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A review on developments in artificial roughness in solar air heater for forced convection

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Abstract
Technique of providing artificial roughness on underside of absorber plate surface is an important practice to enhance heat transfer of air flowing in air heater duct. In the past years various types of rib geometries have been designed and used to investigate heat transfer and friction features of air heater. The design of the roughness shape and arrangement is very important to optimize the heat transfer parameters. The roughness parameters and ribs arrangement are accountable to vary the flow pattern. This flow pattern primarily governs the heat transfer mechanisms. In the present article, a critical review on various artificial roughness elements available in literature has been carried out and the effects of the roughness patterns are discussed. A comparison study of thermohydraulic performance of different roughness elements has also been underlined.

Keywords: Artificial roughness, Air heater, Forced convection

1. Introduction

Energy in different forms plays a very crucial role in world wide economic progress and industrialization. The rise in world population coupled with rising material needs has increased the rate of energy usage [1].

Any civilization requires energy for its sustenance and well-being ever since it came into existence. Man discovered fire and started to make use of wood and other biomass to supply the energy needs for cooking and for keeping himself warm. With the time, man started farming. He further started to domesticate and train the animals to work for him in pulling carts etc. With further increase in the requirement for energy, man started to harness the wind energy for sailing ships and driving windmills, and then he used the force of falling water to turn water wheels for getting required power. This is to emphasize that the sun was and is supplying all the energy needs of man either directly or indirectly and that man was using only renewable source of energy [2].

Renewable energy is the energy that we get from natural sources that are continuously naturally replenished on a human timescale. This includes solar, geothermal, wind, tidal, hydro and various forms of biomass. This energy is not exhausted and is constantly renewed. Renewable energy resources are available in nature free of cost. They produce either no or very less pollution. Thus, to a large extent, they are environment friendly. They generally require less maintenance than traditional generators. But, in general, the energy is available in dilute form from various renewable energy resources and also has transportation. Although they are available freely in nature with uncertainty, the cost of utilization is generally high.

Non- renewable energy sources have limited in quantity and do not get replenished after their consumption e.g., fossil fuels, uranium, etc. At present the utilization cost of non renewable energy resource lower than renewable energy resources and their storage is easy and convenient for certain period of time. They are very convenient to use as technology for their conversion and have higher efficiency.

Solar energy is non-polluting and inexhaustible source of energy. It is non-ending and its conversion to some other energy form is nonpolluting. Nowadays, solar energy is used in many applications like electricity generation, water distillation, food and cloth drying, air heater etc. One of the drawbacks of solar energy is its uncertainty. Solar energy is not available in night as well in cloudy weather.

Today, we have big challenge in front of us, for utilizing the energy of sun in proper and efficient way. Solar air heater is one of the regular applications of solar energy.

Solar air heating is a solar thermal technology in which the energy from the sun is utilized by an absorbing medium and used to heat air. It is a renewable energy heating technology used to heat or condition air for buildings or process heat applications. It is the most cost-effective out of all the solar technologies, typically in commercial and industrial applications and addresses the largest usage in building heating, industrial process heating and food drying etc [3].

2. Basics of artificial roughness

Generally, the performance of smooth absorber plate is considered to be low due to low convective heat transfer coefficient. The sub laminar layer developed over absorber plate acts as thermal resistant to flowing air. For augmenting the heat transfer rate, sub laminar layer needs to be disturbed or broken which can be done by creating local turbulence which can be done by artificial roughness. Artificial roughness are created underside of absorber plate using repeated geometries of various forms of small height wires attached to absorber plate. During the air flow over roughened surface, separation and reattachment occurs in between the repeated ribs that lead to local wall turbulence and thus, enhancement of convective heat transfer coefficient of absorber plate. Secondary recirculation flows further increases the heat transfer rate because it promotes the mixing. The increase in heat transfer is also gives rise to increase in pressure drop in term of friction factor which is not desirable. Therefore, it is necessary to minimize the pressure drop penalty as extra energy for creating turbulence is required from the blower. This difficulty can be tackled by keeping the rib height small in comparison to duct height. Small height roughness creates the turbulence on the surface and it does not disturb the core flow. Roughness parameters like ribs arrangement, shape of wires, rib pitch and rib height affect the heat transfer and friction factor. Various rib arrangements have been investigated and some arrangements are transverse ribs, angled ribs, V-ribs, W-ribs, multi V-ribs, rib with groove, staggered ribs, chamfered ribs and discrete ribs [4].

