, relative roughness pitch (p/e), relative gap position (d/W), relative gap width (g/e) . The roughness element can be V-shaped continuous or broken, discrete elements, transverse or angled ribs. It may be noted that square ribs are the most commonly used geometry but chamfered, circular, semi-circular and grooved sections have been investigated in order to get most beneficial arrangement from thermo-hydraulic analysis.

III. FLOW PATTERN

Different types of artificial roughness have different shapes, orientation and rib arrangements. Enhancement of heat transfer totally depends upon resulting flow pattern.

3.1 Effect of rib

In case of air flow the rib is responsible for the generation of two flow separation regimes, one on each side of the rib. Rib vortices generated are responsible for the creation of turbulence at the vicinity of rib arrangement. Friction losses also take place but enhancement of heat transfer becomes the core criterion.

3.2 Effect of rib height and pitch

Fig. 1 and 2 shows reattachment point that is responsible for the enhancement of heat transfer rate and it also shows the flow pattern downstream corresponding to as the pitch is changed. With relative roughness pitch ratio (p/e) less than about 8 reattachment of shear layer does not occur. The reattachment will not occur for relative roughness pitch considerably less than about 8 resulting in the decrease of heat transfer enhancement. A similar effect can be produce by increasing the relative roughness pitch (p/e) for a fixed relative roughness height (e/D). Decrease in enhancement of heat transfer rate occurs due to increase in relative roughness pitch beyond about 10. After investigation optimum combination of pitch and height necessary for maximum enhancement of heat transfer rate can be evaluated.

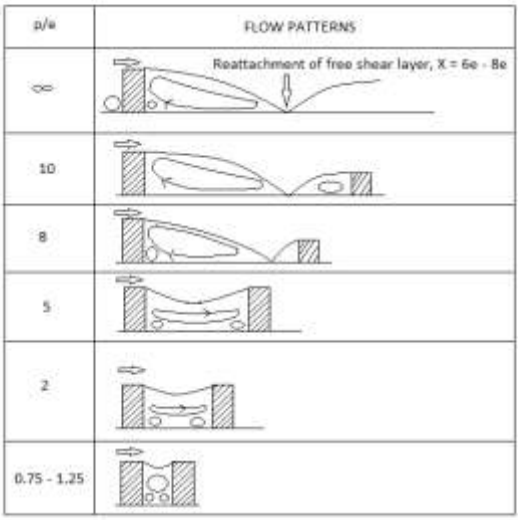


Fig. 1. Flow pattern as a function of relative roughness pitch

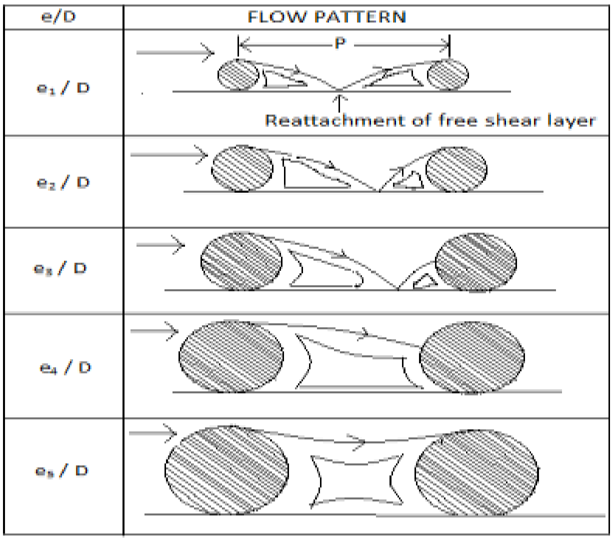


Fig. 2. Flow pattern as a function of relative roughness height

IV. DEVELOPMENT OF ARTIFICIAL ROUGHNESS IN SOLAR AIR HEATER

4.1. Transverse ribs

4.1.1 Transverse continuous ribs

Varun et al. [1] carried out an experimental study on heat transfer and friction characteristics by using a combination of transverse and inclined ribs on the heated plate of solar air heater duct. Small diameter transverse roughness was introduced by Prasad and Mullick [2].The study parameters of Prasad and Mullick [2] were relative roughness pitch as 12.7 and relative roughness height as 0.019. They reported that the application of protruding wires led to improvement in plate efficiency factor from 0.63 to 0.72.

