A review of solar air heaters using roughness geometry

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ABSTRACT

The use of an artificial roughness on a surface is an effective technique to enhance the rate of heat transfer to fluid flow in the duct of a solar air heater. Experimental investigations appropriate to distinct roughness geometries shows that the enhancement in heat transfer is accompanied by considerable rise in pumping power Several studies have been carried out to determine the effect of different roughness element geometries on heat transfer and friction in solar air heaters. The objective of this paper is to review various studies, in which different artificial roughness elements are used to enhance the heat transfer rate with little penalty of friction. Heat transfer coefficient and friction factor correlations developed by various investigators for artificially roughened ducts of solar air heaters have also been reported in the present article. The effects of various rib parameters on heat transfer and fluid flow processes are also discussed.

Keywords*: Solar air heater, Artificial Roughness, Roughness Geometry, Reynolds Number, Friction factor, Nusselt Number.*

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1. Introduction

Energy has played an increasingly important role in world wide progress and industrialization. The rapid increase in the population and desire for a higher standard of living has led to very sharp increase in the consumption of conventional energy resources. Therefore only conventional sources of energy e.g. oil, coal and natural gas are insufficient to meet the growing demand of energy required in future as these sources are limited and exhaustible. The alternative sources of energy like solar, biomass, wind, hydro need to be exploited to meet the growing demand of energy.

Solar energy has the greatest potential among all the sources of renewable energy and even a small amount of this renewable source of energy is sufficient to meet the total energy demand of the world. If we can use 5% of this energy, it will be 50 times of the energy requirement of the world. The rapid increase of energy usage and the fast depletion of fossil fuels have made it mandatory to look for alternative energy resources to meet the energy demands of the future. Among the various alternative energy resources, solar energy is the most promising. It is most abundant, pollution free and inexhaustible form of energy available on earth to meet growing energy needs with a minimum of adverse environmental risks.

In today's climate of growing energy needs and increasing environmental concern, alternatives to the use of non-renewable and polluting fossil fuels have to be investigated. One such alternative is solar energy.

Solar energy is quite simply the energy produced directly by the sun and collected elsewhere, normally the Earth. The sun creates its energy through a thermonuclear process that converts about 650, 000, 0001 tons of hydrogen to helium every second. The process creates heat and electromagnetic radiation. The heat remains in the sun and is instrumental in maintaining the thermonuclear reaction. The electromagnetic radiation (including visible light, infra-red light, and ultra-violet radiation) streams out into space in all directions.

Only a very small fraction of the total radiation produced reaches the Earth. The radiation that does reach the Earth is the indirect source of nearly every type of energy used today. The exceptions are geothermal energy, and nuclear fission and fusion. Even fossil fuels owe their origins to the sun; they were once living plants and animals whose life was dependent upon the sun.

Solar energy has been used since prehistoric times, but in a most primitive manner. Before 1970, some research and development was carried out in a few countries to exploit solar energy more efficiently, but most of this work remained mainly academic. After the dramatic rise in oil prices in the 1970s, several countries began to formulate extensive research and development programmers to exploit solar energy.

Nomenclature

A_p	Absorber plate area, m^2	T_i	Inlet air temperature, °C
A_{duct}	Flow Cross-section area=WH, m^2	T_o	Outlet air temperature, °C
A_o	Throat area of orifice plate, m^2	P	Rib pitch, m
A_s	Area of smooth plate, m^2	P/e	Relative roughness pitch
e	Rib height ,mm	T_{pav}	Mean plate temperature, °C
e/Dh	Relative roughness height	T_{fav}	Average temperature of air, °C
f	Friction factor	Re	Reynolds number
W	Duct width, m	W/H	Channel aspect ratio
H	Duct depth, m	V	Velocity of air
K	Thermal conductivity of air, W/mK	d/W	relative gap position
m	Mass flow rate, kg/s	ΔPo	Pressure drop in duct, Pa
C_d	Coefficient of discharge (0.62)	Nu	Nusselt number of roughened duct
C_p	Specific heat of air, KJ/kg K	Nus	Nusselt number of smooth duct
D_o	Diameter of the orifice of the orifice plate		
D_p	Inside diameter of the pipe	Greek symbols	
h	Convective heat transfer coefficient, W/m^2K	α	rib angle of attack,degree
g	Gap width, m	ß	ratio of orifice diameter to pipe diameter
g/e	Relative gap width	η	thermo-hydraulic performance parameter
Δh	Difference of height on manometer fluid	ρ	density of air, kg/ m^3
I	Heat flux .W/m^2	ρ	density of manometric fluid,kg/ m^3

Energy demand analysis and forecasting

A reasonable knowledge of present and past energy consumption and future demand are primary requirements for energy planning. An accurate energy demand forecasts is primarily required to enable timely, reasonable and reliable availability of energy supplies to ensure proper functioning of the economy. Errors in demand projections lead to shortages of energy, which may have serious repercussions on economic growth, and development of a nation.

Demand forecasts can be made either on the basis of statistical evaluation and projections of past consumption or on the basis of specific micro studies. Energy demand models are used to aid planners and policy makers in evaluating past experiences, studying the impact of future policies and forecasting demand for planning purposes.

Solar Air Heater

Solar air heater is one of the basis equipment through which solar energy is converted into thermal energy. The solar air heater has an important place among solar heat collectors. It can be used as sub-systems in many systems meant for the utilization of solar energy. Possible applications of solar air heaters are drying or curing of agricultural products, space heating for comfort regeneration of dehumidifying agents, seasoning of timber, curing of industrial products such as plastics. When air at high temperature is required the design of a heater becomes complicated and very costly. As far as the ultimate application for heating air to maintain a comfortable environment is concerned, the solar air heater is the most logical choice. In general solar heaters are quite suitable for low and moderate temperatures application as their design is simple.

Direct use of air circulated through the solar air heater as the working substance also reduces the number of components required in the system. Solar heater air could be used more effectively for drying under controlled condition. Solar heater supplying hot air to a conventional drier or special design combining the drying cabinet in one package has cost and efficiency advantage problems, which may be difficult and costly to overcome. The cost of the air heater could be substantially lower than the liquid systems. Higher pressures experienced in liquid heaters necessitate the use of heavy gauge sheet metal or tubes. The air heaters could be designed using less material even some scrape of no commercial value.

Solar air heater is a device to produce hot air for any industrial or farmer level drying applications by using freely available SUN, without using any conventional fuels like electricity, diesel, LPG, firewood, coal, etc., But It could be coupled with an existing conventional drying systems like Tray driers, Tunnel Driers, Conveyor Drier, FBD drier and bin drier operated by conventional fuels to save fuel consumption.

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. Flows from the core to the surface reduce the thickness of boundary layer and secondary flows from the surface to the core flow promote mixing. Energy for creating turbulence has to come from a blower and excessive turbulence results in greater power Therefore, it is desirable that the turbulence must be created only in the region very close to the heat transferring surface, so that the power requirement may be reduced.