3. Recent developments in artificial roughness provided in solar air heater

Many researchers like Alam and Kim [4], Yadav and Bhagoria [5] and Lanjewar *et al*. [6] provided a comprehensive review on developments in the field of heat characteristics in solar air heaters with the incorporation of artificial roughness. This article is a further attempt to discuss the characteristics of various geometrical roughness and latest developments in terms of friction factor and heat transfer features.

3.1 Chamfered ribs

Karwa *et al*. [7] explored the characteristics of air in air heater with chamfered rib on absorber plate. The aspect ratios investigated were 4.8, 6.1, 7.8, 9.66 and 12.0. The range of parameters studied were viz. Reynolds numbers from 3000 to 20000; relative roughness heights from 0.0141 to 0.0328; relative roughness pitch of 4.5, 5.8, 7.0 and 8.5; and rib chamfer angles of -15, 0, 5, 10, 15 and 18°. The Stanton number and friction factor were enhanced by 2 and 3 folds, respectively.

3.2 Wedge ribs

Bhagoria *et al*. [8] performed experiments for heat transfer and friction data on forced convection in solar air heater duct with one absorber plate roughened by wedge shaped transverse integral ribs. The experiment were conducted for the Reynolds number range from 3000 to 18000; relative roughness height 0.015 to 0.033; the relative roughness pitch $60.17\Phi^{-1.0264} < p/e < 12.12$; and rib wedge angle of 8, 10, 12 and 15°. An increase of 2.4 folds in Nusselt Number and that of friction factor by 5.3 times in comparison to smooth. Maximum increase in transfer of heat was found at wedge angle of 10º. Heat transfer was highest for relative roughness pitch of 7.57.

3.3 Transverse ribs

3.3.1 Transverse continuous ribs

Prasad and Mullick [9] provided protruding wires on the below the absorber plate for enhancing the heat transfer rate and plate efficiency factor. The improvements in the plate efficiency factor of the unglazed collector with a corrugated galvanized iron absorber are from 0.63 to 0.72 for a Reynolds number of 40000.

Gupta *et al*. [10] carried out experiments on rectangular air ducts with an absorber plate having transverse wire roughness for transition flow region ($5 < e^+ < 70$) for the Reynolds number ranging from 3000 to 18000 for a duct aspect ratio of 6.8-11.5, relative roughness height of 0.018-0.052 at a relative roughness pitch of 10.

Verma and Prasad [11] studied the optimal energy performance of solar air heaters with artificial 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 5000-20,000. Roughness Reynolds number which combines the roughness and flow effect and is expressed as $e^+ = e/D\,(f_x/2)^{0.5}\,Re$ was considered. Thermo hydraulic performance was defined by the equation $\eta_{thermo} = (St_r = St_s)^3/(f_r/f_s)$. It was observed that $e^+_{opt} = 24$ gives the optimal thermo hydraulic performance. The value of optimal thermohydraulic performance has been found to be about 71% corresponding to $e^+_{opt} = 24$.

3.3.2 Transverse discrete ribs

Sahu and Bhagoria [12] studied the heat transfer features using broken transverse ribs on absorber plate of an air heater. The roughened wall has roughness with pitch (P), ranging from 10–30 mm, height of the rib of 1.5 mm and duct aspect ratio of 8. The air flow rate corresponds to Reynolds number between 3000 and 12,000. The heat transfer results have been compared with those for smooth ducts under similar flow and thermal boundary condition. Maximum Nusselt number was attained for a pitch of 20 mm. The heat transfer coefficient increased by 1.25–1.4 times in roughened absorber plate as compared to smooth.

