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Effect of Artificial Roughness on Absorber Plate on Thermal Performance of a Solar Air Heater-A Comprehensive Review

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ABSTRACT: Enhancement of heat transfer in the solar air heater ducts can be achieved by several means like using baffles, fins, ribs and groves. Until now, various attempts have been made to investigate the effects of these geometries on the enhancement of the heat transfer rate; however it is achieved at the cost of the increase in the pressure drop across the surfaces on which these elements are mounted. This paper is an attempt to summarize and conclude the investigations involving the use of small height elements and surface protrusions on absorber plate and channel walls as artificial roughness elements of various geometries and its effect on heat transfer and friction factor through experiments. It also summarizes the various correlations which have been developed for Nusselt number (Nu) and Friction factor (f) and reported in the previous investigations. The comparative study has been done to understand the results of these investigations for solar air heaters with different roughness elements on its absorber surface.

Keywords: Artificial roughness; Thermo-hydraulic; Heat transfer; Solar air heater

I. INTRODUCTION

The energy demand is growing continuously and rapidly, and it is impossible to meet the future demand with the presently available exhaustible energy sources. So, the technology is focusing on harnessing new and renewable sources of energy. Furthermore, the conventional energy sources are causing an alarming health hazard to the planet life. The use of solar energy is an intelligent option for the use of mankind which is available free of cost, in abundant and is a clean source for various applications [1]. The solar energy can be used directly or indirectly by converting it into thermal energy. Instead of direct use of solar energy, it is more useful when converted into thermal energy. Solar air heater is such a device, which converts solar energy into thermal energy. It can be used for various applications like the heating of building, wood seasoning, drying of crops of fruits and vegetables, chicken brooding [2] as well as curing of industrial products [3]. It has many advantages like low fabrication, installation, and operational costs, and can be constructed by using cheaper and lesser amount of material. However, its efficiency is poor. The lower efficiency of solar air heater is attributed to poor heat transfer characteristics of air, and also the air cannot be used as storage fluid due to low thermal capacity [4]. The low efficiency of the solar air heater can be increased either by increasing the surface area of the absorber plate or by using certain artificial geometries on the absorber plate with some adverse effect of the increase in frictional loss in ducts which is needed to be taken care of by using proper, geometrical parameters and flow conditions. The use of artificial roughness rib elements on the absorber plate is one of the effective ways which enhances the heat transfer coefficient of the air, thus increasing the heat transfer rate. These roughness rib elements breaks up the boundary layers and induces turbulence which results in heat transfer enhancement. These roughness elements being smaller in height as compared to duct size causes turbulence in the laminar sub layer adjacent to the wall without affecting the main turbulent zone in the flow. Several attempts have been made by various researchers in their experimental work to achieve the heat transfer enhancement through these solar air heaters by using different roughness elements on the surface of absorber plate. The researchers have used several geometries of artificial rib roughness elements with different parameters and materials till now.

But still this area of research has large opportunity for doing novel work to achieve the heat transfer enhancement with new geometry with different parameters. This review is an attempt to summarize all these efforts and to arrive at a conclusion regarding the previous experimentation works and providing an opportunity in this area to the researchers to inquest the new materials, geometries and techniques to achieve the desired result of enhancement of heat transfer.

II. FLUID FLOW AND HEAT TRANSFER CHARACTERISTICS OF ROUGHENED SURFACE

Earlier experiments dealt with roughness elements in pipe flow with water as flowing liquid. Use of ribs in pipe flow was extensively studied by Nikuradse [5]. He developed the velocity and temperature profile for sand grain roughened pipe flow and contributed to the study of the laws governing turbulent flow of fluids in roughened tubes, channels, and along rough plane surfaces with the law of similarity given by his previous authors. Nikuradse defined three regions or range of the fluid flow based on roughness Reynolds number (e+) through the roughened pipe which is described below.

(i) In the first range, the roughness height has no effect on the resistance for low Reynolds numbers. This range includes complete laminar flow and partly turbulent flow. The portion of turbulent flow included increases as the relative roughness height decrease.

(ii) In the second region, called as transition range, the effect of the roughness height is higher. The resistance increases with the increase in Reynolds number. The resistance depends on the Reynolds number and relative roughness of the surface.

(iii) The third region is the turbulent region where the resistance due to roughness is independent of the Reynolds number. It follows the quadratic law of resistance.