This can be done by keeping the height of the roughness element small in comparison with the duct dimension. Although there are several parameters that characterize the arrangement and shape of the roughness are
1. Relative roughness pitch (p/ e): Relative roughness pitch (p/ e) is defined as the ratio of distance between two consecutive ribs and height of the rib.
2. Relative roughness height (e/ D): Relative roughness height (e/ D) is the ratio of rib height to equivalent diameter of the air passage.
3. Angle of attack (α): Angle of attack is inclination of rib with direction of air flow in duct.
4. Aspect ratio: It is ratio of duct width to duct height. This factor also plays a very crucial role in investigating thermo-hydraulic performance.
5. *Shape of roughness element*: The roughness elements can be two-dimensional ribs or three dimensional discrete elements, transverse or inclined ribs or V-shaped continuous or broken ribs with or without gap. The roughness elements can also be arc-shaped wire or dimple or cavity or compound rib-grooved. The common shape of ribs is square but different shapes like circular, semi-circular and chamfered have also been considered to investigate thermo hydraulic performance. The different types of roughness elements and the parameters that characterize the roughness element geometry and influence the performance are given in Table 1.

Table 1.

Rib geometries and important parameters

S.No.	Investigators	Rib geometry	parameter
1	Prasad and Mullick	Transverse wire rib	e/D=0.019,P/e=12.7
2	Gupta	Inclined wire rib	e/D=0.023,P/e=10
3	Momin	V-shaped rib	e/D=0.032,P/e=10
4	Karwa	Chamfered rib	e/D=0.0441,P/e=4.58
5	Jaurker	Rib-grooved roughness	e/D=00363,P/e=6
6	Bhagoria	Transverse wedge	e/D=0.033,P/e=7.57

		shaped rib	
7	Saini and Saini	Arc shaped rib	e/D=0.0422,P/e=10
8	Karmare and Tikekar	Metal grit rib	e/D=0.044,P/e=17.5
9	Pawar	Wedge shaped rib-groove rougheness	e/D=0.033,P/e=8
10	Aharwal	60° inclined square rib with gap	e/D=0.037,P/e=8
11	Arvind kumar	Discrete W-shaped rib	e/D=0.0388,P/e=10
12	Atul	W-shaped(up and down rib)	e/D=0.0337,P/e=10
13	Sukhmeet	V-down rib having gap	e/D=0.043,P/e=8
14	Bopche and Tandale	Inverted U-shaped turbulators	e/D=0.03985,P/e=6.67
15	Anil kumar	Multi V-shaped ribs with gap	e/D=0.043,P/e=10

Effect of rib parameters on flow pattern

There are several parameters that characterize the roughness elements, but for solar air heater the most preferred roughness geometry is repeated rib type, which is described by the dimensionless parameters viz. relative roughness height e/D,relative roughness pitch P/e and angle of attack (α) etc. The friction factor and Stanton/Nusselt number are function of these dimensionless parameters, assuming that the rib thickness is small relative to rib spacing or pitch. The effect of various parameters of artificial roughness geometry on heat transfer and friction characteristics based on the literature is given below:

Effect of rib

The most important effect produced by the presence of a rib on the flow pattern, is the generation of two flow separation regions, one on each side of the rib. The vortices so generated are responsible for the turbulence and hence the enhancement in heat transfer as well as in the friction losses takes place.**Fig.1.** shows the effect of rib height on laminar sub layer.

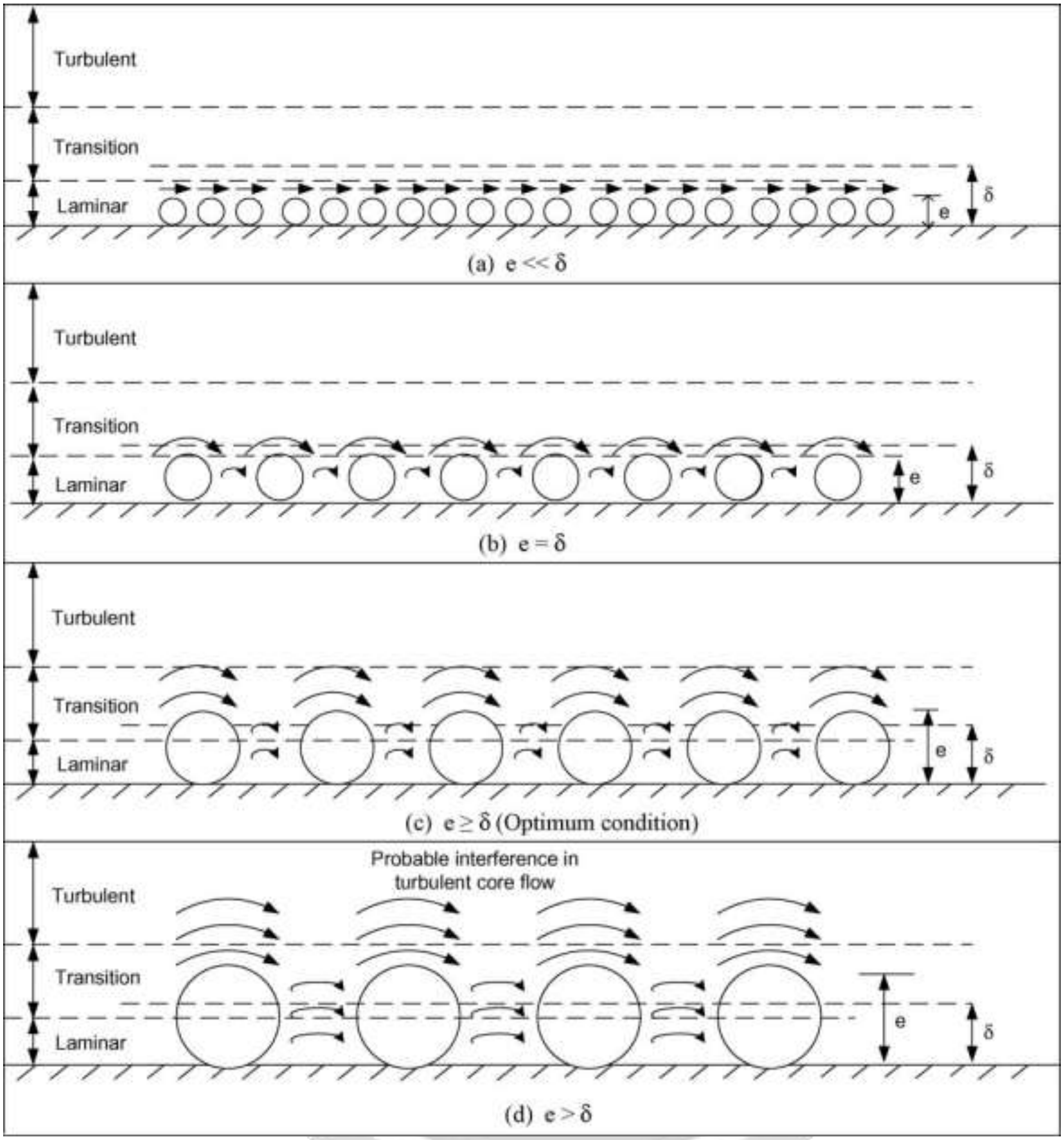
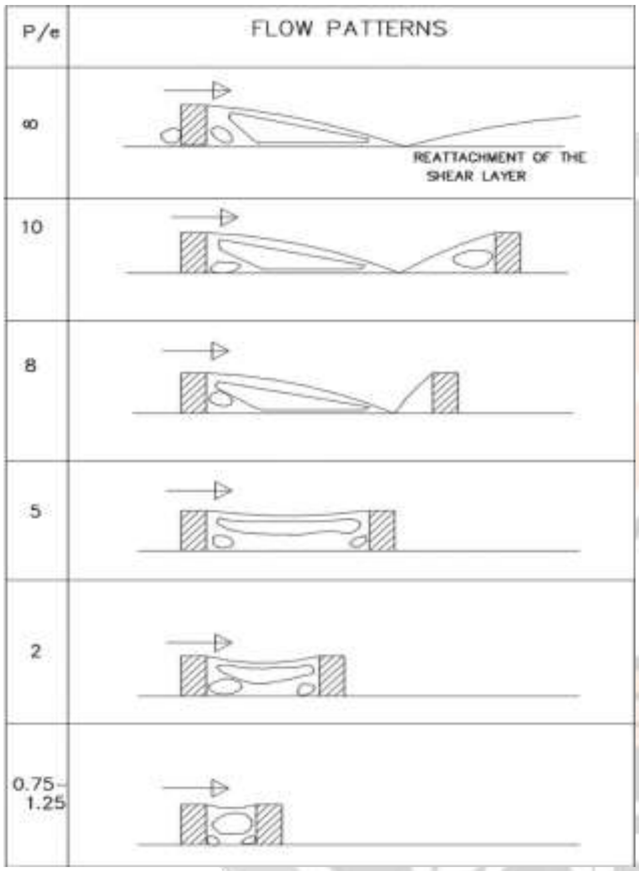