3.4 Wire mesh

3.4.1 Expanded metal mesh

Saini and Saini [13] studied fully developed turbulent flow in a Rectangular duct with aspect ratio (11: 1) and expanded metal mesh as artificial roughness. The range of the system and operating parameters included relative long way length of mesh (*L/e*) from 25 to 71.87, relative short way length of mesh (*S/e*) from 15.62 to 46.87 for Reynolds numbers from 1900 to 13 000. Enhancement in heat transfer coefficient and friction factor of order of 4 and 5 times over smooth duct corresponding to angle of attack of 61.91 and 721, respectively were reported. Correlations for the Nusselt number and friction factor in terms of these parameters were also developed.

3.4.2 Discretized metal mesh

Karmare and Tikekar [14] studied heat transfer to the airflow in the rectangular duct of an aspect ratio 10:1. The top wall surface is made rough with metal ribs of circular cross section in staggered manner to form defined grid. The effect of relative roughness height of grid (e/Dh), relative roughness pitch of grit (p/e), relative length of grit (l/s) on the heat transfer coefficient and friction factor is investigated. The range of variation of system parameters and operating parameters is investigated within the limits, as e/D_h: 0.035 to 0.044, p/e: 12.5–36 and l/s: 1.72–1, against variation of Reynolds number: 4000 – 17,000. The optimal performance was found at, l/s = 1.72, e/D_h = 0.044, p/e = 17.5.

3.5 Inclined ribs

3.5.1 Continuous inclined ribs

Gupta *et al*. [15] proposed an improvement over transverse ribs by using inclined circular rib. The experiments were carried out for Reynolds number: 3000– 18000, duct aspect ratio: 6.8–11.5, relative roughness height: 0.018–0.052 for relative roughness pitch of 10. An enhancement in thermal efficiency by 1.16–1.25 as compared to smooth plate in same range of parameters investigated was observed.

3.5.2 Broken inclined ribs

Aharwal *et al*. [16] investigated repeated square cross-section inclined split-rib with a gap. The duct has a width to height ratio (W/H) of 5.84, relative roughness pitch (P/e) of 10, relative roughness height (e/D_h) of 0.0377, and angle of attack (α) of 601. The gap width (g/e) and gap position (d/W) were varied in the range of 0.5–2 and 0.1667–0.667, respectively. The Reynolds numbers was varied from 3000 to 18,000. The maximum enhancement in Nusselt number and friction factor was found to be 2.59 and 2.87 times of that of the smooth duct, respectively. The maximum value of thermo-hydraulic performance parameter is found for the relative gap width of 1.0 and the relative gap position of 0.25.

3.6 V-shaped ribs

The effect of various V-shape ribs on heat transfer and friction characteristics have been discussed below.

3.6.1 Continuous V-ribs

Momin *et al*. [17] reported the experimental results of the effect of geometrical parameters of absorber plate with V-shaped ribs in rectangular duct of a solar air heater. The investigation covered a Reynolds number (Re) in the range of 2500–18000, relative roughness height ($e=D_h$) of 0.02–0.034 and angle of attack of flow (α) of 30–90° for a fixed relative pitch of 10. The maximum enhancement factor in Nusselt number and friction factor were found to be 2.30 and 2.83, respectively, for angle of attack of 60°. The Nusselt number of V-shape ribs was increased 1.14 times as compared to inclined.

Isanto *et al*. [18] investigated the effect of V-shaping of ribs on heat and friction features. Angle of attack was varied between 30° and 80°, relative rib pitch and relative rib height were fixed as 10 and 0.033, respectively. Maximum augmentation in friction factor and Nusselt number were reported as 2.45 and 2.34 times over smooth duct, respectively.

