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A review on Types of Roughness Element Used in Solar Air Heater to Enhance Heat Transfer Coefficient

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ABSTRACT
Solar air heaters provides the efficient use of solar energy, which uses the absorber plate to absorb the incoming solar radiations, converting it to thermal energy at its surface, and transferring the thermal energy to the fluid flowing through the collector. The most common and effective way to improve the performance of the solar air heater is to provide artificial roughness elements on the underside of the absorber plate. For the enhancement of rate of heat transfer of flowing air in the duct of a solar air heater, by applying an artificial roughness on its surface is one of the very effective technique of solar air heater absorber plate, till now numbers of geometries of roughness element has been investigated and their effect on enhancement of heat transfer has been carried out. This paper is an attempt has been made to classify and review various study of roughness geometries used for creating artificial roughness.
Keywords: Absorber plate, Heat transfer enhancement ratio, Reynolds number, Solar air heater, V-shaped ribs

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I. INTRODUCTION

Solar energy, a renewable energy source, is most readily converted to heat using a heat exchanger called a solar collector. Solar collectors are usually water or air heaters. The output of the collector is fluid at an increased temperature. The solar air heater has an important place among solar heat collectors. With the recent trend of providing both heating cooling with solar energy, liquid heaters for high temperature operation have gained more popularity. As far as the ultimate application of heating air to maintain a comfortable environment is concerned, the solar air heater is most logical choice. Regarding artificial roughened absorber plate, many experimental investigated have been reported in literature by various authors.

II. CONCEPT OF ARTIFICIAL ROUGHNESS

Artificial roughness is basically a heat transfer enhancement technique by which thermo hydraulic performance of a solar air heater can be improved. The thermal efficiency of solar air heater is generally poor due to low heat transfer co-efficient between the absorber plate and the air flowing in to the duct due to the formation of laminar sub layer on the absorber plate which acts as heat transferring surface. So there is a need to break the laminar sub layer. Artificial roughness, provided on the underside of the absorber plate, creates local wall turbulence. Secondary recirculation flows further enhance the convective heat transfer. Due to low value of convective heat transfer coefficient, efficiency of flat plate solar air heater is low. Low value of convective heat transfer coefficient is due to presence of laminar sub layer that has to broken by applying artificial roughness of different geometry and to create turbulence which results in increase in heat transfer rate. However artificial roughness's result in high friction losses to more power require to flow the fluid. So turbulence has to create in a region very close to heat transferring surface. This is achieving by keeping height of roughness element small in comparison to duct dimension. The 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 pitch (p/e), relative roughness (e/Dh).

III. VARIOUS ROUGHNESS GEOMETRIES USED IN SOLAR AIR HEATER

3.1 Transverse Continuous Ribs

Prasad and Saini (1988) studied the effect of roughness and flow parameters such as relative roughness height (e/D) and relative roughness pitch (p/e) on heat transfer and friction factor. The type and orientation of roughness geometry used have been shown in Figure 1.They developed expressions for the heat transfer and friction factor for a fully turbulent flow. It was observed that maximum heat transfer occurred in the vicinity of reattachment points and reattachment of free shear layer does not occur if relative roughness pitch (p/e) is less than about 8 to 10.

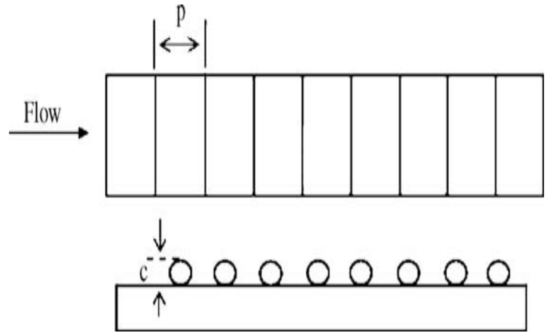

Fig: 1 Transverse continuous ribs. [Prasad and Saini (1988)]