Fig.1. Effect of rib height on laminar sub layer

Effect of relative roughness pitch(P/e)

Fig.2. shows the flow pattern downstream of a rib with variation in relative roughness pitch .Due to flow separation downstream of a rib, reattachment of the shear layer does not occur for a pitch ratio of less than about 8.Maximum heat transfer has been found to occur in the vicinity of a reattachment point.It is reasonable to accept that a similar effect can be produced by decreasing the relative roughness pitch (P/e) for a fixed relative roughness height (e/D).For relative roughness pitch considerably less than about 8, the reattachment will not occur at all resulting in the decrease of heat transfer enhancement .However, an increase in pitch beyond about 10 also results in decreasing the enhancement. For larger relative roughness pitch at a P/e value of about 10 the reattachment point is reached and a boundary layer begins to grow before the succeeding rib is encountered. However, enhancement decreases with an increase in P/e beyond about 10.



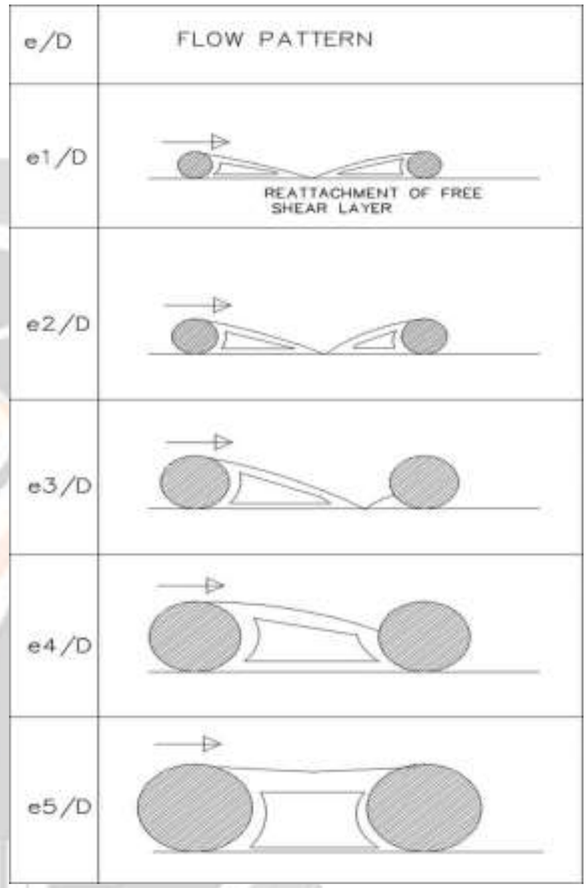


Fig.2. Flow pattern downstream the roughness as a function of e/D

Fig.3. Flow pattern the roughness as a function of P/e

Effect of relative roughness height(e/D)

Fig.3.shows the pattern downstream of a rib with variation in relative roughness height. The enhancement of heat transfer coefficient depends on the flow rate a and relative roughness height. As the relative roughness height increase, both the friction factor and nusselt number increase. The rate of increase of average friction factor increase whereas the rate of increase of average nusselt number decreases, with the increase of relative roughness height .At very low Reynolds number the effect of e/D is in significant on enhancement of nusselt number. If the roughness height is less than thickness of laminar sub-layer then there will not be any enhancement in heat transfer, hence the minimum roughness height should be of same order as thickness of laminar sub-layer at the lowest flow Reynolds number. The maximum rib height should be such that the fin and flow passage blockage effects are negligible.

Effect of rib cross-section

Rib cross-section affects the size of separated region and level of disturbance in the flow. The friction factor is less for circular cross-section ribs in comparison to that of rectangular or square cross-section ribs on account of reduction in the size of separated region. This results in decrease in inertial losses and increase in skin friction, thereby, decreasing the friction factor. As the size of separated region diminishes, level of disturbance in flow also decreases which affects the heat transfer adversely. Another possible factor contributing to the Nusselt number decrease is the reduction in heat transfer surface area associated with circular cross-section ribs.

Effect of inclination of rib

Apart from the effect of rib height and pitch, the parameter that has been found to be most influential is the angle of attack of the flow with respect to the rib position .As the angle of attack decrease, the friction factor reduces rapidly. However, there is marginal decrease in nusselt number with change in angle of attack from 90° to 45°. Span wise counter rotating secondary flows created by angling of the rib, appear to be responsible for the significant span wise variation of heat transfer coefficient. It is pointed out that whereas the two fluid vortices immediately upstream and downstream of a transverse rib are essentially stagnant relative to the mainstream flow which raises the local fluid temperature in the vortices and wall temperature near the rib resulting in low heat transfer. The vortices in the case of angled ribs move along the rib so subsequently join the main stream, the fluid entering near the leading end of rib and coming out near the trailing end as shown in Fig.These moving vortices therefore bring in cooler channel fluid in contact with leading end raising heat transfer rate while the trailing end heat transfer is relatively lower. This phenomenon therefore results in strong span wise variation of heat transfer.

