Impact of Artificial Roughness on Heat Transfer of Solar Air Heater: A Review

Maneesh Kumar Dubey[1], Deepak Kumar Singh[2], Danish Ahmed Siddiqui[3], Gaurav Soni[4]
[1]Assistant Professor, Dept of Mechanical Engineering
[2, 3, 4]Dept of Mechanical Engineering
[1, 2, 3, 4] Lakshmi Narain College of Technology, Bhopal, MP India

Abstract- *The conversion, utilization and retrieval of energy invariably involve a heat exchange process, which makes it imperative to design more proficient heat exchanger device. Enhancement in the rate of heat transfer can be efficiently achieved by employing ribs. The use of artificial roughness in different forms, silhouettes and dimensions is the common and effective way to increase the performance of the device. Several studies have been carried out to determine the effect of different roughness element geometries on rate of heat transfer. This technique is gaining importance among the researchers since long time and a lot of research is still going on and has further scope. This paper presents the detailed review of various investigations made on artificial roughness geometries summarizing their outcomes.*

Keywords- Artificial roughness, Ribs, Solar air heater, Turbulators.

I. INTRODUCTION

The rapid exhaustion of fossil fuel resources has demanded an urgent search for alternative sources of energy. Of the many substitutions, solar energy is most promising towards meeting the continuously increasing demand for energy. Solar energy is accessible easily and a native source of energy which provides a clean and pollution free atmosphere. The simplest and the most effective approach to utilize solar energy is to convert it into thermal energy for heating applications by using solar collectors. Solar air heaters, because of their inherent simplicity and most widely used collector devices. Solar air heaters are being used for many applications at low and adequate temperatures. Some of them are crop drying, timber seasoning, space heating etc. The thermal efficiency of solar air heaters is low due to two reasons: low thermal capacity of air and a low heat transfer co-efficient between the absorber plate and air flow through duct. In order to make the solar air heater economically more feasible, their thermal efficiency needs to be enhanced. This can be done by enhancing the heat transfer co-efficient between the absorber plate and air flow through a duct. Enhancing heat transfer surface are used in many engineering applications such as gas turbine blade cooling passages (i.e. channel/duct), air heater, heat exchanger surfaces, gas-cooled reactor fuel elements, ventilation equipment of micro-electronic systems and air conditioning/ refrigeration systems, hence many techniques have been investigated on enhancement of heat transfer rate and decrease the size and cost of the involving equipment especially in heat exchangers. One of the most important techniques used are passive heat transfer technique. These techniques when adopted in heat transfer surfaces proved that the overall thermal performance improved significantly. In the past decade, heat transfer enhancement technology has been developed and widely applied to heat exchanger applications; for example, refrigeration, auto-motives, process industry, solar air heater, solar water heater, rectangular duct, etc. The aim of augmentative heat transfer is to accommodate high heat fluxes (or heat transfer coefficient). In general, heat transfer co-efficient enhancement techniques can be divided into two groups; active and passive. The active techniques require external forces, e.g. electric field, pulses and vibrations etc. The passive techniques require special surface geometries, artificial roughness which makes the flow turbulent and increases overall heat transfer co-efficient of between air flow and the absorber plate in solar air heaters. Artificial roughness is basically a passive heat transfer enhancement technique by which thermo hydraulic performance of a solar air heater can be improved. The artificial roughness has been used broadly for the enhancement of forced convective heat transfer, which further involves flow at the heat-transferring surface to be turbulent. However, energy for generating such turbulence has to be derived from the fan or blower and the excessive power is required to flow air over the duct. Therefore, it is desirable that the turbulence must be created only in the zone very close to the heat transferring surface, so that the power requirement may be reduced. This can be achieved by keeping the height of the roughness features to be small in comparison to the duct dimensions.

II. ARTIFICIAL ROUGHNESS AND ITS IMPLICATIONS

All materials have naturally rough surfaces that can be envisaged through naked eyes or by placing it under the microscope. Nonetheless, in a finished metallic surface, the microscopic size of roughness elements hardly alters the fluid flow behaviour and the convective heat transfer process. It has been perceived that the presence of artificial roughness elements of optimal dimension can lead to a substantial change in the fluid flow and heat transfer. The roughness of different shapes and size can be applied over surfaces that are exposed to fluid stream to stimulate the fluid flow pattern in the nearby region. The popular roughness geometries include grit, ribs, dimples, protrusions, wings, blockages etc. Sparrow et al. [1] showed in the experimental and numerical study that the position of maximum heat transfer coefficient and position of reattachment point are alike. Okamoto et al. [2] experimentally found that at reattachment point the local heat transfer has highest value. Joule [3] found significant improvement in the thermal performance of steam condenser by the application of artificial roughnessinside the tube. It has been observed that the presence of artificial roughness over the heated surface promotes the turbulence near wall due to separated flow over the periodically repeated roughness elements. The higher turbulence intensity give rise to local turbulent kinetic energy and thereby enhances the turbulent kinetic energy dissipation rate in the flow that brings out significant enhancement in wall heat transfer rates with the concurrent rise in pressure drop. Nikuradse [4] studied the effect of roughness on friction and velocity distribution and developed a friction correlation based on law of similarity by using sand grains roughness in pipe flow.