3.2 Transverse Broken Ribs with Circular Cross-Section

Sahu and Bhagoria (2005) investigated the effect of 90° broken ribs on thermal performance of a solar air heater for fixed roughness height (e) value of 1.5 mm, duct aspect ratio (W/H) value of 8, pitch (p) in the range of 10–30 mm and Reynolds number (Re) range of 3000–12,000. Roughened absorber plate increased the heat transfer coefficient by 1.25 to 1.4 times as compared to smooth one under similar operating conditions. Corresponding to roughness pitch (p) value of 20 mm, maximum value of Nusselt number was obtained that decreased on the either side of this roughness pitch (p) value. Based on the experimental investigation, the thermal efficiency of roughened solar air heater was found to be in the range of 51%–83.5% depending upon the flow conditions. The geometry investigated has been shown in Figure 2.

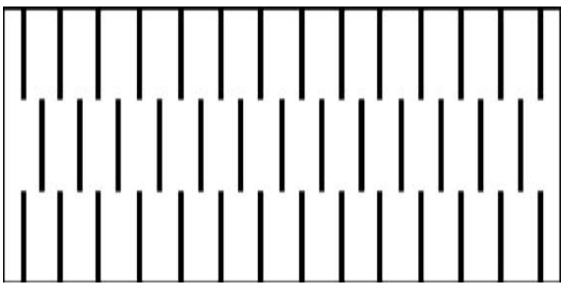

Fig: 2 Transverse broken ribs. [Sahu and Bhagoria (2005)]

3.3 Inclined Continuous Ribs

Gupta et al. [1997] experimentally investigated the effect of relative roughness height (e/d), inclination of rib with respect to flow direction and Reynolds number (Re) on the thermo-hydraulic performance of a roughened solar air heater for transitionally rough flow region (5 < e+ < 70). The roughness geometry investigated has been shown in Figure 3. It was reported that with increase in relative roughness height (e/d), the value of Reynolds number (Re) decreased for which effective efficiency was maximum.

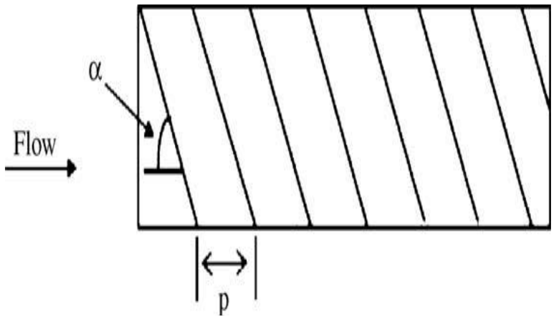

Fig: 3 Inclined continuous ribs. [Gupta et al. (1997)]

3.4 Expanded mesh metal

Saini and Saini (1997) carried out an experimental investigation to study the effect of wire mesh roughened absorber plate on heat transfer augmentation and friction characteristics of solar air heater as shown in Figure 4. The investigation considered relative longway length of mesh (L/e) in range of 25–71.87, relative shortway length of mesh (S/e) in range of 15.62–46.87, relative roughness height (e/D) in range of 0.12–0.039 and Reynolds number (Re) in range of 1900–13,000.

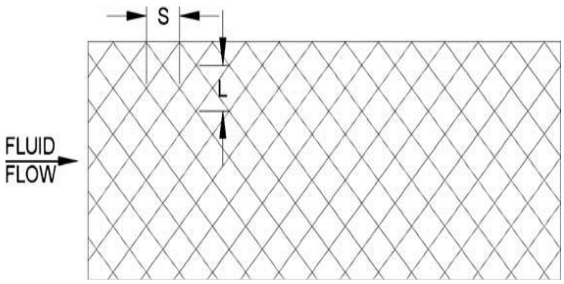

Fig: 4 Wire mesh roughness [Saini and Saini (1997)]

3.5 V-shaped ribs

Momin et al. (2002) experimentally investigated the effect of geometrical parameters of v-shaped ribs, shown in Figure 5, on heat transfer and fluid flow characteristics of rectangular duct of a solar air heater. The investigation covered a Reynolds number (Re) range of 2500–18,000, relative roughness height (e/D) range of 0.02–0.034

and angle of attack of flow (a) range of 30–908 for a fixed relative roughness pitch (p/e) value of 10. Rate of increase of Nusselt number was observed to be lower than the rate of increase of friction factor with an increase in Reynolds number (Re).