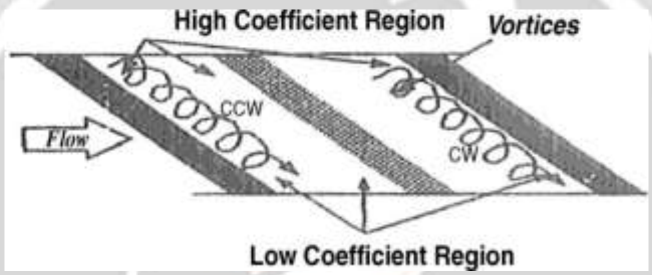


Fig.4.Effect of inclined rib

Effect of width and position of gap in continuous inclined rib

With the introduction of a gap in a rib, secondary flow along the rib joins the main flow to accelerate it, which in turn, energizes the retarded boundary layer flow along the surface resulting in enhancement of heat transfer. Position of gap with respect to leading and trailing edge has a considerable effect on heat transfer enhancement. Position of the gap near the trailing edge, results in more contribution of secondary flow in energizing the main flow through the gap and recirculation loop in the remaining part of the rib, thereby, increasing the heat transfer rate as shown in Fig

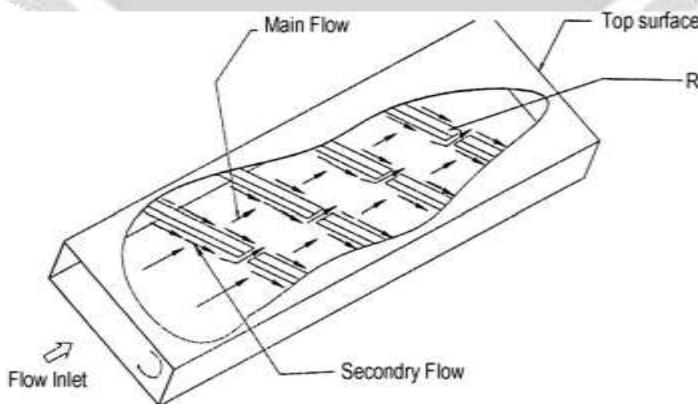


Fig.5. Effect of width and passion of gap in broken inclined rib

Effect of a groove between the two ribs

The concept of combined turbulence promoters comprising groove between the ribs was examined. It is interesting to see if the surface with compound roughness(rib plus grooves) can perform better than the surface with single roughness(rib only).It is well known that ribs break the viscous sub-layer and create local wall turbulence, resulting in enhanced heat transfer. The addition of a groove between two adjacent rib may induce vortices in and around the grooves, which may further enhance the heat transfer on the flat wall portion between the ribs. Therefore, the combined rib and groove turbulence promoters may produce higher heat transfer than that for the only rib promoters.

Effect of V-shaping of rib

The possibility of further enhancing the wall heat transfer by the use of V-shaped ribs is based on the observation of the creation of secondary flow cell due to angling of the rib resulting in a region of higher heat transfer near the leading end. By splitting the long angled rib into a V-shape to form two leading ends and a single trailing end (apex of V), a much larger (about double) region of high heat transfer is produced. It is infect the formation of two secondary
flows cells instead of one as in the case of transverse rib that results in higher overall heat transfer in the case of V-shaped ribs.

Effect of discretizing of V-shaped ribs
The v-shaped ribs along with staggered rib pieces in between further increase the number and area of heat transfer regions. Additional rib parameters related to the size and positioning of rib pieces (length ratio, B/S, segment ratio, S'/S and staggering ratio, P'/P) with respect to main rib produce complex interaction of secondary flow.

Effect of rib chamfering
Chamfering of the rib decreases the reattachment length by deflecting the flow and to reattach it nearer to the rib. The decrease in reattachment length permits to organize the ribs more closely. Chamfering of the rib also increases the shedding of vortices generated at the rib top that results in increase turbulence. The optimum chamfering angle on the basis of thermodynamically performance has been reported equal to 15–18. For higher chamfer angle flow separates from the rib top surface and generates boundary layer, which decreases the heat transfer. The friction factor increases monotonously due to the creation of vortices.

5.Roughness geometries used in solar air heaters

Heat transfer coefficient has been significantly enhanced by providing artificial roughness on absorber plate surface exposed to air which may be created, either by roughening the surface randomly with a sand grain/sand blasting or by use of regular geometric roughness. The use of artificial roughness in solar air heaters owes its origin to several investigations carried out in connection with the enhancement of heat transfer in duct flow, nuclear reactors, cooling of turbine blades and electronic components. As in solar air heater the solar radiation is absorbed by absorber plate, which is the main heat transfer surface; therefore, the solar air heaters are
modeled as a rectangular channel having one rough wall and three smooth walls. This makes the fluid flow and heat transfer characteristics distinctly different from those found in the case of channel with two opposite roughened walls, roughened annular and circular tubes Instead of relative roughness pitch, relative roughness height and angle of attack, shapes of various roughness elements also influence the heat transfer coefficient and friction factor. Different shapes of roughness elements are discussed as below:

5.1 Transverse continuous ribs

Prasad and Saini investigated the effect of relative roughness height (e/D) and relative roughness pitch (p/e) on heat transfer and friction factor. The type and orientation of the geometry is shown in Fig.6. It has been observed that increase in the relative roughness height results in a decrease of the rate of heat transfer enhancement although the rate of increase of friction factor increases. Increase in the relative roughness pitch results in a decrease in the rate of both heat transfer and friction factor. The maximum enhancement in Nusselt number and friction factor were as 2.38 and 4.25 times than that of smooth duct respectively.
Verma and Prasad [58] carried out an outdoor experimental investigation for thermo hydraulic optimization of the roughness and flow parameters for Reynolds number (Re) range of 5000– 20,000, relative roughness pitch (p/e)

range of 10–40 and relative roughness height (e/D) range of 0.01–0.03. The optimal value of roughness Reynolds number (e+) was found to be 24 and corresponding to this value, optimal thermo hydraulic performance was reported to be 71%. Heat transfer enhancement factor was found to vary between 1.25 and 2.08 for the range of parameters investigated. Correlations for heat transfer and friction factor were developed.

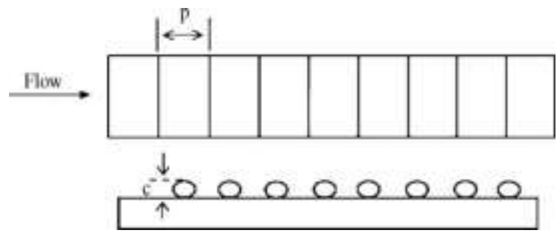


Fig.6. Transverse continuous ribs

5.1.2. Ribs of rectangular cross-section

Karwa experimentally investigated the effect of repeated rectangular cross-section ribs on heat transfer and friction factor for duct aspect ratio (W/H) range of 7.19–7.75, relative roughness pitch (p/e) value of 10, relative roughness height (e/D) range of 0.0467–0.050, Reynolds number (Re) range of 2800–15,000 as shown in Fig. It was explained that vortices originating from the roughness elements beyond the laminar sub-layer were responsible for heat removal as well as increase in friction factor. The enhancement in the Stanton number was reported to be 65–90% while friction factor was found to be 2.68–2.94 times over smooth duct.

5.2.Transverse broken ribs with circular cross-section

Sahu and Bhagoria investigated the effect of 90°broken ribs as shown in Fig.7, on thermal performance of a solar air heater for fixed roughness height (e) value of 1.5 mm, Relative
roughness height (e/D) value of 0.0338, 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. It was found out that the maximum Nusselt number attained for roughness pitch of 20 and decreased with an increase in
roughness pitch. Roughened absorber plates increased the heat transfer coefficient by 1.25–1.4 times as compared to smooth rectangular duct under similar operating conditions at higher
Reynolds number. Based on experimentation it was concluded that the maximum thermal efficiency of roughened solar air heater was to be of the order of (51–83.5%) depending upon the flow conditions.