Parameters such as relative roughness pitch as 10-40, relative roughness height as 0.01-0.03, roughness Reynolds number as 8-42 and Reynolds number as 5000– 20,000 were used by Verma and Prasad [3]. They reported that corresponding to Reynolds number of 24 the thermo-hydraulic performance was calculated as 71%.

Prasad and Saini [4] investigated using small thickness diameter wire as artificial roughness in solar air collector. They used relative roughness height of 0.020–0.033 and relative roughness pitch of 10–20 for the investigation of heat transfer rate and friction factor. Correspond to relative roughness pitch of 10 the maximum value of Nusselt number and friction factor were reported as 2.38 and 4.25 respectively. The shape of roughness geometry is shown in “Fig. 3”.

Gupta et al. [5] used transverse wire in solar air heater for alteration of rough flow regime. They used aspect ratio (W/H) as 6.8–11.5, relative roughness height as 0.018–0.052, relative roughness pitch as 10 and Reynolds number varied from 3000-18000. They concluded that Stanton number increases with increase in Reynolds number and Stanton number achieved maximum value for Reynolds number of 12,000.

4.1.2 Transverse broken ribs

This type of geometry is investigated by Sahu and Bhagoria [6]. They used transverse broken ribs as shown in “Fig. 4”. Investigated parameters are aspect ratio 8, roughness pitch as 10–30 mm, rib height as 1.5 mm and Reynolds number as 3000–12000. For the pitch value as 20 mm the maximum Nusselt number has been observed. Under the similar operating condition the roughened absorber plate increased heat transfer coefficient by 1.25–1.4 times as compare to smooth duct.

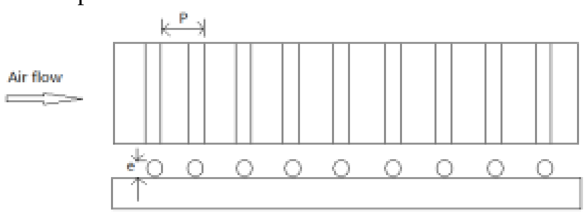


Fig. 3. Transverse small diameter wire

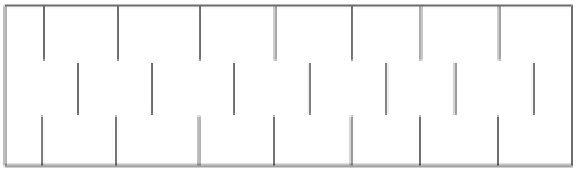


Fig. 4. Transverse broken ribs

4.2. Inclined ribs

4.2.1 Continuous inclined ribs

Gupta et al. [7] investigated inclined ribs as compared to transverse ribs and concluded that inclined ribs give increased effect of heat transfer coefficient and friction factor. They investigated inclined circular ribs as artificial roughness by taking the Reynolds number of 3000-18000, duct aspect ratio as 6.8–11.5, relative roughness height as 0.018–0.052 for relative roughness pitch of 10. The enhancement of thermal efficiency was reported as 1.16–1.25 as compared to smooth plate in range of parameters investigated. The roughness geometry is shown in "Fig. 5".

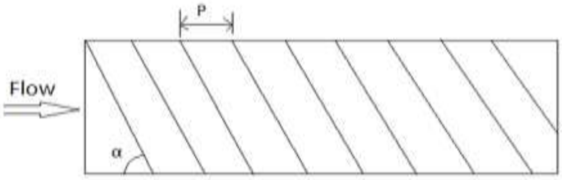


Fig. 5. Inclined continuous ribs

4.2.2 Broken inclined ribs

Aharwal et al. [8] introduced a criterion of secondary flow and main flow through the gap thereby creating local turbulence in inclined ribs. The "Fig. 6". shows roughness geometry. Range of parameters during investigation are aspect ratio 5.84, Reynolds number range as 3000–18,000, relative roughness height as 0.0377, relative roughness pitch and angle of attack of 60^o. Gap position (d/W) and gap width (g/e) were in the range of 0.5–2 and 0.1667–0.667 respectively. As compare to smooth duct the roughened plate has maximum enhancement in Nusselt number and friction factor being reported as 2.59 and 2.87. Maximum thermo-hydraulic performance was reported corresponding for relative gap width of 1.0 and for relative gap position of 0.25.