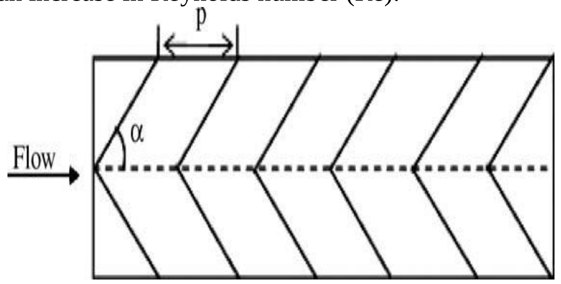

Fig: 5 V-shape ribs [Momin et al. (2002)]

3.6 Chamfered Ribs

Karwa et al. (1999) performed an experimental investigation of heat transfer and fiction for rectangular ducts, having aspect ratio (W/H) in the range of 4.8–12, and roughened with repeated integral chamfered ribs, as shown in Figure 6. The roughness parameters considered for the investigation were Reynolds number (Re) range of 3,000–20,000, relative roughness height (e/ D) range of 0.014–0.0328, relative roughness pitch (p/e) range of 4.5–8.5 and chamfer angle (Φ) varying from 15° to 18°. Stanton number and friction factor increased with increase in chamfer angle and attained maximum value corresponding to chamfer angle (Φ) value of 15°.

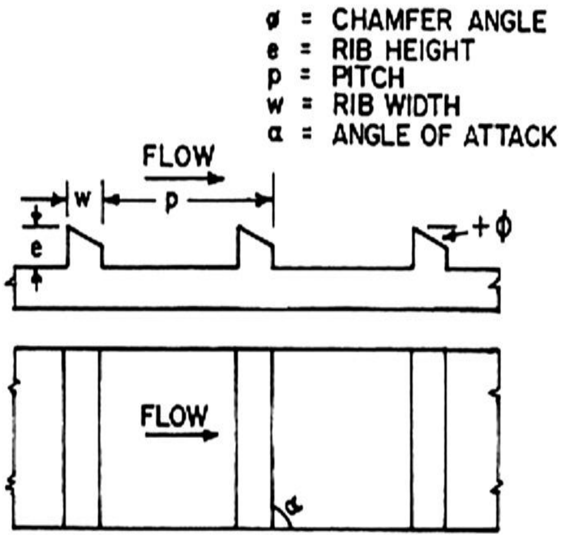

Fig: 6 Chamfered ribs [Karwa et al. (1999)]

3.7 Wedge Shaped Ribs

Bhagoria et al. (2002) experimentally studied heat transfer and flow characteristics in a solar air heater having absorber plate roughened with wedge shaped transverse integral ribs as shown in Figure 7. The investigation encompassed the Reynolds number (Re) range of 3,000–18,000, relative roughness height (e/D) range of 0.015–0.033 and rib wedge angle (F) range of 8°–12°. It was reported that Nusselt number and friction factor increased by 2.4 and 5.3 times over smooth duct in the range of parameters investigated. Statistical correlations for Nusselt number and friction factor were developed.

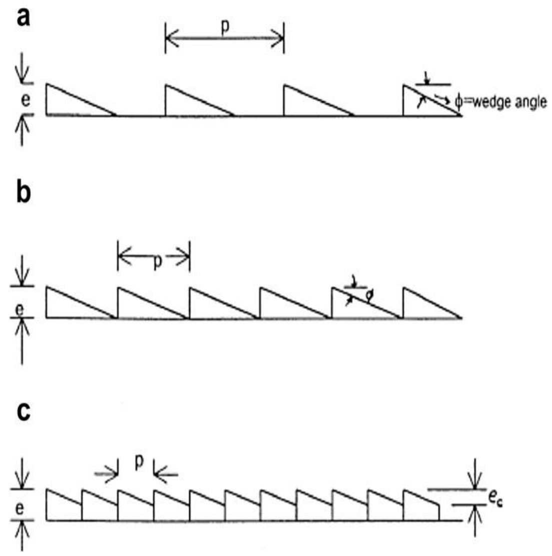

Fig: 7 Wedge shape ribs [Bhagoria et al. (2002)]