3.6.2 Discrete V-ribs

Singh *et al*. [19] experimentally studied the heat and fluid features of absorber plate with repeated 'discrete V-down rib'. Reynolds number (Re) was varied from 3000 to 15000 with relative gap width (g/e) and relative gap position (d/w) range of 0.5-2.0 and 0.20-0.80 respectively. The respective variation in relative roughness pitch (P/e), angle of attack (α) and relative roughness height (e/D_h) have been 4-12, 30°-75° and 0.015-0.043. The maximum increase in f and Nu over that of smooth duct was 3.11 and 3.04 times, 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 = 60º and e/Dh =0.043. Moreover, Singh *et al*. [20] analyzed effective and thermal efficiencies of V-shape ribs with gaps. Optimum thermal efficiency was found to be at α=60°, d/w=0.65, p/e=8 and e/D_h=0.043.

Karwa *et al*. [21] investigated V-discontinuous and V-discrete ribs. The angle of attack, relative roughness length and roughness pitch were considered in the experiments and corresponding values were in the range of 45–60°, 3–6 and 10.63, respectively. Discrete V-ribs with angle of attack of 60°was found to be better than discrete V-ribs with angle of attack of 45°.

Maithani and Saini [22] studied the symmetrical multiple gaps in V-shape ribs. Number of gaps in a single limb of V, relative gap width, angle of attack and relative rib pitch were taken in the ranges of 1-5, 1–5, 30°-75° and 6–12, respectively. Enhancement factor in friction factor and Nusselt number were found upto 3.67 and 3.6 times over smooth absorber plate, respectively.

Kumar *et al*. [23] presented an experimental study on heat transfer and friction characteristics of solar air channel fitted with discretized broken V-pattern baffle on the heated plate. The roughened baffle air channel has a width to height ratio, W/H of 10. The relative baffle gap distance, D_d/L_v and relative baffle gap width, g_w/H_b has been varied from 0.26 to 0.83 and 0.5–1.5, respectively. Experiments have been carried out for the range of Reynolds number, Re from 3000 to 21,000 with the relative baffle height, H_b/H range of 0.25–0.80, relative baffle pitch, P_b/H range of 0.5–2.5; and angle of attack, α_a range of 30°–70°. For Nu_{rs} the greatest enhancement of the order of 4.47 times that of without channel was obtained. The absolute highest data of thermal hydraulic performance parameter was found to be greater corresponding to D_d/L_v of 0.67, g_w/H_b of 1.0, H_b/H of 0.50, P_b/H of 1.5, and α_a of 60°. The maximum value of the thermal hydraulic performance parameter was found to be 3.14.

3.7 Arc shape ribs

Saini and Saini [24] studied the performance of artificial roughness in the form of arc-shape parallel wire. The effect of system parameters such as relative roughness height (e/d) and arc angle (α/90) have been studied on Nusselt number (Nu) and friction factor (f) with Reynolds number (Re) varied from 2000 to 17000. Considerable enhancement in heat transfer coefficient has been achieved with such roughness element. Using experimental data correlations for friction factor and Nusselt number have also been developed for such solar air heaters, which gives a good agreement.

Sahu and Prasad [25] investigated the heat and thermohydraulic features of solar collector for heating air having circular wire rib roughness in the form of arc. A mathematical model incorporating the operating and system parameters was developed and the results were computed using MATLAB. A conventional solar air heater working was considered for the purpose of comparison. At rib height-to-duct hydraulic diameter ratio = 0.0422 and flow-attack-angle = 0.3333 the values of maximum thermal and effective efficiencies were found to be 79.84% and 75.24% respectively. The thermal efficiency, obtained in the study was compared with those obtained for other roughness geometries available in the literature. Optimization of different parameters of wire roughness for optimum thermohydraulic efficiency of solar air heater duct was investigated.

3.8 Multi arc ribs
Effect of multi arc ribs on heat transfer and friction characteristic have been studies by various researchers. Investigations based on multi arc ribs are discussed below.