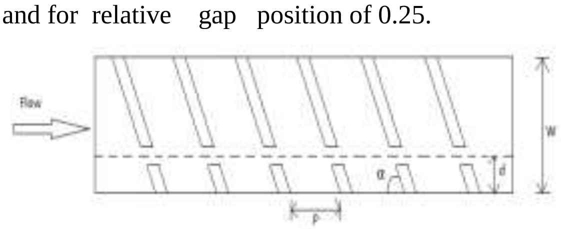


Fig. 6. Inclined ribs with gap

4.3. Wire mesh

4.3.1 Expanded metal mesh

This type of roughness geometry is introduced by Saini et al. [9]. They studied the effect of relative long way length of mesh (l/e) and relative short way length of mesh (s/e) on heat transfer and friction factor. The optimum parameters reported are angle of attack of 61.9^o and 72^o respectively for enhanced heat transfer rate and friction factor. Enhancement of heat transfer coefficient and friction factor is reported of order of 4 and 5 times as compare to smooth duct. The geometry of artificial roughness is shown in "Fig. 7".

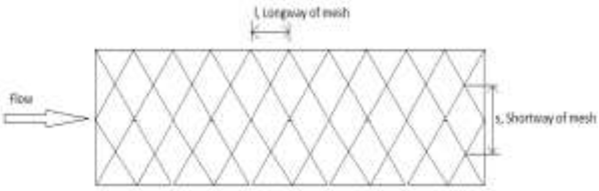


Fig. 7. Expanded metal mesh

4.3.2 Discretized metal mesh

Metal mesh geometry further discretized by Karmare and Tikekar [10]. They investigated heat transfer and friction factor for metal grit ribs as shown in "Fig. 8". Parameters used for investigation were p/e as 12.5–36, e/D_h as 0.035–0.044, l/s as 1.72–01 and Reynolds numbers as 4000–17000. The optimum performance was reported for discretized metal mesh corresponding to l/s as 1.72, e/D_h 0.044 and p/e as 17.5 showed optimum performance.

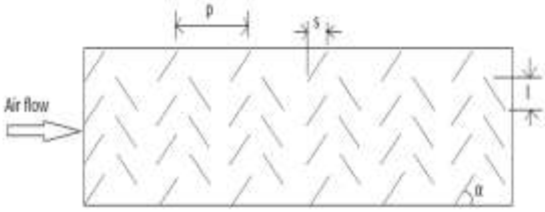


Fig. 8. Metal grit ribs

4.4. Chamfered ribs

Chamfered rib artificial roughness was investigated by Karwa et al. [11] as shown in "Fig. 9". Investigation showed two and three times increase in Stanton number and friction factor respectively. With the chamfer angle of 15^o both Stanton number and friction factor were reported to be highest. The various parameters of investigation were chamfer angle (ϕ) as 15^o to 18^o, duct aspect ratio as 4.8–12, relative roughness height as 0.014–0.0328, Reynolds number as 3000–20,000 and relative roughness pitch as 4.5–8.5. The heat transfer increases with increasing of aspect ratio from 4.65 to 9.66 and the roughness function decreases with the increase in aspect ratio from 4.65 to 7.75. Investigation showed increase in thermal efficiency about 10 to 40% with enhancement of Nusselt number in order of 50 to 120%.

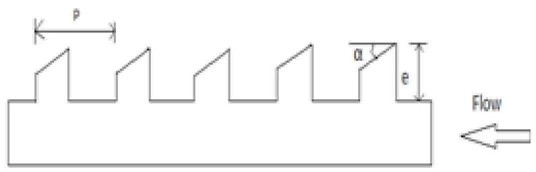


Fig. 9. Integral chamfered ribs

4.5. Wedge ribs

Bhagoria et al. [12] proposed the enhancement of heat transfer rate using wedge shaped transverse integral ribs as shown in "Fig. 10". On the experimental analysis basis it is concluded that enhancement of Nusselt number is 2.4 times while of friction factor as 5.3 times as compare to smooth duct in range of parameters investigated. They also investigated the effect of relative roughness height, relative roughness pitch and wedge angle on heat transfer rate and friction factor. They concluded relative roughness pitch of 7.57 was better for maximum heat transfer rate corresponding to wedge angle of 10.