3.8 Arc Shaped Ribs

Saini and Saini (2008) studied the effect of arc shaped ribs on the heat transfer coefficient and friction factor of rectangular ducts with Reynolds number (Re), relative roughness height (e/D) and relative arc angle (a) varying from 2000 to 17,000, 0.0213 to 0.0422 and 0.3333 to 0.6666, respectively. It was reported that relative arc angle (a) had an opposite effect on heat transfer enhancement and friction factor. With decrease in relative arc angle (a) value, Nusselt number value increased while friction factor value decreased. Enhancement of Nusselt number and friction factor was reported to be of order 3.6 and 1.75 times respectively over smooth duct for relative arc angle (a) value of 0.3333 and relative roughness height (e/D) value of 0.0422. Based on the experimental results, correlations for Nusselt number and friction factor were developed. The geometry investigated has been shown in Figure 8.

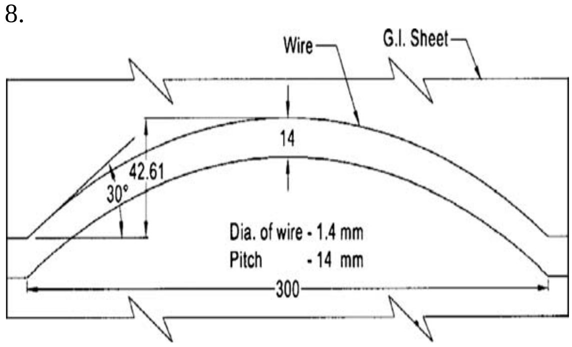

Fig: 8 Arc shape ribs [Saini and Saini (2008)]

3.9 Dimpled Surfaces

Saini and Verma (2008) studied the effect of roughness and operating parameters on heat transfer and friction factor in a roughened duct provided with dimple-shape roughness geometry for the range of Reynolds number (Re) from 2000 to 12,000, relative roughness height (e/D) from 0.018 to 0.037 and relative pitch (p/e) from 8 to 12. For the range of parameters investigated, Nusselt number was found to be maximum corresponding to relative roughness height (e/D) value of 0.0379 and relative roughness pitch (p/e) value of 10. For fixed value of relative roughness pitch (p/e) of 10, friction factor attained the maximum and minimum values corresponding to relative roughness height (e/d) values of 0.0289 and 0.0189, respectively. Correlations for Nusselt number and friction factor have been developed. The geometry investigated has been shown in Figure 9.

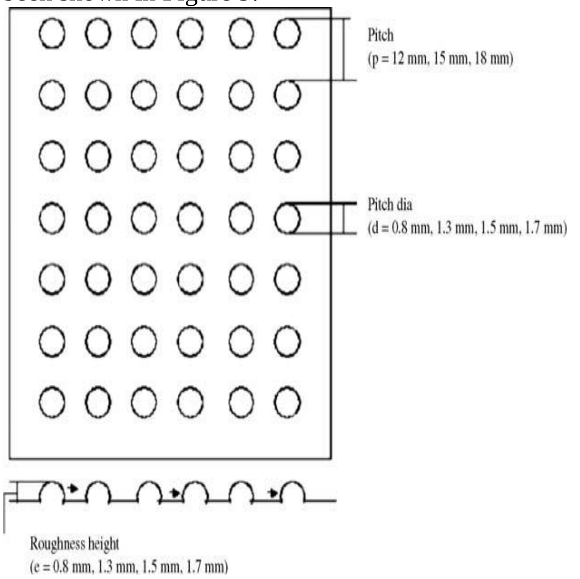

Fig: 9 Dimple shape ribs [Saini and Verma (2008)]

3.10 Metal Grit Ribs

Karmare and Tikekar (2007)experimentally investigated heat transfer and friction characteristics of a rectangular duct having absorber plate roughened with a defined grid of metal ribs of circular cross-section and the roughness geometry investigated has been shown in Figure 10. The investigation considered relative roughness height (e/D) range of 0.035–0.044, relative roughness pitch (p/e) range of 12.5–36, relative grit length (l/s) range of 1– 1.72 and Reynolds number (Re) range of 4000–17,000. Enhancement in Nusselt number was found to be 187% and the friction factor increased by 213% and optimum performance was observed for relative grit length (l/s) value of 1.72, relative roughness height (e/D) value of 0.044 and relative roughness pitch (p/e) value of 17.5 for the range of parameters studied. Based on the experimental results, correlations for Nusselt number and friction factor were developed.