3.8.1 Continuous ribs
Singh *et al*. [26] studied the effect of geometrical parameters of multiple arc shaped roughness element on heat transfer and friction characteristics. The experiments carried out encompasses Reynolds number (Re) in the range of 2200–22,000, relative roughness height (e/D_h) range of 0.018–0.045, relative roughness width (W/w) ranges from 1 to 7, relative roughness pitch (p/e) range of 4–16 and arc angle (α) ranges from 30º to 75°. The performance was found to be best for relative roughness width (W/w) of 5.

3.8.2 Ribs with gap
Pandey *et al*. [27] studied thermal performance in rectangular a channel which is having multiple-arc shaped with gaps as roughness element. The investigation encompassed Reynolds number (*Re*) ranges from 2100 to 21,000 (7 values), relative roughness height (*e*/*D*) ranges from 0.016 to 0.044 (4 values), relative roughness pitch (*p*/*e*) ranges from 4 to 16 (4 values), arc angle (*α*) values are 30–75° (4 values), relative roughness width (*W*/*w*) ranges from 1 to 7 (5 values), relative gap distance (*d*/*x*) values are 0.25–0.85 (4 values) and relative gap width (*g*/*e*) ranges from 0.5 to 2.0 (4 values). The maximum increment in Nusselt number (*Nu*) and friction factor (*f*) is 5.85 and 4.96 times in comparison to the smooth duct.

Gill *et al*. [28] studied the thermal performance of air heater duct with aspect ratio of 12, whose absorber is roughened with “broken arc rib combined with staggered rib piece”. The rib roughness has fixed relative staggered rib position, relative roughness height, relative gap size, relative gap position, arc angle and relative roughness pitch of 0.4, 0.043, 1.0, 0.65, 30° and 10 respectively. The relative staggered rib size and Reynolds number were varied from 1 to 6 and 2000 to 16,000 respectively. The effect of staggered rib on the flow pattern has also been observed using ANSYS Academic Research CFD 15.0. The maximum increase in friction factor and Nusselt number over that of broken arc rib roughened duct under similar flow and boundary conditions has been found to be 2.27 and 2.60 times respectively. The corresponding enhancements over that of smooth duct were 3.06 and 2.50 times respectively. The performance of duct with rib roughness has been considerably enhanced and was found to be highest for relative staggered rib size of 4.

3.9 W-shape ribs
3.9.1 Continuous W-ribs
Lanjewar *et al*. [29] studied W-shaped ribs for performance characteristics with an inclination. Duct had W/H of 8.0, p/e of 10, e/D_h 0.018-0.03375 and α 30°-75°. The Reynolds number used was in between 2300 and 14000.

3.9.2 Discrete W-ribs
Kumar *et al*. [30] studied thermal characteristics of air heater using discrete W-shaped roughness with an aspect ratio of 8:1. The study was carried out at Re ranging from 3000 to 15,000, e/D_h: 0.0168–0.0338, p/e 10 and α in the range of 30°–75º. Maximum increase in Nu and f was observed as 2.16 times and 2.75 times that of smooth duct corresponding to α of 60° and e/D_h of 0.0338.

3.10 Multiple V-ribs
3.10.1 Multiple continuous V-ribs
Hans *et al*. [31] studied multi V-shaped rib with gap roughness. Re ranges from 2000 to 20,000, G_d/L_v 0.24-0.80, g/e 0.5-1.5, e/D 0.022-0.043, P/e 6-12, W/w 1-10, α 30°-75°. For Nu, the maximum enhancement of the order of 6.74 times as compared to that of smooth duct has been recorded, however the friction factor (f) has also been seen to increase by 6.37 folds of that of the smooth duct. The rib parameters corresponding to maximum increase in Nu and f were G_d/L_v = 0.69, g/e = 1.0, e/D = 0.043, P/e = 8, W/w= 6 and α= 60°.