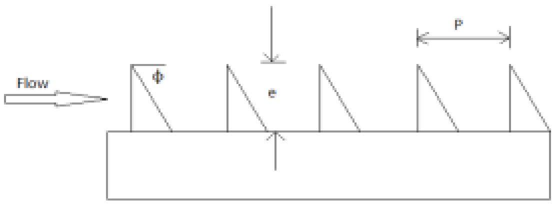


Fig. 10. Wedge shaped transverse integral ribs

4.6. V-shaped rib

4.6.1 Continuous V-ribs

Momin et al. [13] investigated the effect of continuous ribs on heat transfer rate and friction factor. They concluded that inclined rib give better result as compare to transverse ribs due to increase in secondary vortices. V-shaping of angled rib gives maximum secondary vortices. V-shaped rib roughness geometry is shown in "Fig. 11". Necessary parameters of investigation were relative roughness height as 0.02-0.034, angle of attack of flow (α) as 30^o – 90^o and Reynolds number of 2500–18,000. Maximum enhancement of heat transfer coefficient and friction factor was reported as 2.30 and 2.83 times as compare to smooth duct for angle of attack of 60^o.

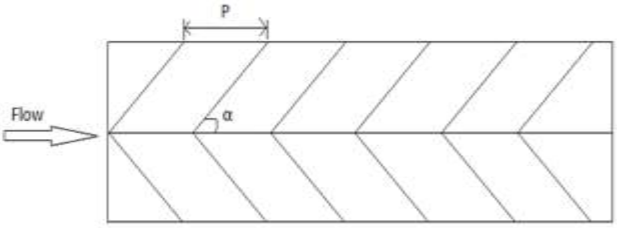


Fig. 11. V-shaped ribs

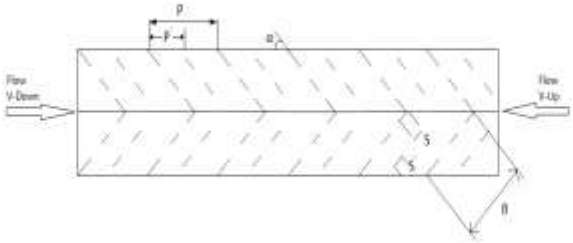
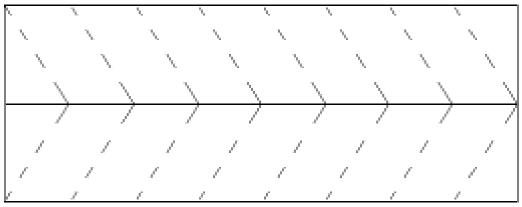
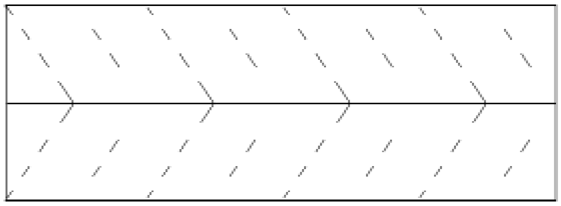


Fig. 12. Discretized V-ribs



V discontinuous rib



V- discrete rib

Fig. 13. V-shaped rib of different configurations.

4.6.2 Discrete V-ribs

Muluwork et al. [14] worked on transverse staggered discrete ribs and compared it with staggered discrete V-apex up and V-down ribs and evaluated thermal performance. The roughness geometry is shown in "Fig. 12". They reported maximum enhancement of Stanton number, was in case of V-down discrete ribs as compare to corresponding V-up and transverse ribs.

Karwa et al. [15] investigated V-discontinuous and V-discrete rib with range ofparameters of relative roughness length (B/S) as 3 and 6, relative roughness pitch as 10.63, angle of attack as 45^o and 60^o and Reynolds number as 2850–15,500. They concluded that angle of attack of 60^o perform better as compare to 45^o and also discrete ribs give better performance as compare to discontinuous ribs. This type of roughness geometry is shown in "Fig. 13".