Efficiency of flat plate solar air heater is low because of low convective heat transfer coefficient between absorber plate and flowing air. Higher thermal resistance increases absorber plate temperature leading to greater heat losses to environment. Low value of heat transfer coefficient is due to the presence of laminar sub-layer that is broken by providing artificial roughness on heat transferring surface [1]. Efforts for enhancing heat transfer have been directed towards artificially destroying laminar sub-layer. Artificial roughness creates turbulence near wall and breaks laminar sub-layer. However artificial roughness results in high frictional losses leading to more power requirement for fluid flow. Hence turbulence has to be created in a region very close to heat transferring surface. Core fluid flow should not be unduly disturbed to limit pumping power requirement. This is achieved by keeping height of roughness element small in comparison to duct dimensions [2]. Important parameters that characterize roughness element are roughness element height (e) and pitch (p). These are expressed in terms of dimensionless parameters such as relative roughness height (e/D_h) and relative roughness pitch (p/e).

III. DEVELOPMENT OF ARTIFICIAL ROUGHNESS IN SOLAR AIR HEATER

A. *Transverse ribs*

Transverse continuous ribs. Prasad and Mullick [3] were the first to apply small diameter wire as roughness in solar air heater. The parameters for study were relative roughness height as 0.019 and relative roughness pitch as 12.7. They reported application of protruding wires led to improvement in plate efficiency factor from 0.63 to 0.72. Prasad and Saini [4] used small diameter wire as roughness in solar air heater. They investigated effect of relative roughness height and relative roughness pitch on heat transfer and friction factor. Range for relative roughness height was 0.020–0.033 and for relative roughness pitch was 10–20. Maximum value of Nusselt number and friction factor were reported as 2.38 and 4.25 respectively for relative roughness pitch of 10.

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

Verma and Prasad [6] did outdoor experimental study using transverse wire roughness. Parameters for study were relative roughness height as 0.01–0.03, relative roughness pitch as 10–40, roughness Reynolds number as 8–42 and Reynolds number varied from 5000 to 20,000. They reported optimal thermo-hydraulic performance of 71% corresponded to roughness Reynolds number of 24.

Transverse broken ribs. Sahu and Bhagoria [7] investigated transverse broken ribs as shown in Fig. 2. Investigation was carried for Reynolds number as 3000–12000, roughness pitch as 10–30 mm, rib height as 1.5 mm with aspect ratio 8. Maximum Nusselt number was attained for pitch 20 mm. Roughened absorber plate increased heat transfer coefficient by 1.25–1.4 times as compared to smooth duct operating under similar conditions.

Inclined ribs.

Continuous inclined ribs

An improvement proposed over transverse ribs was inclined rib that was investigated to study effect of rib inclination on heat transfer and friction factor by Gupta *et al.* [8]. They used inclined circular ribs as artificial roughness for Reynolds number as 3000–18000, duct aspect ratio as 6.8–11.5, relative roughness height as 0.018–0.052 for relative roughness pitch of 10. They reported enhancement in thermal efficiency by 1.16–1.25 as compared to smooth plate in range of parameters investigated.

Broken inclined ribs. Inclined rib was reinvestigated by Aharwal et al. [9] with a gap provision so as to allow release of secondary flow and main flow through the gap thereby creating local turbulence. The roughness geometry is shown in Fig. 4. Investigation covered Reynolds number as 3000–18,000, aspect ratio as 5.84, relative roughness pitch as 10, relative roughness height as 0.0377 and angle of attack as 60°. Gap width (g/e) and gap position (d/W) were in range of 0.5–2 and 0.1667–0.667 respectively. Maximum enhancement in Nusselt number and friction factor was reported as 2.59 and 2.87 times that of smooth plate respectively. Thermo hydraulic performance was reported to be maximum for relative gap width of 1.0 and relative gap position of 0.25.

Wire mesh

Expanded metal mesh. Saini e*t al.* [10] used expanded metal mesh as roughness geometry. They investigated 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. They reported enhancement in heat transfer coefficient and friction factor of order of 4 and 5 times over smooth duct corresponding to angle of attack of 61.9° and 72° respectively. 3.3.2. Discretized metal mesh

Metal mesh was further discretized by Karmare and Tikekar [11] who investigated heat transfer and friction factor for metal grit ribs. Range of parameters for investigation were Reynolds number as 4000–17000, e/D_h as 0.035–0.044, p/e as 12.5–36 and l/s as 1.72–01. They reported that plate with roughness parameters l/s as 1.72, e/D_h as 0.044 and p/e as 17.5 showed optimum performance.