III. METHOD TO INVOKE ARTIFICIAL ROUGHNESS

Transverse Ribs:

Prasad and Mullick[5] were the first researcher to apply small diameter wire as roughness in solar air heater. The constraint used for study were, relative roughness pitch as 12.7 and relative height as 0.019. The outcome of their result gives an account of application of protruding wires led to improvement of plate efficiency from 0.63 to 0.72. The figure is illustrated below for the given ribs as Fig. 1.

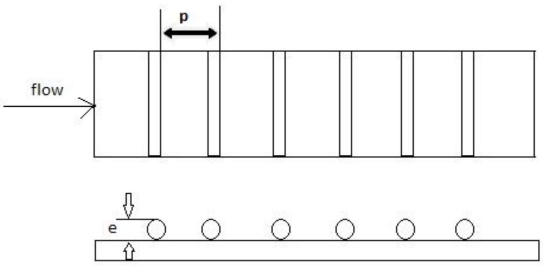

Fig. 1. Transverse small diameter wire

Transverse Broken Ribs:

Sahu and Bhagoria [6] inspected transverse broken ribs as shown in fig.2. They found Reynolds number varied from 3000-12000, rib height as 1.5mm, roughness pitch as 10-30mm with aspect ratio 8. Maximum Nusselt number attained for pitch 20 mm. By these arrangement heat transfer coefficients increased by 1.25-1.4 times as compared to smooth duct operating under similar condition.

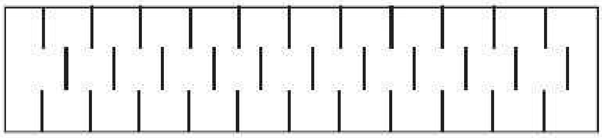

Fig. 2. Transverse broken ribs

Continuous Inclined Ribs:

Gupta et al. [7] did experiment over transverse ribs with inclined rib. They used inclined circular ribs as simulated roughness for Reynolds number as 3000-18000, relative roughness height as 0.018-0.052 for relative roughness pitch of 10. They reported augmentation in thermal efficiency by 1.16-1.25 as compared to smooth plate in range of parameter investigated. Roughness used in the process is shown in Fig.3.

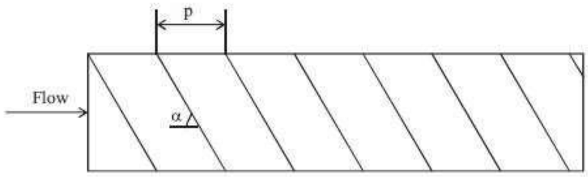

Fig. 3. Inclined continuous ribs

Broken Inclined Ribs:

Aharwalet al. [8] examined inclined rib with a gap provision so as to allow release of tributary flow and main flow through the gap by creating local turbulence. Roughness used is represented in Fig.4, investigation found Reynolds number as 3000-18000, aspect ratio as 5.84, relative roughness pitch as 10, relative roughness height as 0.0377 and angle of attack as 60. Gap position (d/w) and gap width (g/e) were in range of 0.1667-0.667 and 0.5-2.

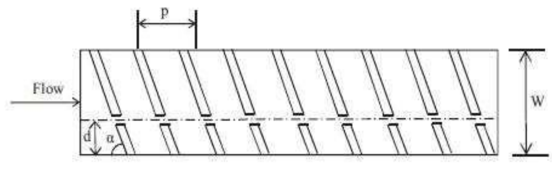

Fig. 4. Inclined ribs with gap

Chamfered Ribs:

Karwaet al. [9] investigated outcome of chamfered ribs as artificial roughness. These investigations covered rib chamber angle (ψ) as-15 to 80˚, Reynolds number as 3000-20,000, relative roughness pitch of 4.5-8.5, roughness height as 0.0141-0.0328. They reported two and three times increase in Stanton number and friction factor respectively. Highest value of both obtained at angle 15˚. Fig. 5. shows chamfered ribs.

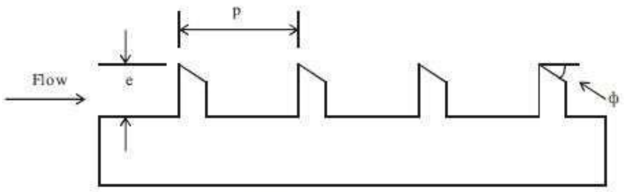

Fig. 5. Chamfered ribs

Arc Shaped Ribs:

Saini et al. [10] utilize first Arc shaped ribs. Investigation embodied duct with an aspect ratio of 12, Reynolds number from 2000-17,000, relative roughness height as 0.0213-0.0422, relative, angle of attack 33-66˚. They reported maximum enhancement in Nusselt number as 3.80 times equivalent relative arc angle (α/90) of 0.33 at relative roughness height of 0.0422. Corresponding increase in friction factor for this parameter was 1.75 times only. Roughness geometry shown in Fig.6.