Singh et al. [16] investigated discrete V-down ribs roughness geometry as shown in "Fig. 14".The range of investigated parameters are relative roughness pitch as 4–12, relative gap width (g/e) as 0.5–2.0 and relative gap position (d/w) as 0.20–0.80 respectively, relative roughness height as 0.015– 0.043 and Reynolds number from 3000 to 15,000. Maximum increase in Nusselt number and friction factor are 3.04 and 3.11 times respectively as compare to smooth duct. For maximum increase in Nusselt number and friction factor the parameters used are

e/D_h as 0.043, d/w as 0.65, p/e as 10, g/e as 1.0 and α as 60^o.

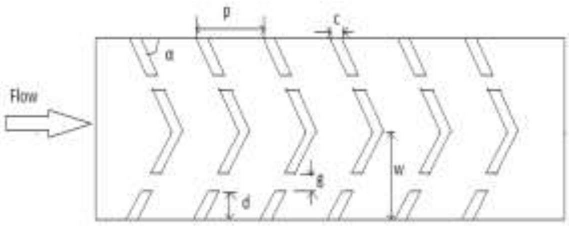


Fig. 14. Discrete V-down ribs

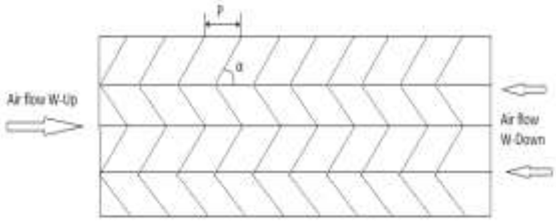


Fig. 15. W-shaped rib roughness

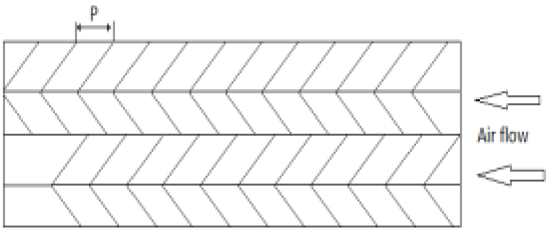


Fig. 16. Discrete W-shaped ribs

4.7. W-shaped ribs

4.7.1 Continuous W-ribs

Lanjewar et al. [17] used concept of increased secondary cell responsible for the enhancement of heat transfer rate. The roughness geometry is shown in “Fig. 15”. After investigation they concluded that maximum enhancement of Nusselt number and friction factor observed was 2.36 and 2.01. They also reported that W-down arrangement with angle of attack of 60^o give optimum thermo-hydraulic performance. The different range of parameters were relative roughness height as 0.018–0.03375, relative roughness pitch as 10 and angle of attack as 30^o – 75^o.

4.7.2 Discrete W-ribs

Kumar et al. [18] investigated discrete W-shaped rib. The roughness geometry is shown in “Fig. 16”. The range of parameters used are relative roughness height as 0.0168–0.0338, relative roughness pitch as 10 and angle of attack as 30^o–75^o and Reynolds number as 3000 to 15,000. They reported that maximum enhancement of Nusselt number and friction factor was 2.16 and 2.75 times as compare to smooth duct with angle of attack as 60^o.

4.8. Multiple V-ribs

4.8.1 Multiple continuous V-ribs

Hans et al. [19] introduced a phenomenon of secondary flow cells in multiple V-ribs and also investigated with such geometry. After investigation they concluded that the maximum enhancement of Nusselt number and friction factor was 6 and 5 times respectively as compare to smooth duct for range of parameters investigated and also angle of attack of 60^o is responsible for maximum enhancement of heat transfer and friction factor. There roughness geometry is shown in “Fig. 17”. The experiment conducted on the basis of several important parameters such as Reynolds number from 2000 to 20,000, relative roughness pitch as 6-12, relative roughness height as 0.019–0.043, relative roughness width (W/w) range as 1–10 and angle of attack as 30^o–75^o.