3.10.2 Multiple V-ribs with gap
Kumar *et al*. [32] studied the effect of geometrical parameters of Multi V-shaped ribs with gap on heat transfer and fluid flow characteristics. The study used Reynolds number (Re) in the range from 2000 to 20,000, relative width ratio (W/w) 6, relative gap distance (G_d/L_v) 0.24–0.80, relative gap width (g/e) of 0.5–1.5, relative roughness height (e/D) of 0.043, relative roughness pitch (P/e) of 10, angle of attack (α) of 60°. The maximum increase in Nusselt number and friction factor was recorded ase 6.32–6.12 folds of that of the smooth duct, respectively. The thermo-hydraulic performance parameter is found to be the best for the relative gap distance of 0.69 and the relative gap width of 1.0.

3.11 Dimpled surfaces
3.11.1 Transverse dimple roughness
Saini and Verma [33] explored the effect of roughness and operating parameters on heat transfer and friction factor in a roughened duct provided with dimple-shape roughness geometry. The investigation encompasses Reynolds number (Re) in the range of 2000-12,000, relative roughness height (e/D) 0.018-0.037 and relative pitch (p/e) 8-12. The Nu was found at e/D of 0.0379 and p/e of 10. Minimum value of f was found at e/D of 0.0289 and p/e of 10.

3.11.2 Protrusions roughness
Bhushan and Singh [34] analysed the effect of artificial roughness having protrusions as roughness geometry on the performance of air heater duct. Range of parameters were: relative short way length (S/e) 18.75–37.50, relative long

way length (L/e) 25.00–37.50, relative print diameter (d/D) 0.147–0.367, relative roughness height 0.03, aspect ratio 10 and Reynolds number 4000–20000. Maximum increase of Nu and f was 3.8 and 2.2 times, respectively as compared to smooth duct. Maximum enhancement in heat transfer coefficient was observed for relative short-way length of 31.25, relative long way length of 31.25 and relative print diameter of 0.294.

Lian *et al*. [35] provided hemispherical protrusion/ dimple asroughness and analyses the performance from the two aspects viz. optics and thermodynamics. This arrangement improves the efficiency. For the purpose of enhancing the absorption rate, the optical path shinning on the dimple and protrusion artificial roughness was simulated by using TRACEPRO software. The optical path of hemispherical and the spherical cap dimple was simulated too. It was found that the hemispherical dimple is the best in term of the optics. The investigation has encompassed Re ranging from 3000 to 11,000, e/Dh from 0.033 to 0.1 and p/e from 3.5 to 5.5.

3.11.3 Arc shaped dimple roughness

Yadav *et al*. [36] investigated the effect of heat features of turbulent flow of air through rectangular duct roughened by circular protrusions arranged in angular arc fashion. Experiments covered the Re of 3600-18,100, p/e 12-24, e/D_h 0.015-0.03 and arc angle of protrusions 45º-75º. The maximum increase in heat transfer and friction factor is 2.89 and 2.93 times as compared with smooth duct.

Sethi *et al*. [37] investigated the effect of artificial roughness on thermal characteristics in air heater duct having dimple shaped elements arranged in angular fashion (arc). Duct has W/H of 11, p/e 10–20, e/D_h 0.021–0.036, α 45–75° and Re 3600-18,000.

3.13 Roughness elements combination

3.13.1 Transverse and inclined ribs combination

Varun *et al*. [38] investigated the performance of a air heater duct provided with transverse and inclined ribs as artificial roughness. The range of parameters for the present study was taken as: Reynolds number (Re) 2000–14,000, p/e 3–8 and a fixed value of e/D of 0.030. The effective efficiency has been computed based on the experimentally determined values for the range of parameters considered. Further an attempt was made to optimize the thermal efficiency for the same system under similar conditions by Taguchi method.