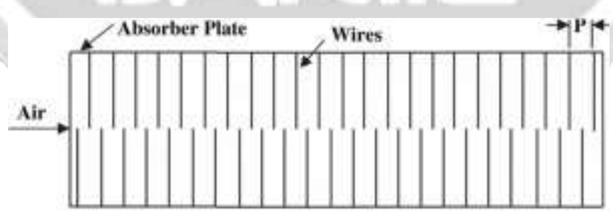


Fig.7. Transverse broken ribs

5.3. Inclined continuous ribs

Gupta investigated the effect of relative roughness height, angle of attack and Reynolds number on heat transfer and friction factor in rectangular duct having circular wire ribs on the absorber plate. The orientation of the geometry was as shown in Fig. 8. It was found that the heat transfer coefficient in roughened duct could be improved by a factor up to 1.8 and the friction factor had been found to increase by a factor up to 2.7 times of smooth duct. The maximum heat transfer coefficient and friction factor were found at an angle of attack of 60°and 70° respectively in the range of parameters investigated. The thermo-hydraulic performance of roughened surfaces had been found best corresponding relative roughness height e/D of 0.033 and the Reynolds number corresponding to the best thermo-hydraulic performance were around 14,000 in the range of parameters investigated.

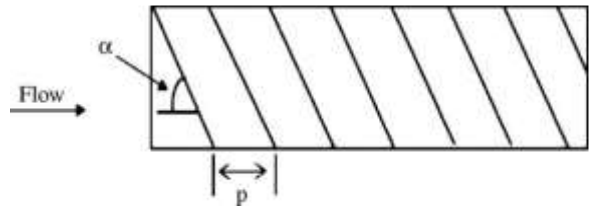


Fig.8. Inclined continuous ribs

Aharwal,Saini,Gandhi done this experiment to present the experimental investigation of heat transfer and friction factor characteristics of a rectangular duct roughened with repeated square cross-section split-rib with a gap, shown in Fig.9 on one broad wall arranged at an inclination with respect to the flow direction. The duct has a width to height ratio (W/H) of 5.84, relative roughness pitch (P/e) of 10,relative roughness height (e/Dh) of 0.0377, and angle of attack (α) of 60˚. 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 heat transfer and friction characteristic of this roughened duct has been compared with those of the smooth duct under similar flow condition. The effect of gap position and gap width has been investigated for the range of flow Reynolds numbers from 3000 to 18,000.In this investigation it was found that a gap in the inclined rib arrangement enhances the heat transfer and friction factor of the roughened ducts. The increase in Nusselt number and friction factor is in the range of 1.48–2.59 times and 2.26–2.9 times of the smooth duct, respectively, for the range of Reynolds numbers from 3000 to 18,000. The maximum values of Nusselt number and friction factor were observed for a gap in the inclined repeated ribs with a relative gap position of 0.25 and a relative gap width of 1.0.

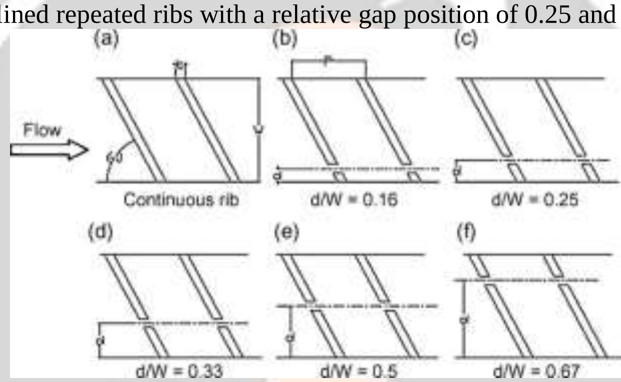


Fig.9 .Inclined rib with gap

5.4 V-shaped ribs

Momin experimentally investigated the effect of geometrical parameters of V-shaped ribs on heat-transfer and fluid flow characteristics in rectangular duct of solar air heater. The investigated geometry was as shown in Fig.10 . The investigation covered Reynolds number range of 2500–18,000, relative roughness height of 0.02–0.034 and angle of attack of flow (a) of 30–90_ for a fixed relative pitch of 10. For this geometry it was observed that the rate of increase of Nusselt number with an increase in Reynolds number is lower than the rate of increase of friction factor. The maximum enhancement of Nusselt number and friction factor as result of providing artificial roughness had been found as 2.30 and 2.83 times to smooth surface respectively for an angle of attack of 60°. It was also found that for relative roughness height of 0.034 and angle of attack of 60°, the V-shaped ribs enhance the value of Nusselt number by 1.14 and 2.30 times over inclined ribs and smooth plate respectively. It was concluded that V-shaped ribs gave better heat transfer performance than the inclined ribs for similar operating conditions.

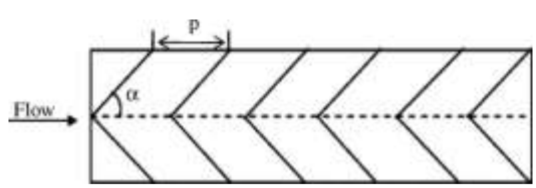


Fig.10. V-shape ribs

Muluwork compared the thermal performance of staggered discrete V-apex up and down with corresponding transverse staggered discrete ribs as shown in Fig.11. The relative roughness length ratio (g/p) had been considered as dimensionless geometric parameter of roughness element to compare three different configurations. It was observed that the Stanton number increases with the increase of relative roughness length ratio. The Stanton number for V-down discrete ribs was higher than the corresponding V-up and transverse discrete roughened surfaces. The Stanton number ratio enhancement was found 1.32–2.47 in the range of parameters covered in the investigation .It was also observed that the friction factor increases with an increase in the relative roughness length ratio. Further for Stanton number, it was seen that the ribbed surface friction factor for V-down discrete ribs was highest among the three configurations investigated.

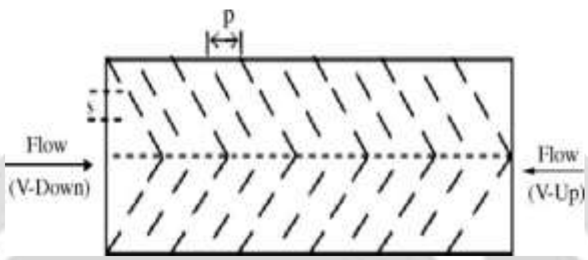


Fig.11. Discrete V-shape ribs

Sukhmeet experimentally investigated the heat and fluid flow characteristics of rectangular duct having its one broad wall heated and roughened with periodic 'discrete V-down rib' as shown in Fig.12.The experiment encompassed Reynolds number (Re) from 3000-15000 with relative gap width (g/e) range of 0.5-2.0, relative gap position (d/w) range of 0.20-0.80, relative roughness
pitch (P/e), angle of attack (α) and relative roughness height (e/D) range of 4-12, 30°-75° and 0.015-0.043 respectively. The maximum enhancement of Nu and f for the roughened duct in comparison to that for smooth duct was found to be 3.04 and 3.11 folds respectively, for the investigated range of parameters. The maximum value of Nu and f occur at P/e of 8.0, and these decrease on the both sides of this pitch. Similar trend was observed for a, d/w and g/e with maxima of both Nu and f occurring at 60°, 0.65 and 1.0 respectively. Statistical correlations for Nu and f were developed as function of Re and rib roughness parameters.