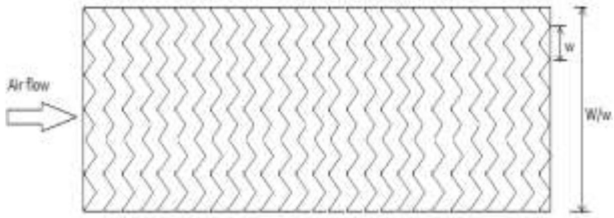


Fig. 17. Multiple V-ribs

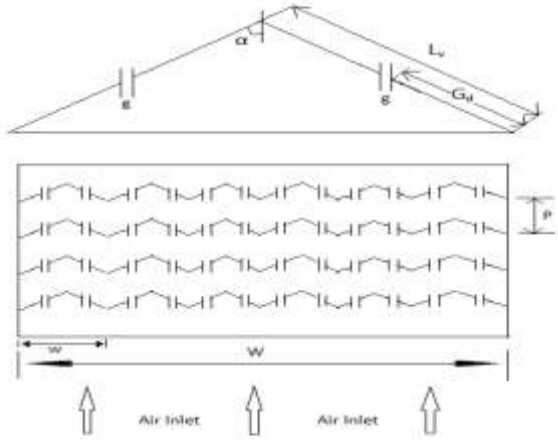


Fig. 18. Multi V-shaped ribs with gap.

4.8.2 Multiple V-rib with gap

Kumar at al. [20] introduced a phenomenon of local turbulence and acceleration of flow by putting gap. After completion of experimental analysis they concluded that maximum enhancement of Nusselt number and friction factor was 6.32 and 6.12 times respectively as compare to smooth duct for range of parameters investigated. During investigation they used different parameters such as relative roughness height as 0.043, relative gap width as 0.5–1.5, relative gap distance ratio as 0.24 – 0.8, Reynolds number from 2000 to 20,000, angle of attack as 60^o and relative width ratio as 6. Roughness geometry is shown in “Fig. 18”.

4.9. Roughness element combination

4.9.1 Transverse and inclined ribs combination

Varun at al. [1] introduced concept of combination roughness of inclined ribs and transverse ribs. The roughness geometry is shown in “Fig. 19”. They concluded that roughened collector with roughness pitch of 8 gave better result as compare to smooth one. The range of parameters used is Reynolds number from 2000 to 14,000, relative roughness height as 0.030, relative roughness pitch in between 3–8.

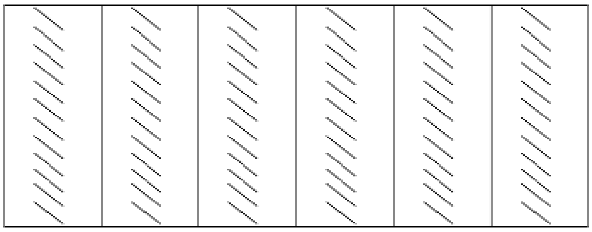


Fig. 19. Transverse and inclined ribs

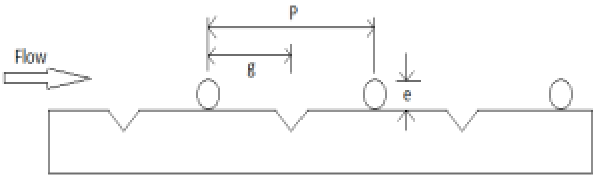


Fig. 20. Rib groove roughness

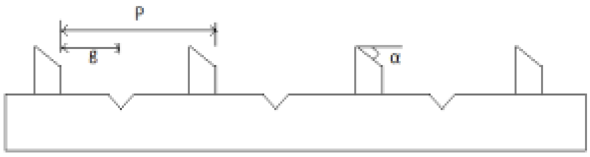


Fig. 21. Integral transverse chamfered rib groove roughness

4.9.2 Transverse rib groove combination

Jaurker et al. [21] proposed transverse rib roughness by incorporating groove between two transverse ribs. They investigated rib grooved artificial roughness and the geometry is shown in “Fig. 20”. After investigation they concluded that maximum heat transfer occurs at relative roughness pitch of 6 and optimum heat transfer was registered for groove position to pitch ratio of 0.4.

4.9.3 Chamfered rib groove combination

Layek et al. [22] used chamfered rib roughness geometry for the enhancement of heat transfer rate and friction characteristic of repeated integral transverse chamfered rib groove roughness as shown in “Fig. 21”. Parameters used during investigation are Reynolds number range from 3000–21,000, relative roughness pitch as 4.5 – 10, relative groove position as 0.3–0.6, chamfered angle as 5–30 and relative roughness height as 0.022– 0.04. They reported that Nusselt number and friction factor increased by 3.24 and 3.78 times respectively as compared to smooth duct. With relative groove position of 0.4 maximum enhancements of Nusselt number and friction factor were observed.