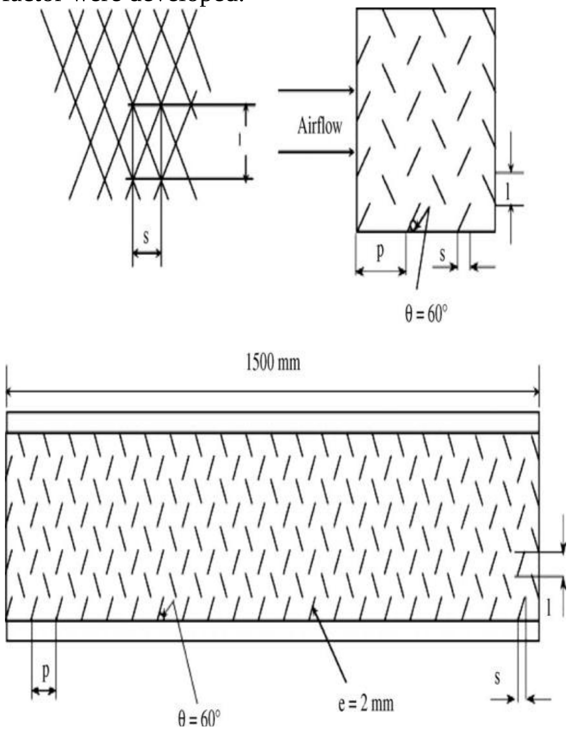

Fig: 10 Metal grit roughnesses [Karmare and Tikekar (2007)]

3.11 Discrete W-Shaped Ribs

Kumar et al. (2008) carried out an experimental investigation to determine the heat transfer distributions in solar air heater having its absorber plate roughened with discrete w-shaped ribs. The experiment encompassed Reynolds number (Re) range from 3000 to 15,000, rib height (e) values of 0.75 mm and 1 mm, relative roughness height (e/D) 0.0168 and 0.0225 and relative roughness pitch (p/e) of 10 and angle of attack (a) 458. Thermal performance of roughened solar air collector was compared with that of smooth one under similar flow conditions and it was reported that thermal performance of the roughened channel was 1.2–1.8 times the smooth channel for range of parameters investigated. Discretization was found to have significant effect on heat transfer enhancement. The geometry investigated has been shown in Figure 11.

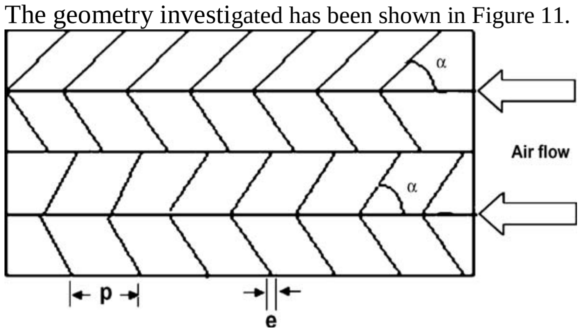

Fig: 11 discrete w-shape roughnesses [Kumar et al. (2008)]

3.12 Combination of Different Roughness Elements

Rib-Groove 1: Jaurker et al. (2006) experimentally investigated heat transfer and friction characteristics of rib-groove roughened rectangular duct as shown in Figure 12.The effect of relative roughness pitch (p/e), relative roughness height (e/D) and relative groove position (g/P) on the heat transfer coefficient and friction factor had been studied. The presence of rib-grooved artificial roughness yielded Nusselt number and friction factor up to 2.7 and 3.6 times respectively in comparison to smooth absorber plate. The maximum heat transfer occurred for a relative roughness pitch (p/e) of about 6 and relative groove (g/P) value of 0.4. Correlations for Nusselt number and friction factor were developed.