Chamfered ribs. Karwa *et al.* [12] investigated effect of chamfered rib as artificial roughness. Investigation covered rib chamfer angle (φ) as –15° to 18^o, duct aspect ratio as 4.8–12, Reynolds number as 3000–20,000, relative roughness height as 0.0141–0.0328 and relative roughness pitch as 4.5–8.5. They reported two and three times increase in Stanton number and friction factor respectively. Both Stanton number and friction factor were reported to be highest for chamfer angle of 15°.

Wedge ribs. Possibility of improvement over chamfered integral ribs was studied by Bhagoria et al. [13]. They proposed wedge shaped transverse integral ribs. They investigated effect of relative roughness pitch, relative roughness height and wedge angle on heat transfer and friction factor and reported enhancement in Nusselt number as 2.4 times while of friction factor as 5.3 times as compared to smooth duct in range of parameters investigated. Maximum enhancement in heat transfer was obtained at wedge angle of 10°. Heat transfer was the maximum for relative roughness pitch of 7.57.

V-shaped ribs

Continuous V-ribs. Inclined rib [8] resulted in better performance than transverse ribs due to increase in secondary vortices. The number of secondary vortices was increased by V-shaping of angled rib by Momin *et al.* [14]. They investigated V-shape rib roughness and studied thermo hydraulic performance of solar air heater for Reynolds number as 2500–18,000, relative roughness height as 0.02–0.034, angle of attack of flow (α) as 30–90° for fixed relative roughness pitch of 10. Maximum enhancement of Nusselt number and friction factor was reported as 2.30 and 2.83 times that of smooth plate for angle of attack of 60°.

Discrete V-ribs. V-shaped rib was discretized by Muluwork *et al.* [15] who compared thermal performance of staggered discrete V-apex up and V-down ribs with corresponding transverse staggered discrete ribs. The roughness geometry of Muluwork *et al*. [15]. They reported Stanton number for V-down discrete ribs higher than corresponding V-up and transverse discrete ribs. Stanton number enhancement was reported as 1.32–2.47 in range of parameters investigated.

Karwa *et al.* [16] did experimental study using v-discrete and v-discontinuous rib. Range of parameters was relative roughness pitch as 10.63, relative roughness length (B/S) as 3 and 6, angle of attack as 45° and 60° and Reynolds number as 2850–15,500. They reported that discrete ribs perform better than discontinuous rib and 60^o ribs performed better than 45° ribs. Roughness geometry.

Comparison of transverse inclined, V-down continuous, V-up continuous, V-down discrete and V-up discrete was investigated by Karwa [17]. He reported that based on equal pumping criteria discrete V-down arrangement gives best heat transfer performance.

Discrete V-down ribs was investigated by Singh et al. [18]. Investigation was carried for Reynolds number from 3000 to 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 pitch as 4–12, angle of attack 30–75° and relative roughness height as 0.015–0.043. Maximum increase in Nusselt number and friction factor over smooth duct was 3.04 and 3.11 times respectively. Rib parameters corresponding to maximum increase in Nusselt number and friction factor were d/w=0.65, g/e=1.0, p/e=10, α=60 and e/D_h=0.043.

W-shape ribs

Continuous W-ribs. Utilizing concept of increasing number of secondary cell, W-shaped rib roughness was investigated by Lanjewar *et al.* [19]. Range of parameters was relative roughness pitch 10, relative roughness height 0.018–0.03375 and angle of attack 30–75°. They reported W-down arrangement with angle of attack 60° gives optimum thermo hydraulic performance. Maximum enhancement of Nusselt number and friction factor was 2.36 and 2.01 times that of smooth plate for angle of attack of 60°.

Discrete W-ribs. W-shaped rib was discretized and discrete W-shape rib was investigated by Kumar *et al.* [20]. The investigation encompassed Reynolds number from 3000 to 15,000, relative roughness height as 0.0168–0.0338, relative roughness pitch as 10 and angle of attack 30–75°.

Maximum enhancement of Nusselt number and friction factor was reported as 2.16 times and 2.75 times that of smooth duct corresponding to angle of attack of 60° and relative roughness height of 0.0338.