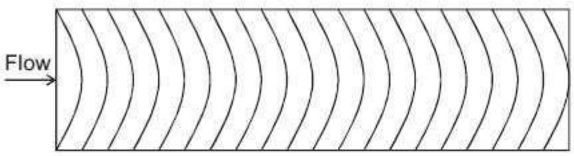

Fig. 6 Arc shaped wire roughness

Stagerred Dimple Roughness:

Bhushan et al. [11] investigated staggered dimple roughness in place of transverse dimple roughness. Range of parameter investigated were relative short way length (S/e) as 18.75-37.50, relative long way length (L/e) as 25.00-37.50, relative print diameter (d/D) as 0.147-0.367, relative roughness height as 0.03, aspect ratio as 10 and Reynolds number from 4000-20,000. Under given condition maximum enhancement of Nusselt number and friction factor was 3.8 and 2.2 times respectively in comparison to smooth duct.

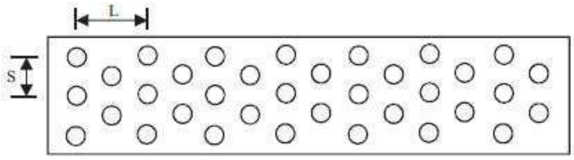

Fig. 7. Staggered dimple roughness

Wavy-Rib and Groove Turbulator:

Skullonget al. [12] carried out a tentative study to investigate the airflow friction and heat transfer characteristics in a high aspect ratio solar air heater channel fitted with combined wavy-rib and groove turbulators for turbulent regime, Re of 4000–21,000. The application of the rib groove at smaller PR causes a much high pressure drop increase, f/f_o= 14–134, especially for the inline rib-groove, and also provides considerable heat transfer augmentations, Nu/Nu_0 = 4.4–7.69, depending on PR, rib array and Re. The Nu/Nu0 augmentation tends to decrease slightly with the rise in Re. The combined rib-groove on the absorber plate at smaller PR should be applied instead of using the groove alone to obtain higher heat transfer and thermal performance of about 49–52%, leading to higher performance solar air heater system. The best operating regime for using these compound turbulators is found for the smaller PR at lower Re values. The absorber wall fitted with rib-groove turbulators at PR = 0.5 yields the highest TEF of about 1.75 at lower Re.

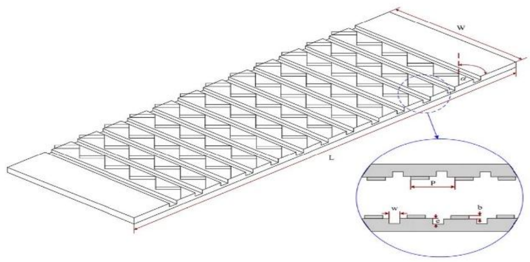

Fig.8.Wavy rib geometry

Circular Sectioned Rib:

Yadav et al. [13] experimentally investigated the effect of rib (circular sectioned) typography on average Nusselt number and friction factor in an artificially roughened solar air heater (duct aspect ratio, AR = 5:1) is studied by adopting the computational fluid dynamics (CFD) approach. Statistical solutions are obtained using commercial software ANSYS FLUENT v12.1. The computations based on the finite volume method with the semi-implicit method for pressure-linked equations (SIMPLE) algorithm have been conducted. Circular sectioned transverse ribs are applied at the underside of the top of the duct, i.e., on the absorber plate. The rib-height-to-hydraulic diameter ratio (e/D) is 0.042. The rib-pitch-to-rib-height (P/e) ratios studied are 7.14, 10.71, 14.29 and 17.86. For each rib spacing simulations are executed at six different relevant Reynolds numbers from 3800 to 18000. The thermo-hydraulic performance parameter for P/e = 10.71 is found to be the best for the investigated range of parameters at a Reynolds number of 15000.

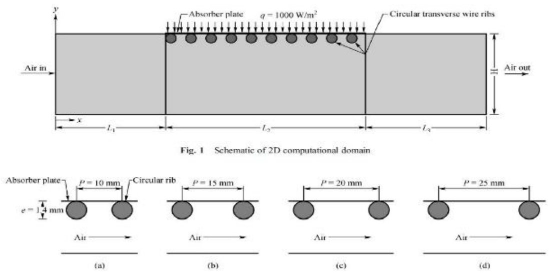

Fig.9. Circular sectioned rib

Change in Flow Value:

Yadav [14] in his experiment observed that the artificially roughened solar air heaters have enhanced rate of heat transfer as compared to smooth solar air heaters under the same working circumstances. Augmentation of heat transfer and friction factor, hence the thermal enhancement factor of artificially roughened solar air heaters, depends upon the values of flow Reynolds number (Re), relative roughness pitch (P/e), and relative roughness height (e/D). The Nusselt number of roughened solar air heaters increase with the increasing values of flow Reynolds numbers and relative roughness heights for a given value of relative roughness pitch. Friction factor of roughened solar air heater increases with the decreasing values of flow Reynolds number and increasing values of relative roughness height for a certain value of relative roughness pitch. It is also observed that the rate of increase of friction factor is higher than that of the Nusselt number. A solar air heater, roughened with circular- sectioned transverse rib roughness on the absorber plate with e/D = 0.042 provides better thermal enhancement factor of 1.635 at a Reynolds number of 15,000 and hence can be employed for heat transfer augmentation. The results predicted by the present CFD analysis are quite close to previous investigational results. It can therefore, be concluded that the present numerical results have demonstrated the validity of the proposed system.