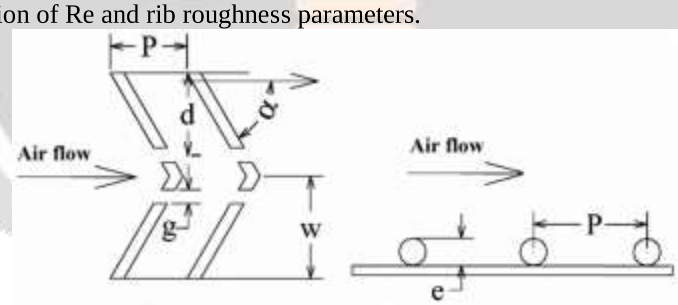


Fig.12. Discrete V- down rib

5.4 W-shaped ribs

Lanjewar, Bhagoria and Sarviya carried out this experiment to study heat transfer, friction characteristics and thermo hydraulic performance of roughened absorber plate in solar air heater by using W-shape rib roughness, the roughened wall being heated while the remaining three walls insulated shown in Fig.13. The roughened wall has relative roughness height (e/Dh) 0.018, relative roughness pitch (p/e) 10, rib height 0.8 mm, angle of attack in the range of 30°-60° and duct aspect ratio (W/H) 8. The air flow rate corresponds to Reynolds number between 2300-14000. It was reported that the enhancement in Nusselt number over the smooth duct was 32-92%, 31-81% and 9-56% for 60º, 45° and 30° respectively. Friction factor ratios for these arrangements were 1.39-1.57, 1.32-1.43 and 1.17-1.27 respectively. Thermo hydraulic performance parameter improved with increasing the angle of attack of flow and best performance occurs with an angle of attack of 60° Friction factor results were compared with the correlation for a smooth rectangular duct given by modified blasius equation fs = 0.085 Re-0.25.

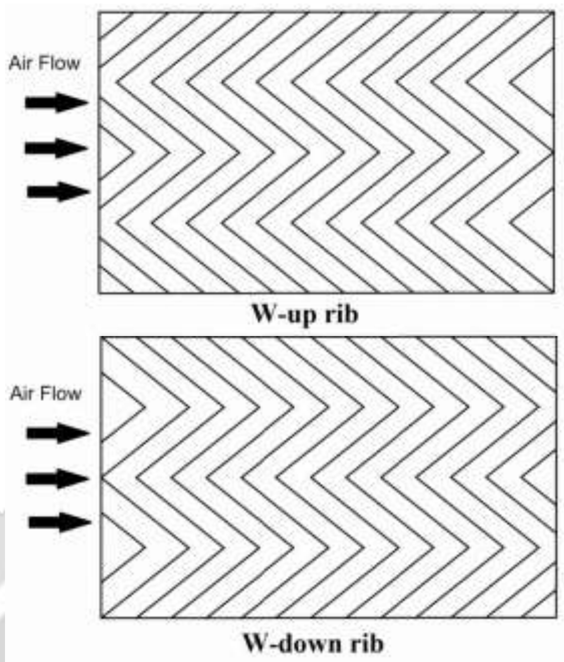


Fig.13.W-shape rib roughness

Arvind kumar experimentally investigated heat transfer and friction characteristics in solar air heater by using discrete W-shaped roughness on one broad wall of solar air heater as shown in Fig.14, with an aspect ratio of 8:1, the roughened wall being heated while the remaining three walls are insulated. The experiment encompassed Reynolds number (Re) range from 3000 to 15,000, relative roughness height (e/D) in the range of 0.0168–0.0338, relative roughness pitch (p/e) 10 and the angle of attack (α) in the range of 30–75°. Correlations for heat transfer and friction were developed as a function of roughness and flow parameters. Nusselt number increases with an increase of Reynolds number. The maximum enhancement of Nusselt number was found to be 1.44, 1.54, 1.67 and 1.61 times that for smooth duct for angles of attack of 30°, 45°, 60° and 75° for relative roughness height of 0.0168 whereas for relative roughness height of 0.0338, the maximum enhancement in Nusselt number was found to be 1.88, 1.99, 2.16 and 2.08 times for corresponding angles of attack of 30°, 45°, 60° and 75° respectively. Friction factor decreases with an increase of Reynolds number. For relative roughness height of 0.0168, the maximum enhancement in friction factor was found to be 1.53, 1.71, 1.82 and 1.76 times that of smooth duct for angles of attack of 30°, 45°, 60° and 75° respectively whereas for relative roughness height of 0.0338, the maximum enhancement was found to be 2.34, 2.61, 2.75 and 2.69 times for corresponding values of angles of attack of 30°, 45°, 60° and 75° respectively. The maximum enhancement of Nusselt number and friction factor as a result of providing artificial roughness was found to be 2.16 and 2.75 times that of smooth duct for an angle of attack of 60° and relative roughness height of 0.0338.

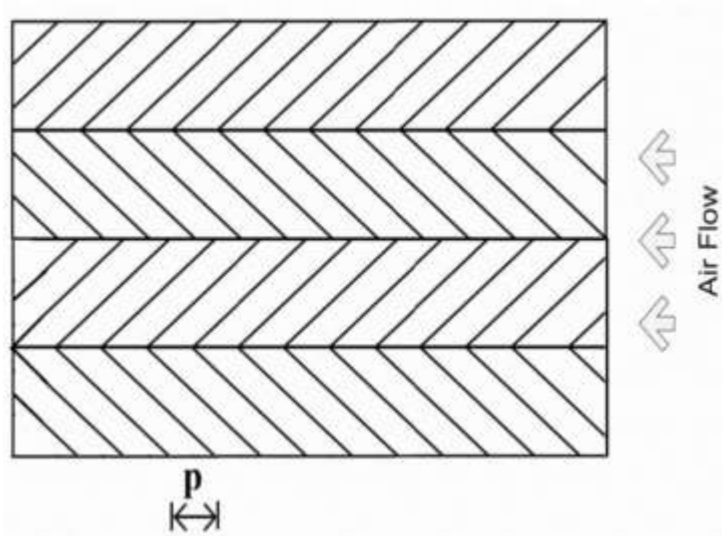


Fig.14. Discrete W-shape ribs

5.5 Chamfered ribs

Karwa performed experimental study to predict the effect of rib head chamfer angle (Ø) and duct aspect ratio on heat transfer and friction factor in a rectangular duct roughened with integral chamfered ribs as shown in Fig.15 . As compared to the smooth duct, the presence of chamfered ribs on the wall of duct yields up to about twofold and threefold increase in the Stanton number and the friction factor respectively in the range of parameters investigated. The highest heat transfer as well as highest friction factor exists for a chamfer angle (Ø) of 15°. The minima of the heat transfer function occur at roughness Reynolds number of about 20. As the aspect ratio (H/D) increases from 4.65 to 9.66, the heat transfer function also increases and then attains nearly a constant value. The roughness function decreases with the increase.