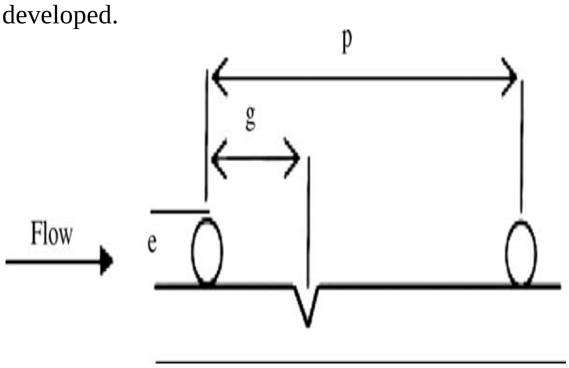

Fig: 12 Combination of transverse and groove roughness (Rib Groove 1) [Jaurker et al.(2006)]

Rib-Groove 2: Layek et al. (2007) carried out an experimental investigation to study heat transfer and friction for repeated transverse compound rib-groove arrangement on absorber plate of a solar air heater. Four relative rib-groove positions (g/P) values of 0.3, 0.4, 0.5 and 0.6 were investigated for fixed relative roughness height (e/D) and relative roughness pitch (p/e) values of 0.03 and 10 respectively. It was found that corresponding to relative roughness pitch (p/e) value of 10, relative groove position (g/P) value of 0.4 provided about 2.42 and 2.6 times increase in the Nusselt number and friction factor respectively for entire range of Reynolds number (Re) studied. Correlations for Nusselt number and friction factor were developed. The geometry investigated has been shown in Figure 13.

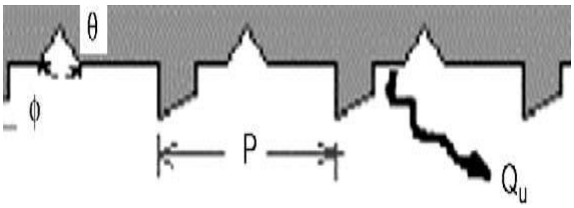

Fig: 13 Combination of chamfered and groove roughness(Rib Groove 2) [Layek et al. (2007)]

IV. THERMOHYDRAULIC PERFORMANCE

Lewis [1975] proposed that the enhancement in thermal performance can be evaluated on the basis of thermohydraulic performance parameter which incorporate both the thermal as well as hydraulic considerations and can be expressed as:

$$\eta = (St/Sts)^3/(f/fs)$$

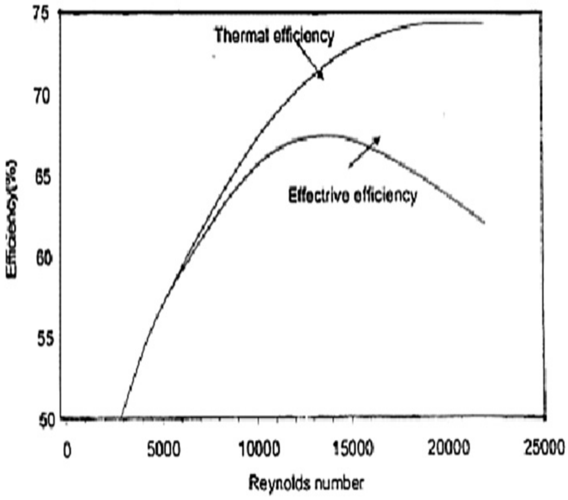

Fig: 14 Plot of Efficiency vs. Reynolds number [Kumar et al, 2012]