4.10. Arc shaped ribs

Saini et al. [23] proposed arc shaped rib roughness geometry. Parameters studied were relative roughness height as 0.0213–0.0422, duct aspect ratio 12, Reynolds number as 2000–17,000, relative roughness pitch 10 and relative angle of attack 0.33–0.66. The roughness geometry is shown in “Fig. 22”. After investigation they reported maximum enhancement in Nusselt number as 3.80 times corresponding to relative arc angle (α/90) of 0.33 at relative roughness height of 0.0422 and corresponding increase in friction factor was 1.75 times only.

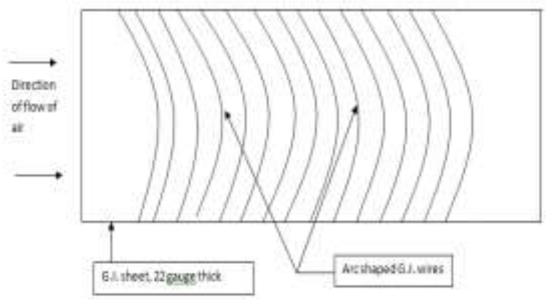


Fig. 22. Arc shaped wire roughness

4.11. Dimple surfaces

4.11.1 Transverse dimple roughness

Saini et al. [24] used dimple shaped artificial roughness in place of transverse ribs. The roughness geometry is shown in “Fig. 23”. Range of parameters used are Reynolds number from 2000 to 12,000, relative roughness pitch as 8–12, and relative roughness height as 0.018–0.037. They reported the maximum value of Nusselt number for relative roughness height of 0.0379 and relative roughness pitch of 10 and minimum value of friction factor observed for relative roughness height of 0.0289 and relative roughness pitch of 10.

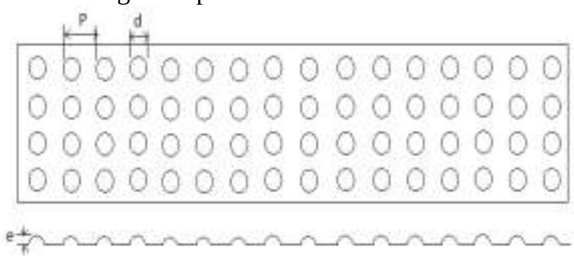


Fig. 23. Dimple shaped artificial roughness

4.11.2 Staggered dimple roughness

Bhushan et al. [25] investigated staggered dimple roughness in place of transverse dimple roughness. The staggered dimple roughness geometry is shown in “Fig. 24”. Maximum enhancement in heat transfer coefficient was observed for relative long way length (L/e) of 31.25, relative short-way length (S/e) of 31.25 and relative print diameter (d/D) of 0.294. The maximum enhancement of Nusselt number and friction factor was 3.8 and 2.2 times respectively as compared to smooth duct surface. The range of parameters for study were Reynolds number as 4000–20,000, relative roughness height as 0.03, relative long way length (L/e) as 25.00 – 37.50, relative short way length (S/e) as 18.75 –37.50 and relative print diameter (d/D) as 0.0147 – 0.367.

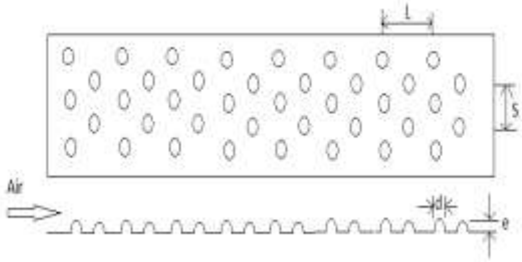


Fig. 24. Staggered dimple roughness

4.11.3 Arc shaped dimple roughness 1

Yadav et al. [26] investigated dimple shaped roughness in arc shaped manner. Maximum enhancement of heat transfer and friction factor was observed at relative roughness pitch of 12, relative roughness height of 0.03 and corresponding arc angle of 60^o. The roughness geometry is show in "Fig. 25". The range of parameters used during investigation are relative roughness pitch as 12 –24, relative roughness height as 0.015 to 0.03, arc angle of protrusion manner as 45–75 and Reynolds number in between the range of 3600 to 18,100.