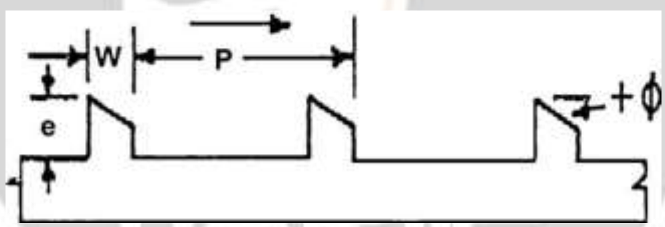


Fig.15. Chamfered ribs

5.6. Metal grit ribs

Karmare and Tikekar investigated about thermo hydraulic performance of roughened solar air heaters with metal rib grits shown in Fig.16. The range of variation of system and operating parameters was investigated within the limits of, e/Dh: 0.035–0.044, p/e: 15–17.5 and l/s as 1.72, against variation of Reynolds number, Re: 3600–17000. The study shows substantial enhancement in thermal efficiency (10–35%), over solar air heater with smooth collector plate. It was discovered that Nusselt number and friction factor increases up to 2 and 3 times respectively when compared to smooth surface. Heat transfer had its maximum value at e/D =0.044, l/s = 1.72, p/e = 17.5 and friction factor had its maximum value at e/D = 0.044, l/s = 1.72, p/e = 12.5.Optimum performance was found for e/D = 0.044, l/s =1.72, p/e = 17.5. The thermal efficiency enhancement was also accompanied by a considerable increase in the pumping power requirement due to the increase in the friction factor (80–250%).

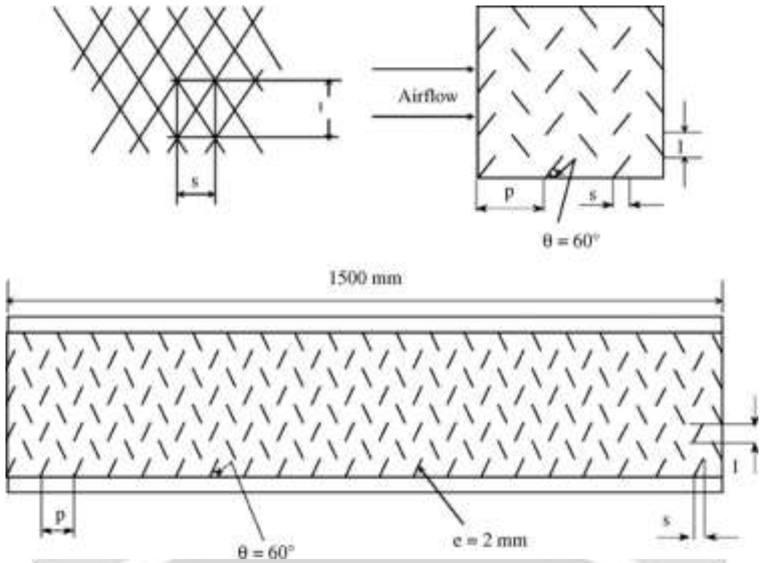


Fig.16. Metal grit ribs

5.7. Arc shaped ribs

Solanki and Saini carried out this experimental study for enhancement of heat transfer coefficient of a solar air heater having roughened air duct provided with artificial roughness in the form of arc-shape parallel wire as roughness element shown in Fig.17. Increment in friction factor by provided with such artificial roughness elements has also been studied. The effect of system parameters such as relative roughness height (e/d)0.0215-0.0422,(p/e)10 and arc angle (α/90)0.3333-0.6666 have been studied on Nusselt number (Nu) and friction factor (f) with Reynolds number (Re) varied from 2000 to 17000.It was concluded that considerable enhancement in heat transfer coefficient is achieved by providing arc-shape parallel wire geometry as artificial roughness with solar air duct. The maximum enhancement in Nusselt number has been obtained as 3.80 times corresponding the relative arc angle (a/ 90) of 0.3333 at relative roughness height of 0.0422. However, the increment in friction factor corresponding to these parameters has been observed 1.75 times only.

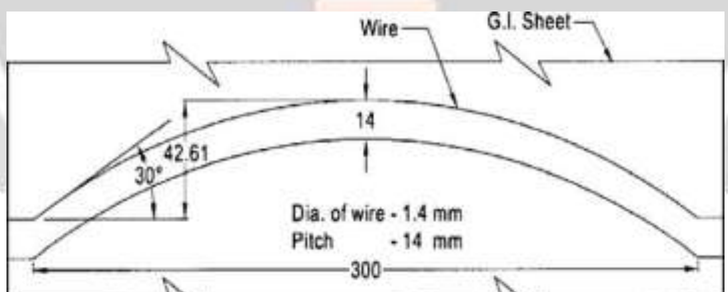


Fig.17. Arc shaped rib

5.8.Wedge shaped ribs

Bhagoria performed experiments to determine the effect of relative roughness pitch, relative roughness height and wedge angle on the heat transfer and friction factor in a solar air heater roughened duct having wedge shaped rib roughness as shown in Fig.18. The presence of ribs yields Nusselt number up to 2.4 times while the friction factor rises up to 5.3 times as compared to smooth duct in the range of parameters investigated. A maximum enhancement in heat transfer was obtained at a wedge angle of about 10_. The heat transfer was found maximum for a relative roughness pitch of about 7.57. The friction factor was decreased as the relative roughness pitch increased.

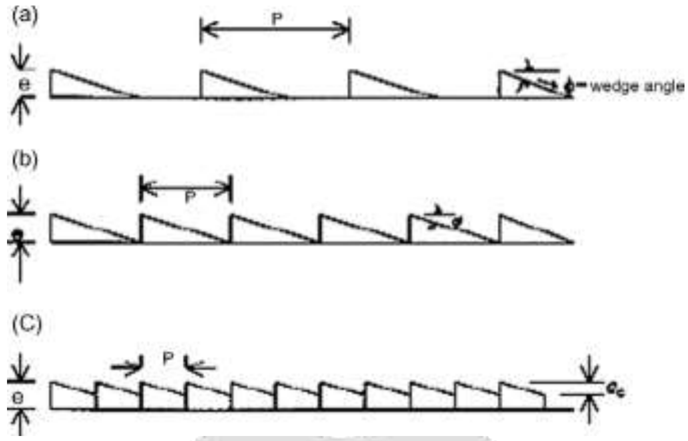


Fig.18.Weged shaped ribs

5.9. Dimple shaped ribs

Saini et al investigated the effect of relative roughness height (e/D) and relative roughness pitch (P/e) of dimple shape roughness geometry on heat transfer and friction factor as depicted in Fig 19. It was found that heat transfer could be enhanced considerably as a result of providing dimple- shape roughness geometry on the absorber plate of a solar air heater duct. The maximum value of the Nusselt number was found to correspond to relative roughness height of 0.0379 and relative roughness pitch of 10, while minimum value of the friction factor was found corresponding to relative roughness height of 0.0289 and relative pitch of 10. It was concluded that the roughness parameters of the geometry can be selected by considering the net heat gain and corresponding power required to propel air through the duct

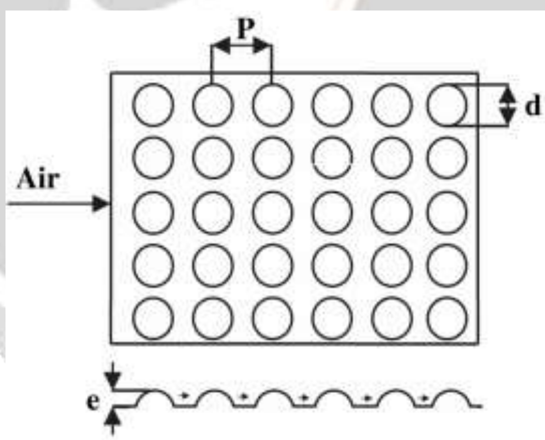


Fig.19. Dimple shape ribs

Conclusions

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. Use of artificially roughened surfaces with different type of roughness geometries of different shapes, sizes and orientation is found to be the most effective technique to enhance the heat transfer rate with little penalty of friction.