4.1 Comparison Thermo-hydraulic performance of roughened solar air heater duct

The study of heat and fluid flow characteristics of the roughened solar air heater ducts and the literature reveals that an enhancement in heat transfer is always accompanied with increased pumping power penalty due to corresponding increase in the friction factor. Therefore, it is essential to determine the geometry that will results in the maximum enhancement in heat transfer and minimum increase in friction factor, thereby lower power penalty. In order to achieve this objective of simultaneous consideration of thermal as well as hydraulic performance, Lewis [1975] proposed a thermohydraulic performance parameter known as efficiency parameter h, which evaluates the enhancement of heat transfer for same pumping power requirement and is defined as,

$$h = (St/Sts)/(f/fs)^{1/3}$$

Thermo-hydraulic performance has been compared using the correlations of heat transfer and friction factor for different roughness geometries. Comparison thermohydraulic performance of different roughness geometries has been shown in Figure 15. Figure 15 shows the variation of Reynolds number used in solar air heaters ducts. Amongst the entire solar air heater ducts roughness geometries considered, Multi v-shaped rib geometry has the best thermohydraulic performance as compare to other roughness geometries as described by Kumar et al., 2012.

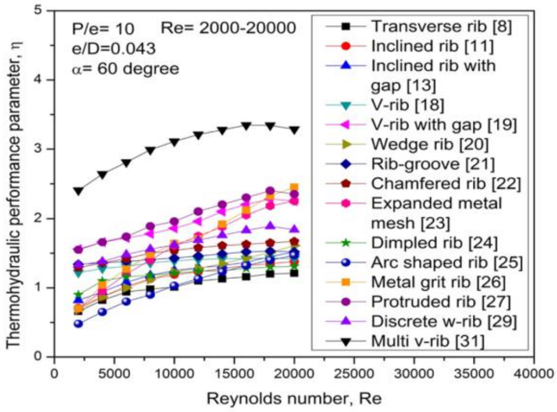

Fig: 15 Comparison of thermohydraulic performance [Kumar et al. 2012]

V. CONCLUSIONS

It can be concluded from the present review substantial enhancement in the heat transfer can be achieved with little penalty of friction. Various investigators have developed correlations for heat transfer and friction factor for solar air heater ducts having artificial roughness of different geometries. These correlations can be used to predict the thermal as well as thermohydraulic performance of solar air heaters having roughened ducts.

In the present study, a review of roughness element geometries has been carried out and thermo-hydraulic performance of solar air heaters roughened with these roughness element geometries has been compared in order to determine the best performing roughness geometry. From the review, following conclusions are drawn:

1. At low air mass flow rates corresponding to high values of temperature rise parameter ΔT/I, solar air heaters with smaller duct depth or high L/H values give better thermo-hydraulic performance while at high flow rates (corresponding to the low temperature rise parameter), the pumping power requirements are significant and solar air heaters with large duct depth or low L/H values are better from the thermo-hydraulic performance consideration.[Karwa, 1999]
2. Nusselt number increases whereas friction factor decreases with increase of Reynolds number. Values of friction factor and Nusselt number are higher as compared to those for smooth absorber plate. This is due to change in flow characteristics because of roughness that causes flow separation, reattachments and generation of secondary flow.[Lanjevar et al. 2011]
3. Roughened solar air heaters are thermohydraulically advantageous for lower Reynolds numbers, whereas a smooth solar air heater will perform better thermohydraulically, although the thermal efficiency of a roughened solar air heater may be more than that of a smooth heater, beyond a certain limiting value of Reynolds number; this limiting Reynolds number has been found to lie in the range of 13,000-l 9,000, the actual value depending upon the actual relative roughness height and insolation. [Gupta and Saini 1997]
4. For discrete multi V-ribs the maximum value of Nusselt no. (Nu) and Friction factor(f) occur at P/e of 8.0(where as for transverse ribs optimum p/e is 10), and these decrease on the both sides of this pitch. Similar trend is observed for angle of attack α, relative gap distance d/w (or Gd/Lv) and relative gap width (g/e) with maxima of both Nu and f occurring at 60o, 0.65 and 1.0 respectively.[Singh et al. 2011]
5. For continous multiple V-ribs the maximum heat transfer enhancement has been found to occur for a relative roughness width (W/w) value of 6 while friction factor attains maximum value for relative roughness width (W/w) value of 10.[Hans et al., 2010]
6. In artificially roughened solar air heaters, there is lot of scope for use of flow visualization techniques in order to analyze flow and heat transfer enhancement processes.

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