Multiple V-ribs

Multiple continuous V-ribs. Using concept of increasing number of secondary flow cells, multiple V-ribs were investigated by Hans *et al.* [21]. The experiment encompassed Reynolds number from 2000 to 20,000, relative roughness height as 0.019–0.043, relative roughness pitch as 6–12, angle of attack as 30–75° and relative roughness width (W/w) range as 1–10. Maximum heat transfer occurred for relative roughness width (W/w) of 6 while friction factor attained maximum value for relative roughness width (W/w) of 10. Both Nusselt number and friction factor attained maxima corresponding to angle of attack of 60°. Maximum enhancement of Nusselt number and friction factor was 6 and 5 times respectively in comparison to smooth duct for range of parameters investigated.

Multiple V-rib with gap. Concept of local turbulence and acceleration of flow by providing gap was utilized by Kumar *et al.* [22]. Range of parameter encompasses. Reynolds number from 2000 to 20,000, relative width ratio as 6, relative gap distance ratio as 0.24–0.8, relative gap width as 0.5–1.5, relative roughness height as 0.043 and angle of attack as 60°. They reported maximum enhancement in Nusselt number and friction factor as 6.32 and 6.12 times that of smooth duct respectively.

Roughness elements combination

Transverse and inclined ribs combination. Concept of combination roughness of transverse and inclined ribs was investigated by Varun *et al.* [23]. Experimental investigation encompassed Reynolds number from 2000 to 14,000, relative roughness pitch 3–8 and relative roughness height as 0.030. They reported that roughened collector having roughness pitch of 8 gave best performance.

Transverse rib groove combination. Performance of transverse rib roughness was sought to be enhanced by providing groove between two transverse ribs. Jaurker *et al.* [24] investigated heat transfer and friction characteristics of rib grooved artificial roughness. Effect of relative roughness height, relative roughness pitch and relative groove position were investigated. Maximum heat transfer was achieved for relative roughness pitch of 6. Optimum heat transfer was reported for groove position to pitch ratio of 0.4.

Chamfered rib groove combination. Performance of chamfered rib roughness was enhanced by Layek *et al.* [25] who investigated heat transfer and friction characteristics of repeated integral transverse chamfered rib groove roughness. The study was carried for Reynolds number range of 3000–21,000, relative roughness pitch as 4.5–10, chamfer angle as 5–30°, relative groove position as 0.3–0.6 and relative roughness height as 0.022–0.04. They reported Nusselt number and friction factor increased by 3.24 and 3.78 times respectively as compared to smooth duct. Maximum enhancement of Nusselt number and friction factor were achieved for relative groove position of 0.4.

Arc shaped ribs. Arc shaped rib roughness was first utilized by Saini *et al.* [26]. Investigation encompassed duct aspect ratio 12, relative roughness pitch 10, relative roughness height 0.0213–0.0422, relative angle of attack 0.33–0.66 and Reynolds number 2000–17,000. They reported maximum enhancement in Nusselt number as 3.80 times corresponding to relative arc angle ($\alpha/90$) of 0.33 at relative roughness height of 0.0422. Correspondingly increase in friction factor for these parameters was 1.75 times only.

Dimpled surfaces

Transverse dimple roughness. Instead of transverse ribs a new concept of dimple shape artificial roughness was first employed by Saini *et al.* [27]. Investigation covered range of Reynolds number from 2000 to 12,000, relative roughness height as 0.018–0.037, relative roughness pitch as 8–12. They reported maximum value of Nusselt number for relative roughness height of 0.0379 and relative roughness pitch of 10. Minimum value of friction factor corresponded to relative roughness height of 0.0289 and relative roughness pitch of 10.

Staggered dimple roughness. In place of transverse dimple roughness, staggered dimple roughness was investigated by Bhushan *et al.* [28]. Range of parameters investigated were relative short way length (S/e) as 18.75–37.50, relative long way length (L/e) as 25.00–37.50, relative print diameter (d/D) as 0.147–0.367, relative roughness height as 0.03, aspect ratio as 10 and Reynolds number from 4000–20000. Maximum enhancement of Nusselt number and friction factor was 3.8 and 2.2 times respectively in comparison to smooth duct. Maximum enhancement in heat transfer coefficient was reported for relative shortway length (S/e) of 31.25, relative long way length (L/e) of 31.25 and relative print diameter (d/D) of 0.294.