3.13.2 Transverse rib groove combination

Jaurker *et al*. [39] studied the rib-grooved artificial that shows that Nusselt number can be further enhanced beyond that of ribbed duct while keeping the friction factor enhancement low. The experimental study covered Reynolds number range from 3000 to 21,000; relative roughness height 0.0181–0.0363; relative roughness pitch 4.5–10.0, and groove position to pitch ratio 0.3–0.7. The investigation clearly demonstrates that the heat transfer coefficient for rib-grooved arrangement is higher than that for the transverse ribs, whereas the friction factor is slightly higher for rib-grooved arrangement as compared to that of rectangular transverse ribs of similar rib height and rib spacing. The conditions for best performance have been determined. 3.13.3

3.13.3 Chamfered rib groove combination

Layek *et al*. [40] investigated thermal features of turbulent flow in a rectangular duct having periodic transverse chamfered rib-groove roughness. Re 3000–21,000; p/e of 4.5–10, chamfer angle of 5°–30°, relative groove position of 0.3–0.6 and relative roughness height of 0.022–0.04. The effect of roughness parameters on Nu and f are are compared with the square rib-grooved and smooth.

3.14 Wavy winglet roughness

Skullong *et al*. [41] studied heat transfer characteristics in a solar air heater channel using wavy grooves incorporated with pairs of trapezoidal-winglets (TW) placed on the absorber. The Reynolds numbers was in a range of 4500–22,000. The TW characteristics include three relative winglet-pitches (P_R) and five relative winglet height or blockage ratios (B_R) at a single attack angle of 45° whereas the wavy rectangular-groove parameters are three relative groove-pitch lengths (P_R) similar to the TW case but at a fixed width and height. It was found that the TW together with the groove provided considerable enhancement in heat transfer over the smooth channel. The TW alone gives much higher heat transfer but the groove yields considerably lower pressure drop. The combined groove and TW devices at a given B_R, perform the highest heat transfer and friction factor at smaller P_R and also provides considerably higher thermal performance than the single device acting alone. At $P_R = 1$, the compound device with $B_R = 0.28$ offers the highest heat transfer and friction factor while the one with $B_R = 0.24$ gives the maximum thermal performance.

Sawhney *et al*. [42] investigated the thermal features of a solar air heater duct roughened with wavy-up delta winglet vortex. Reynolds number encompassed in the range 4000–17300. The investigated parameters of wavy delta winglets were as follows: no of waves (ϕ): 3, 5, 7 and relative longitudinal pitch (P/H): 3, 4, 5 and 6, respectively at single angle of attack (α): 60°. The comparison of the staggered and inline arrangement reveals that the inline arrangement produces the higher Nusselt Number. The maximum Nusselt number enhancement was found to be 223% over the flat plate using a relative longitudinal pitch of 3 with five wave winglets at Reynolds number of 4000 with an increase in friction factor by 10.3 times. The thermohydraulic performance obtained for the configuration was 2.09.

4. Conclusions

Present article explored the latest developments in artificial roughness incorporated in the heating plate in solar air heater ducts. Effects of roughness parameters and rib arrangement used by various researchers on friction and heat transfer characteristics have been discussed. After the review, following conclusions are drawn.

1. Small diameter wire as artificial roughness considerably increases the heat transfer rate, but at the same time, it also leads to increase in friction factor.
2. It was reported by most of the studies on inclined rib, V ribs and W ribs that angle of attack of 60° gives better results.
3. The use of Multi V-ribs with gap provided maximum increase in friction factor and Nusselt number, followed by multi arc ribs with gap.
4. Gap provided in continuous V-ribs, Multi V-ribs, arc ribs, multi arc ribs to a greater extend increases the heat transfer rate and friction factor.

5. Dimples provided in the ribs were found to be hydraulically better because of low increment in friction factor as compared to increment in heat transfer rate.
6. Many geometries like combination of ribs with groove, metal grit, expanded metal mesh and L-shaped ribs needed machining process due to their complex designs.
7. Recently, roughness with wavy winglet has been incorporated with trapezoidal and delta shapes which give much higher heat transfer as compared to smooth geometry.

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