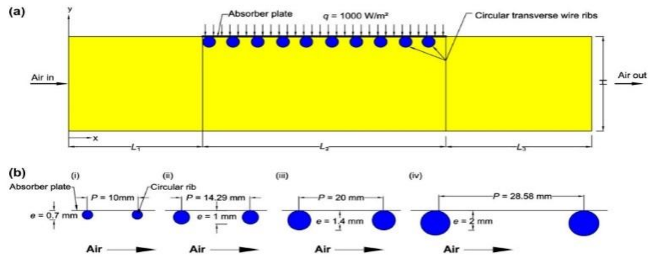

Fig.10.Circular transverse ribs

Staggered Thin Rib:

Skullong et al. [15] An experimental study has been carried out to investigate airflow friction and heat transfer characteristics in a solar air heater channel fitted with different rib geometry and with staggered thin ribs at different BR and PR for the turbulent regime, Re of 5000–24,000. The summary results can be drawn as follows: a) The use of rib turbulators with in-line array causes a very high pressure drop, especially for the thin rib and also provides considerable heat transfer augmentations, Nu/Nu0 = 2.13–2.16. b) The thin rib provides higher heat transfer rate, friction factor and thermal enhancement factor than the square rib. Thus, the use of thin rib turbulator yields the TEF around 3–7 % higher than that of the square rib, especially for the staggered thin rib. c) The Nu of the staggered thin rib shows the uptrend with the rise in Re and BR, but the downtrend with increasing PR. d) n comparison, the staggered thin rib with BR = 0.2 and PR = 0.75 provides the highest TEF.

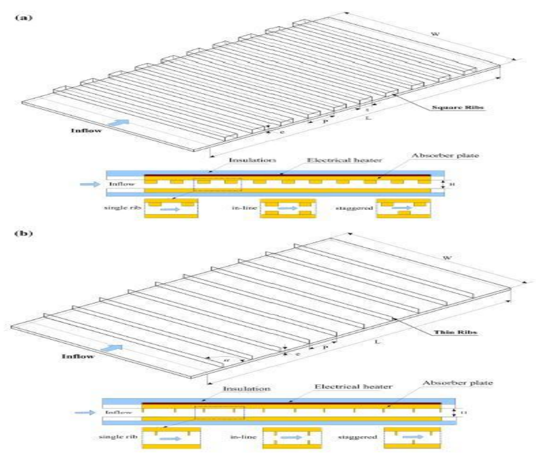

Fig.11. Staggered thin rib

Cubical Roughness:

Nanjundappa [16] investigated experimentally the effect of cubical three-dimensional roughness configurations on the absorber surface of a solar heater to improve its performance. Author used cubical roughness elements as roughness elements since these produces better heat transfer characteristics and used eighteen different roughness configuration plates for his experiments in which nine plates were arranged in an inline roughness manner and remaining nine plates in a staggered manner. Author determined that presence of cubical roughness enhances heat transfer because of interruption of the viscous sublayer, which yields flow turbulence, separation and reattachment leading to a higher heat transfer coefficient. Author stated that the most important effect produced by the presence of a cube on the flow pattern is the generation of two flow separation regions, one on each side of the cube. It is concluded that the enhancement of heat transfer by flow separation and reattachment caused by cubical roughness is significantly higher as compared to that by the increased heat transfer by means of fin-effect.

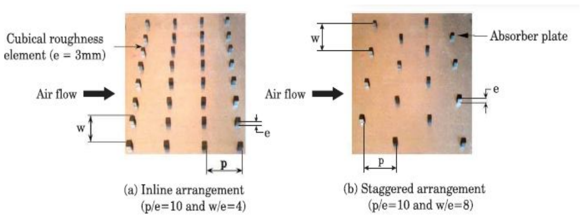

Fig.12.Cubical three-dimensional roughness configurations

Multi V-Shaped Ribs:

Jin et al. [17] carried out a numerical investigation of heat transfer and fluid flow in a solar air heater duct with multi V-shaped ribs on the absorber plate.

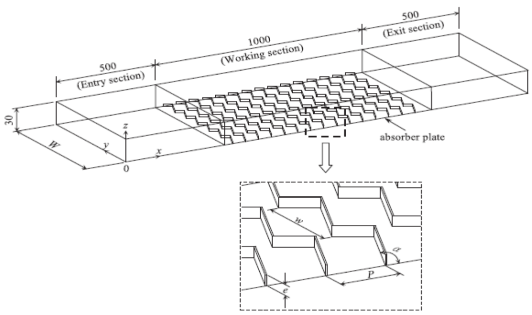

Fig.13.SAH Roughened with Multi V-Shaped Ribs

Authors stated that the multi V-shaped ribs generate helical vortex flows, which stimulate the fluid mixing between the colder mainstream fluid and the warmer fluid adjacent to the absorber wall. In addition, the moving subsidiary vortex structure at the inter-rib region further augments the local fluid mixing. Therefore, the heat transfer is significantly improved when compared to a smooth wall channel. Authors concluded that the average Nusselt number, friction factor, and thermohydraulic performance parameter all tend to decrease with the increase in relative rib pitch for the range of parameters investigated.