Arc shaped dimple roughness 1. Dimple shaped roughness in arc shaped manner was employed by Yadav *et al.* [29]. Roughness geometry is shown in Fig. 23. Experiment encompassed Reynolds number range from 3600 to 18,100, p/e as 12 to 24, e/D_h as 0.015 to 0.03 and arc angle of protrusion arrangement as 45–75°. Maximum enhancement of Nusselt number and friction factor was found to be 2.89 and 2.93 times smooth duct for range of parameters investigated. Maximum heat transfer enhancement and friction factor occurred for relative roughness height of 0.03, relative roughness pitch of 12 and for arc angle value of 60°.

Arc shaped dimple roughness 2. Dimple shaped roughness but with different set of parameters were again investigated by Sethi *et al.* [30].

Investigation covered duct aspect ratio 11, relative roughness pitch 10–20, relative roughness height 0.021–0.036, arc angle 45–75° and Reynolds number range from 3600–18,000. They reported maximum value of Nusselt number corresponded to relative roughness height of 0.036, relative roughness pitch of 10 and arc angle 60°. Literature survey shows that roughness of many types has been investigated and improvements over previous roughness have progressed. As per literature no study has been conducted so far to see the effect of orientation of double arc shaped roughness on thermo-hydraulic performance of solar air heater. In this paper effect of orientation of double arc rib on thermo-hydraulic performance of solar air heater is presented.

IV. CONCLUSIONS

In the present paper, an attempt is made to review development of artificial roughness for heat transfer enhancement in solar air heater over the years as given in Table 1 and performance evaluation for orientation of double arc rib roughened solar air heater is presented.

Table 1: Heat transfer coefficient and friction factor correlation for various geometries applied in solar air heaters.

Investigator	Roughness used	Heat transfer correlation
Prasad and Saini [4]	Transverse rib	St=(f/2)/[1+√(f/2){4.5Pr0.57(e+)0.28−0.95(p/e)0.53}]
Gupta *et al.* [5]	Transverse wires	Nu=0.000824(e/D)−0.178(W/H)0.284(Re)1.062e≤35
Verma and Prasad [6]	Transverse wire roughness	Nu=0.00307(e/D)−0.469(W/H)0.245(Re)0.812e≥35
Gupta *et al.* [8]	Inclined ribs with gap	Nur=0.0245(p/e)−0.016(e/D)0.021Re0.802e≥24
Aharwal *et al.* [9]	Expanded metal mesh	Nu=0.0024(e/D)0.001(W/H)−0.06Re1.084[exp{−0.04(1−α/60)2}] for e+<35Nu=0.0071(e/d)−0.24(W/H)−0.028Re0.88[exp{−0.475(1−α/60)2}] for e+>35
Saini and Saini [10]	Metal grit ribs	Nu=0.002Re1.08(p/e)1.87×exp[−0.45(ln (p/e))2](α/60)0.006×exp[−0.65(ln α/60)2](d/W)−0.32×exp[−0.12(ln d/W)2](g/e)−0.03×exp[−0.18(ln g/e)2](e/D)0.5
Karmare and Tikekear [11]	Integral chamfered rib	Nu=4×10−4×Re1.22×(e/D)0.625×(S/10e)2.22×(L/10e)2.66×[exp{−1.25 (ln (S/10e))2}]×[exp{−0.824(ln (L/10e))2}]
Karwa *et al.* [12]	Wedge shaped rib	Nu=2.4×10−3×(Re)1.3×(e/D)0.42×(l/s)−0.146×(p/e)−0.27
Bhagoria *et al.* [13]	V-shaped rib	G=103.77 e−0.006Ø(W/H)0.5(p/e)−2.56×exp[0.7343{ln ((p/e))}2](e+)−0.31for 7≤e+<20G=32.26e-0.006Ø(W/H)0.5(p/e)−2.56×exp[0.7343 {ln ((p /e))}2](e+)0.08for 20≤e+<60
Momin *et al.* [14]	Discrete V-shaped ribs	Nu=1.89×10−4(e/D)0.426Re1.21(p/e)2.94[exp(−0.71(ln(p/e)))2](φ/10)−0.018[exp{−1.50(ln (φ/10°))2}]
Muluwork *et al.* [15]	Discrete V-down ribs	Nu=0.067 (e/D)0.424Re0.888(α/60)−0.077[exp{−0.782(ln(α/60))}2]
Singh *et al.* [18]	W-shaped ribs	Nu=0.00534Re1.299(B/S)1.346(S′/S)1.112(e/D)0.270(p′/p)0.762exp[−2.25(ln(p′/p))]2exp[−0.376(ln(1−α/60))]2
Lanjewar *et al.* [19]	Discrete W-shaped ribs	Nu=2.36×10−3 Re0.90 (p/e)3.50 (α/60)−0.023(d/W)−0.043(g/e)−0.014(e/D)0.47 exp(−0.84(ln (P/e)2) exp(−0.72 (ln (α/60)2) exp(−0.05(ln (d/W)2) exp(−0.15(ln (g/e)2)
Kumar *et al.* [20]	Multi V-shaped rib	Nu=0.0613(Re)0.9079(e/Dh)0.4487(α/60)−0.1331[exp(−0.5307(ln(α/60))2)]