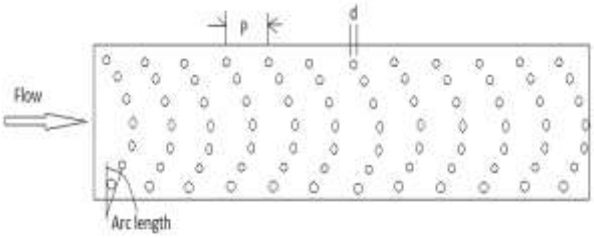


Fig. 25. Dimple roughness in arc manner

4.11.4 Arc shaped dimple roughness 2

Sethi et al. [27] investigated again dimple shaped roughness with different set of parameters. Roughness geometry is same as shown in "Fig. 25". After investigation they concluded that maximum value of Nusselt number observed corresponded to relative roughness pitch of 10, relative roughness height of 0.036 and arc angle of 60^o. The investigated range of parameters are relative roughness height as 0.021–0.036, relative roughness pitch as 10–20, duct aspect ratio 11, Reynolds number in between 3600–18,000 and arc angle from 45^o–75^o.

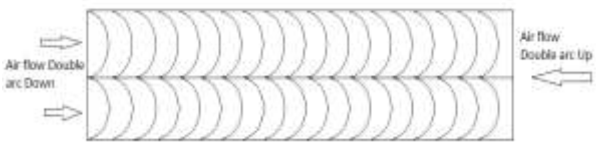


Fig. 26. Double arc rib roughness with up and down orientation

Lanjewar et al. [28] investigated on double arc shaped roughness geometry. They investigated the effect of orientation of double arc shaped roughness on thermo-hydraulic performance of solar air heater. Roughness geometry is shown in "Fig. 26". After investigation on double arc down, double arc up and single arc rib they concluded double arc down gives maximum enhancement of Nusselt number as 102.57-162.45%. Enhancement of Nusselt number for double arc-up and single arc rib roughness were 66.99-115.24% and 45.55-169.61%. They also found double arc-up rib perform better as compare to single arc till Reynolds number 8000 beyond that Nusselt number of double arc-up rib is lower than single arc. The experimentation involved relative roughness pitch 10, angle of attack of 45, relative roughness height 0.029, relative angle of attack (α/90), duct aspect ratio 8 and Reynolds number from 4000 to 14000. Investigation showed double arc down has higher Nusselt number as compare to double arc up and single arc roughness over the entire range of Reynolds number.

V. CONCLUSIONS

This review paper reveals various artificial roughness geometry to enhance heat transfer coefficient in solar air heater. Several investigators have carried out research to investigate the effect of artificial roughness of different shapes and size on heat transfer and friction factor and also have developed correlation for heat transfer coefficient and friction factor. These correlations can be used to predict the thermal as well as thermo-hydraulic performance of solar air heater having roughened duct. Substantial enhancement of heat transfer coefficient can be achieved with little penalty of friction factor using artificial roughness.

NOMENCLATURES

A_p Area of absorber plate, m^2
B half length of V-rib element (m)
D, D_h hydraulic diameter of duct (m)
d dimple diameter
e rib height (m)
g groove position (m)
H duct height (m)
l longway length of mesh
p pitch (p)
s shortway length of mesh
S length of main segment of rib (m)
W duct width (m)

Dimensionless parameters
B/S relative roughness length ratio
d/D relative print diameter
d/W relative gap position
e/D_h relative roughness height
f_r friction factor for roughened duct

f_s friction factor for smooth duct
g/e relative gap width
g/p groove position to pitch ratio
l/e relative longway length of mesh
l/s relative length of metal grid
m Mass flow rate of air
Nu_r Nusselt number of roughened duct
Nu_s Nusselt number of smooth duct
p/e relative roughness pitch
p´ /p relative roughness staggering ratio
s/e relative shortway length of mesh
S´ /S relative roughness segment ratio
W/H duct aspect ratio
W/w relative roughness width
ε enhancement factor

Greek symbols
α angle of attack (^{o})
ϕ wedge angle (^{o})

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