V-Ribs with Symmetrical Gaps:

Maithani and Saini [18] carried out an investigation for heat transfer and friction factor correlations for a solar air heater duct roughened artificially with V-ribs having symmetrical gaps as turbulence promoter. Experiments were conducted on the rectangular duct having one broad wall roughened with V-rib with symmetrical gaps and subjected to a constant heat flux. Authors used a wire of circular cross section of height 2 mm having symmetrical gaps provided on both limbs of the V-ribs. Authors concluded that the Nusselt number increases while the friction factor decreases with increase in Reynolds number values. Values of Nusselt number and friction factor were higher in comparison to smooth duct. For the range of number of gaps, the maximum Nusselt number is witnessed for number of gap equal to 3. On increasing the number of gaps above 3 leads to reduction in the heat transfer rate.Similarly,the Nusselt number increases with increase in relative gap width up to a value of 4 and thereafter decreases.

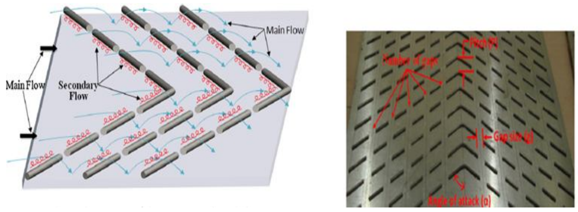

Fig.14. Flow Pattern&test plate

Semi Ellipse Shaped Obstacles:

Alam et al. [19] performed a numerical study on thermal hydraulic performance improvement in solar air heater duct with semi ellipse shaped obstacles. Obstacles were placed on the absorber plate in V-down shape at different angle of attack (a), ranging from 30^o to 90^o. Two different arrangements of obstacles namely inline and staggered arrangements were investigated. Their work utilised finite volume based numerical method to analyse 3-dimensional incompressible Nervier-Strokes flow through solar air heater duct having semi ellipse shaped obstacles in V arrangements. Authors stated that Nusselt number and friction factor were found to be strong function of angle of attack (a) and obstacles arrangement. Authors concluded that Staggered arrangement of obstacles were found to be thermodynamically better than that of inline arrangement of obstacles for all values of angle of attack (a) investigated in the study, however inline arrangement are hydraulically better.

Multigap V-Ribs Combined with Staggered Ribs:

Deo et al. [20] conducted an experiment to investigate heat transfer, friction factor and thermohydraulic performance characteristics of flow in a rectangular duct artificially roughened on one side with multi-gap V-down ribs combined with staggered ribs. Authors concluded that for all combinations of the roughness geometry parameters, Nusselt number increases whereas friction factor decreases with increase in the Reynolds number. Values of the Nusselt number and friction factor were quite higher as compared to those obtained using smooth absorber plate. This is due to the increase in turbulence near the heat transfer surface on account of flow separations-reattachments, flow acceleration through the gaps, generation of secondary flows and effect of staggered rib pieces. Comparison of the thermohydraulic performance of the geometry used in the study with the other continuous and broken V-rib geometries proved the superior performance of the used roughness geometry for all Reynolds number values.

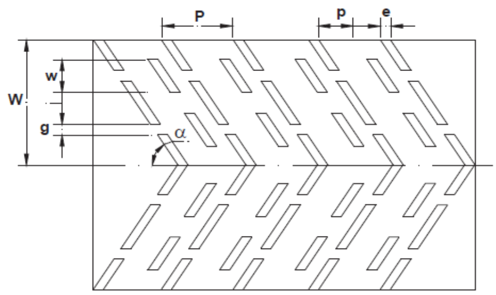

Fig.16. Multigap V-Ribs Combined with Staggered Ribs

Broken Arc Shaped Rib:

Gill et al. [21] investigated solar air heater duct having aspect ratio 12 roughened with broken arc rib. The broken arc was formed by creating symmetrical gap in continuous arc with gap width equal to roughness height. Author investigated the influence of position of gap in arc rib on Nusselt number as well as on friction factor. For this purpose, five broken arc rib roughened plates having relative gap position ranging 0.2–0.8 were studied for values of Reynolds number 2000–16000. The remaining roughness parameters like relative roughness height, arc angle, and relative roughness pitch were taken as 0.043, 30o and 8 respectively. The presence of fragmented arc ribs enhanced the Nusselt number, friction factor and thermo-hydraulic performance up to 2.37, 2.55 and 1.94 respectively, compared to smooth duct. The results of ducts roughened with broken arc rib and continuous arc rib were compared under identical flow conditions. The effect of gap in continuous arc rib on the flow pattern has also been observed using ANSYS.

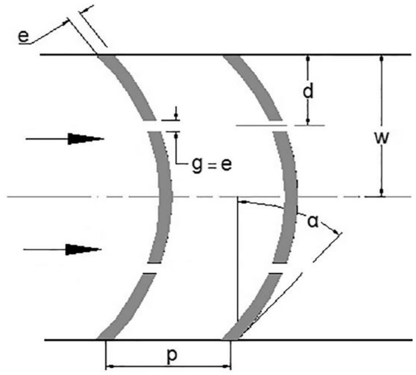

Fig.17. Broken Arc Shaped Rib

Hyperbolic Geometry of Rib:

Thakur et al. [22] studied thermo-hydraulic performance of artificially roughened solar air heater's absorber plate with novel hyperbolic ribs using ANSYS FLUENT. The study was derived from the fact that formation of eddies across a rib do influence thermo-hydraulic performance of a flat plate solar air heater. The design of hyperbolic ribs is such that it prevents entrapment of eddies facilitating higher heat transfer rate leading to superior thermo-hydraulic performance. The developed model was authenticated for smooth (duct without artificial roughness) as well as roughened ducts. The rib profile parameters were optimized by performing simulation runs by varying roughness height (e) from 0.5 mm to 2 mm and pitch (P) from 10 mm to 20 mm. The optimum performance is achieved for e ¼ 1 mm and P ¼ 10 mm at Re ¼ 6000. The performance of this novel rib was compared with rectangular, triangular and semi-circular rib geometries and was found to be the best among all up to Re ¼ 10000.