2. Roughness in the form of ribs and wire matrix were mainly suggested by different investigators to achieve better thermal performance. Among all, rib roughness was found the best performer as far as thermal performance is concerned.

3. Correlations developed for heat transfer and friction factor for solar air heater ducts having artificial roughness of different geometries for different investigators are also shown in tabular form. These correlations can be used to

predict the thermal efficiency, effective efficiency and then hydraulic performance of artificial roughened solar air heater ducts.
4. In artificially roughened solar air heaters, there is lot of scope for use of flow visualization techniques in order to analyse flow and heat transfer enhancement processes.
5. Thermo-hydraulic performance of inclined broken rib geometry has been found to be better in comparison to other roughness element geometries for Reynolds number range between 3000 and 14000 and beyond which are shaped geometry outperforms the inclined broken rib geometry within the range of roughness parameters considered

REFERENCES

[1] Robert Foster, Majid Ghassemi, Alma Cota. Solar Energy: Renewable Energy and the Environment. New York: CRC Press Taylor & Francis group; 2010.
[2] Xianguo Li. Green Energy: Basic Concepts and Fundamentals. 1st ed. New York: Springer; 2011.
[3] Anne Maczulak. Renewable Energy: Sources and Methods. 1st ed. New York: Infobase Publishing; 2011.
[4] Martin Kaltschmitt, Wolfgang Streicher, Andreas Wiese.Renewable Energy: Technology, Economics and Environment. 1st ed. New York: Springer; 2007.
[5] Volker Quaschning. Understanding Renewable Energy Systems. 3rd ed. London: Earthscan; 2005.
[6] John Twidell, Tony Weir. Renewable Energy: Sources . 2nd ed. New York: Taylor & Francis; 2006.
[7] S P Sukhatme, J P Nayak. Solar energy. 3rd ed. New Delhi: Tata McGraw Hill; 2011.
[8] V.V. Tyagia, N.L. Panwarb, N.A. Rahima, Richa Kotharic. Review on solar air heating system with and without thermal energy storage system. Renewable and Sustainable Energy Reviews. 2012; 16: 2289– 2303.
[9] Varun, R.P. Saini, S.K. Singal. A review on roughness geometry used in solar air heaters. Solar Energy.2007; 81: 1340–1350.
[10] Vishavjeet Singh Hans, R.P. Saini, J.S. Saini. Of artificially roughened solar air heaters—A review. Renewable and Sustainable Energy Reviews.2009; 13: 1854–1869.
[11] Webb RL, Eckert ERG. Heat transfer and friction in tubes with repeated-rib roughness. Int J Heat Mass Transf. 971;14:601–17.
[12] Han, J.C., Glicksman, L.R., Rohsenow, W.M., 1978. An investigation of heat transfer and friction for rib roughened surfaces. International Journal of Heat and Mass Transfer 21, 1143–1156.
[13] Han, J.C., Zhang, Y.M., Lee, C.P., 1991. Augmented heat transfer in square channels with parallel, crossed, and V-shaped angled ribs. ASME Journal of Heat Transfer 113, 590–596.
[14] Prasad K., Mullick S.C., ―Heat transfer characteristics of a solar air heater used for drying purposes‖, Appl Energy, 13(2), 83-93, 1983.
[15] Prasad BN, Saini JS. Effect of artificial roughness on heat transfer and friction factor in a solar air heater.Solar Energy. 1988;41(6): 555–560.
[16] Prasad BN, Saini JS. Optimal thermo-hydraulic performance of artificially roughened solar air heaters.Solar Energy. 1991;47:91–6.
[17] Gupta D, Solanki SC, Saini JS. Heat and fluid flow in rectangular solar air heater ducts having transverse rib roughness on absorber plates. Solar Energy.1993;51(1) :31–7.
[18] Saini RP, Saini JS. Heat transfer and friction factor correlations for artificially roughened ducts with expanded metal mesh as roughened element. Int J Heat Mass Transfer. 1997; 40: 973–86.
[19] Karwa R, Solanki SC, Saini JS. Heat transfer coefficient and friction factor correlations for the transitional flow regime in rib-roughened rectangular ducts. Int J Heat Mass Transfer. 1999; 42: 1597–1615.
[20] Verma SK, Prasad BN. Investigation for the optimal thermohydraulic performance of artificially roughened solar air heaters. Renew Energy. 2000; 20:19–36.
[21] Karwa R, Solanki SC, Saini JS. Thermo-hydraulic performance of solar air heaters having integral chamfered rib roughness on absorber plates. Energy 2001; 26: 161–76.
[22] Momin AME, Saini JS, Solanki SC. Heat transfer and friction in solar air heater duct with v- shaped rib roughness on absorber plate. Int J Heat Mass Transfer.2002;45:3383–96.
[23] Bhagoria JL, Saini JS, Solanki SC. Heat transfer coefficient and friction factor correlations for rectangular solar air heater duct having transverse wedge shaped rib roughness on the absorber plate. Renew Energy. 2002; 25: 341–69.
[24] Sahu MM, Bhagoria JL. Augmentation of heat transfer coefficient by using 90 broken transverse ribs on absorber plate of solar air heater. Renew Energy. 2005;30: 2057–63.
[25] Jaurker AR, Saini JS, Gandhi BK. Heat transfer and friction characteristics of rectangular solar air heater duct using rib-grooved artificial roughness. Solar Energy.2006; 80: 895–907.
[26] Karmare SV, Tikekar AN. Heat transfer and friction factor correlation for artificially roughened duct with metal grit ribs. Int J Heat Mass Transfer. 2007; 50: 4342–51.

[27] Saini SK, Saini RP. Development of correlations for Nusselt number and friction factor for solar air heater with roughened duct having arc-shaped wire as artificial roughness. Solar Energy. 2008; 82: 1118–30.
[28] Aharwal KR, Gandhi BK, Saini JS. Experimental investigation on heat-transfer enhancement to a gap in an inclined continuous rib arrangement in a rectangular duct of solar air heater. Renew Energy. 2008; 33:585–96.
[29] Saini RP, Verma J. Heat transfer and friction factor correlations for a duct having dimple- shaped artificial roughness for solar air heaters. Energy. 2008; l33: 1277–87.