Hans *et al.* [21]	Multi V with gap	Nu=0.105×(Re)0.873×(e/Dh)0.453×(α/60)−0.081×exp[−0.59×(ln (α/60))2]
Kumar *et al.* [22]	Inclined and transverse ribs	Nu=3.35×10−5Re0.92(e/D)0.77(W/w)0.43(α/90)−0.49exp(−0.1177(ln(W/w))2)×exp(−0.61(ln(α/90))2)(p/e) 8.54×exp(−2.0407(ln(p/e))2)
Varun *et al.* [23]	Rib-grooved roughness	Nu=8.532×10−3(Re)0.932(e/D)0.175(W/w)0.506×exp[−0.0753(ln(W/w))2](Gd/Lv)−0.0348 ×exp[−0.0653(ln(Gd/Lv))2](g/e)−0.0708×exp[−0.223(ln(g/e))2](α/60)−0.0239× exp[0.1153(ln(α/60))2](p/e)1.196×exp[−0.2805(ln(p/e))2]
Jaurker *et al.* [24]	Chamfered rib grooved	Nu=0.0006(Re)1.213(p/e)0.0104
Layek *et al.* [25]	Arc shaped wire roughness	Nu=0.002062Re0.936(e/D)0.349(p/e)3.318×exp[−0.868{ln(p/e)}2](g/p)1.108×exp[2.486{ln(g/p)}2+1.406{ln(g/P)}3]
Saini and Saini [26]	Dimpled shaped rib	Nu=0.00225Re0.92((e/d))0.52(p/e)1.72×exp[−0.22(ln Φ)2]×exp[−0.46{ln(p/e)}2](g/p)−1.21Φ1.24×exp[−0.74{ln(g/p)}2]
Saini *et al.* [27]	Protruded roughness geometry	Nu=0.001047×Re1.3186×(e/D)0.3772×(α/90)−0.1198
Brij Bhushan *et al.* [28]	Protrusion geometry in arc shape	Nu=5.2×10−4Re1.27×(p/e)3.15×[exp(−2.12)(log((p/e)))2](e/D)0.033×[exp(−3)(log((e/d)))2]
Yadav *et al.* [29]	Protrusion geometry in arc shape	Nu=2.1×10−88×Re1.452×(S/e)12.94×(L/e)99.2×(d/D)−3.9×exp[−10.4(ln(S/e))2]×exp[−77.2(ln(L/e))2]×exp[−7.83(ln(d/D))2]
Sethi *et al.* [30]	Transverse rib	Nu=0.154×Re1.017×(p/e)−0.38×(e/D)0.521×(α/60)−0.213×exp(−2.023(ln(α/60))2)

The salient features are:

(i) Application of artificial roughness results in enhancement in performance of solar air heater.
(ii) Early roughness used was transverse rib roughness, which was modified as angled, then V-rib, W-rib, multi W-rib and then introducing gap in inclined rib, V-rib and multi W-rib.
(iii) Also other geometries namely chamfered, wedge shaped and combination roughness such as rib and groove, transverse and inclined, dimple shaped roughness in straight, staggered and arc manner have been studied. As per literature effect of orientation of arc shaped rib have not been reported so far.
(iv) Performance analysis for orientation of double arc rib roughness has been done experimentally.
(v) Based on thermo-hydraulic performance double arc down orientation performs better than double arc up and single arc orientation for low and medium range of Reynolds number which is an operating range for most solar air heaters. Double arc up roughness has poor performance than single arc roughness from thermo-hydraulic considerations for most range of Reynolds number.

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