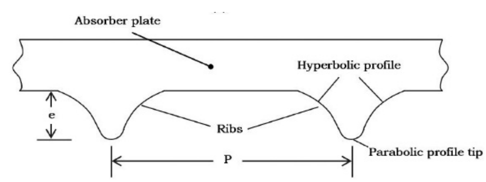

Fig.18. Hyperbolic geometry of rib

Rectangular Sectioned Tapered Rib:

Gupta and Varshney [23] performed numerical analysis of a solar air heater duct provided with artificial roughness in the form of rectangular sectioned tapered rib using Ansys FLUENT. Twelve different configurations of tapered rib with taper angle, a_t of 1.6°, 2.3° and 3.2° for pitch of 10, 15, 20 and 25 mm and constant rib width, w_r = 0.7 mm was considered as roughness element. A three-dimensional nonuniform hybrid grid was generated according to the configuration using cut cell technique. The differential equations involved in the model are solved with a finite-volume numerical method. The RNG k–e turbulence model with enhanced wall function were used to solve the transport equations for turbulent flow and energy dissipation rate. Effect of roughness parameters namely tapered angle and relative roughness pitch on Nusselt number and friction factor for a constant value of heat flux (1000 W/m2) was studied. The optimum values of geometrical parameters were obtained on the basis of the performance index in the range of Reynolds number 3800–18,000. Optimum performance index was found to be 1.91 corresponding to the a_t of 1.6^o and relative roughness pitch, P/e of 10.7 at Reynolds number, Re of 12,000.

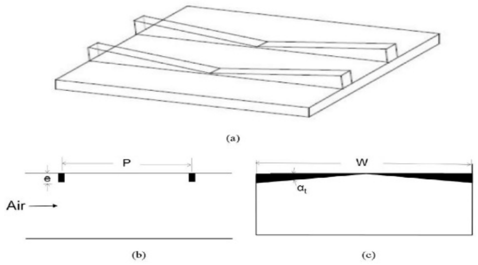

Fig.19. Rectangular sectioned tapered rib

V-Rib Combined with Staggered Pattern:

Patel and Lanjewar [24] carried out an experiment to find out heat transfer in multiple discrete V-patterns combined with staggered ribs in solar air heaters. The experimental results were compared with the smooth plate under similar flow conditions to determine the enhancement in the heat-transfer coefficient and friction factor. For various values of relative staggered rib length (w/e) and fixed values of other roughness parameters Nusselt number and friction factor with Reynolds number (Re) is calculated. Author observed that for all values of staggered rib length, the Nusselt number increases with increase in Reynolds number. It is because the increase in Reynolds number causes the increase in turbulent that increase heat transfer. For relative staggered rib length of 3.5, Nusselt number ratio is 1.94–2.27 over the range of Reynolds number studied. The experimental study of multiple discrete V-patterns combined with staggered rib roughness indicates that the enhancement in heat transfer accompanied with friction power penalty due to a corresponding increment in the friction factor that roughness geometry is better to which heat transfer is maximized friction loss is minimum. It is by considering friction characteristics and heat transfer simultaneously. The studies optimize relative staggered rib length (w/e) = 3.5 the geometrical parameter namely relative roughness pitch (P/e) as 12, relative gap width (g/e) as 1. The correlation has been developed taking into account optimum value of P/e, g/e, p_0/P and for different values of w/e.

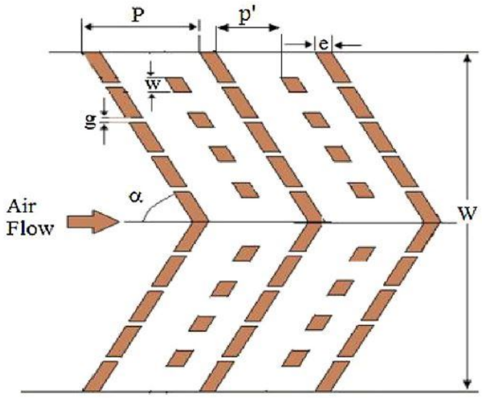

Fig.20. V-Rib combined with staggered pattern

V-Rib and with Staggered Pattern on Both Side of Absorber Plate:

Ravi and Saini [25] carried out an experimental study on heat transfer and friction factor in a counter flow double pass solar air heater (DPSAH) duct with discrete multi V-shaped and staggered rib roughness on two broad surfaces of the heated plate. The study covered a wide range of Reynolds number (Re) from 2000 to 20,000, relative staggered rib pitch (p0/p) from 0.2 to 0.8, relative staggered rib size (r/e) from 1 to 4 and relative roughness width (W/w) from 5 to 8. The optimum values of flow and geometrical parameters of roughness were attained and explained in detail. For the Nusselt number (Nu), the maximum increase of 4.52 times to the corresponding value of smooth double pass duct has been achieved, however it has also been seen that the friction factor (f) enhanced by 3.13 folds as compared to smooth one. The rib parameters corresponding to maximum increase in Nu and f are r/e = 3.5, p0/p = 0.6 and W/w = 7. Further, correlations for Nu and f have also been developed on the basis of experimental data. Based on the experimental data collected for different roughness and flow parameters, thermal and hydraulic characteristics of DPSAH were studied in the section and also compared the results with those achieved for smooth plate double pass collector performing under comparable flow environment to recognize the augmentation in thermal energy and pressure penalty on basis of the use of roughness elements.

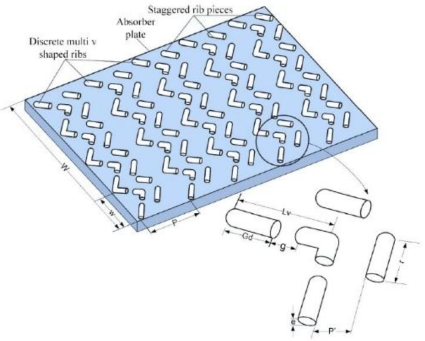

Fig.21. V-Rib and with staggered pattern on both side of absorber plate

Multiple V-Shaped Geometry:

DongxuJin et al. [26] numerically investigated the heat transfer and flow characteristics of a multiple V-shaped rib roughened solar air heater were. Calculations were performed for different geometrical parameters of the channel and rib, focused on their detailed effects on the maximum heat transfer enhancement. The multiple V-shaped ribs greatly enhanced the heat transfer, and the maximum thermohydraulic performance factor was found to be 2.35 in the studied ranges. Increasing the spanwise rib number produces two opposing effects on the heat transfer performance, resulting in an optimal spanwise rib number giving the maximum thermohydraulic performance factor. The geometrical parameters of the rib and channel influence the optimal spanwise rib number by changing the affecting factors of the thermohydraulic performance factor. The optimal spanwise rib number decreased with an increase in the channel height, rib attack angle, and relative rib pitch, whereas it first increased and then remained constant with an increase in the relative rib height.

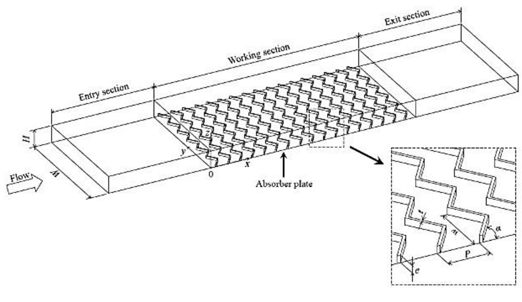

Fig.21. Multiple v-shaped geometry

IV. CONCLUSION

This paper reviews the study carried out by numerous researchers in order to enhance the heat transfer and friction factor by the utilisation of artificial roughness of different silhouettes, dimensions and orientations. It has been evaluated from the former researches that the conventional solar air heater performance is meagre because of the poor heat transfer between the absorber plate and the air drifting over the plate. This is due to the formation of laminar sub layer over the absorber plate. The performance of the heater can be improved by creating turbulence in the laminar sub layer zone. This turbulence can be provided by the artificial roughness elements. It can be deduced that there is a significant enhancement in heat transfer with little penalty of friction. This paper is very advantageous for researchers in carrying out the experimental and numerical investigations to find out and optimize the new geometries for the maximum enhancement of heat transfer.

On the basis of the review of the literature of artificially roughened solar air heaters, the conclusion can be summarized as follows:

1. The use of artificial roughness on a surface is an effective technique to enhance heat transfer to fluid flowing in the duct. Artificially roughened solar air heaters have enhanced rate of heat transfer as compared to the smooth solar air heaters under the same geometric/ operating conditions.
2. It has been found that roughness geometries being used in solar air heaters are of many types depending upon shapes, size, arrangement and orientations of roughness elements on the absorber plate.
3. 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), angle of attack (α) and channel aspect Ratio (W/H) etc.
4. Transverse rib roughness enhances the heat transfer coefficient by flow separation and generation of vortices on the upstream and downstream of rib and reattachment of flow in the inter-rib spaces.
5. It can be concluded that the use of artificial roughness results in higher friction and hence higher pumping power requirements. It is desirable that design of solar air heater should be made in such a way that it should transfer maximum heat energy to the flowing fluid with minimum consumption of blower energy.

REFERENCES

[1] Sparrow EM, Tao WQ, Enhanced Heat Transfer in a Flat Rectangular Duct with Streamwise-Periodic Disturbances at One Principal Wall. Journal of Heat Transfer.

[2] Okamoto S, Seo S, Nakaso K, Effect Of Sectional Shape Of Rib On Turbulent Shear Flow Over Rows Of 2-Dimensional Ribs On A Ground Plane. University Of Tasmania, 1992.
[3] Joule JP, On the Surface-condensation of Steam. President of the Literary and Philosophical Society of Manchester, &c.
[4] Nikuradse J, Laws of Flow In Rough Pipes, National Advisory Committee For Aeronautics, Technical Morandum 1292.
[5] Prasad K and MullickSC, Heat Transfer Characteristics of a Solar Air Heater Used for Drying Purposes. Applied Energys Vol. 13, 83-93, 1983.
[6] Sahu MM, Bhagoria JL. Augmentation of Heat Transfer Coefficient Using 90_Broken Transverse Ribs on Absorber Plate of Solar Air Heater. Renewable Energy (2005).
[7] M.K. Gupta SC. Kaushik. Performance Evaluation of Solar Air Heater for Various Artificial Roughness Geometries Based on Energy, Effective and Energy Efficiencies. (2008).
[8] Aharwal KR, Gandhi BK, Saini JS. Heat Transfer and Friction Characteristics of Solar Air Heater Ducts Having Integral Inclined Discrete Ribs on Absorber Plate. International Journal of Heat and Mass Transfer 52 (2009) 5970–5977.
[9] Karwa R, Solanki SC, Saini JS. Thermo-Hydraulic Performance of Solar Air Heaters Having Integral Chamfered Rib Roughness on Absorber Plates. Energy 26 (2001) 161–176.
[10] Prasad BN, Saini JS., Effect of Artificial Roughness on Heat Transfer and Friction Factor in A Solar Air Heater. Solar Energy (1988)
[11] Bhushan B, Singh R. Nusselt Number and Friction Factor Correlations for Solar Air Heater Duct Having Artificially Roughened Absorber Plate. Solar Energy 85 (2011) 1109–1118.
[12] Skullong S, Kwankaomeng S, Thianpong C, Promvonge P. Thermal Performance of Turbulent Flow in A Solar Air Heater Channel with Rib-Groove Turbulator. International Communications in Heat and Mass Transfer 2014; 50: 34–43.
[13] Yadav AS, Bhagoria JL. Heat Transfer and Fluid Flow Analysis of An Artificially Roughened Solar Air Heater: A CFD Based Investigation. Front. Energy 2014; 8(2): 201–211.
[14] Yadav AS, CFD Investigation of Effect of Relative Roughness Height on Nusselt Number and Friction Factor in An Artificially Roughened Solar Air Heater. Journal of The Chinese Institute of Engineers, 2015.
[15] Skullong S, Kwankaomeng S, Thianpong C, Promvonge P.Effects of Rib Size and Arrangement on Forced Convective Heat Transfer in A Solar Air Heater Channel. Heat Mass Transfer.
[16] Nanjundappa M. Optimum Thermo-Hydraulic Performance of Solar Air Heater Provided with Cubical Roughness on The Absorber Surface. Taylor &Francis 2019.
[17] Jin D, Zhang M, Wang P, Xu S. Numerical Investigation of Heat Transfer and Fluid Flow in A Solar Air Heater Duct with Multi V-Shaped Ribs on The Absorber Plate. Energy Xxx 2015; 1e13.
[18] Maithani R, Saini JS. Heat Transfer and Friction Factor Correlations for A Solar Air Heater Duct Roughened Artificially With V-Ribs with Symmetrical Gaps. Experimental Thermal andFluid Science 2016; 70: 220–227.
[19] Alam T, Kim MH. Numerical Study on Thermal Hydraulic Performance Improvement in Solar Air Heater Duct with Semi Ellipse Shaped Obstacles. Energy 2016; 112: 588e598,
[20] Deo NS, Chander S, Saini JS. Performance Analysis of Solar Air Heater Duct Roughened with Multigap V-Down Ribs Combined with Staggered Ribs. Renewable Energy 2016; 91: 484e500.
[21] Gill RS, Hans VS, Singh S. Investigations on Thermo-Hydraulic Performance of Broken Arc Rib in A Rectangular Duct of Solar Air Heater. International Communications inHeat andMass Transfer 2017; 88: 20–27.
[22] Thakur DS, Khan MK, Pathak M. Performance Evaluation of Solar Air Heater with Novel Hyperbolic Rib Geometry. Renewable Energy 2017; 105: 786e797.
[23] Gupta AD, Varshney L. Performance Prediction for Solar Air Heater Having Rectangular Sectioned Tapered Rib Roughness Using CFD. Thermal Science andEngineering Progress 2017;Thermal Science andEngineering Progress 2017; 4:122–132:122–132.
[24] Patel SS And Lanjewar A. Experimental Analysis for Augmentation of Heat Transfer in Multiple Discrete V-Patterns Combined with Staggered Ribs Solar Air Heater. Renewable Energy Focus _ Volume 25, Number 00 _ June 2018
[25] Ravi R, Saini RP. Nusselt Number and Friction Factor Correlations for Forced Convective Type Counter Flow Solar Air Heater Having Discrete Multi V Shaped and Staggered Rib Roughness on Both Sides of The Absorber Plate.Applied Thermal Engineering 2018; 129: 735–746.
[26] Jin D, Quan S, Zuo J, Xu S. Numerical Investigation of Heat Transfer Enhancement in A Solar Air Heater Roughened by Multiple V-Shaped Ribs. Renewable Energy ;2019: 134 -178.