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Artificial Roughness and Its Significance on Heat Transfer of Solar Air Heater: An Assessment

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Abstract:

The transformation, utilization and retrieval of energy invariably involve a heat exchange process, which makes it essential to design more proficient heat exchanger device. Enhancement in the rate of heat transfer can be efficiently achieved by providing ribs on the surface. The use of artificial roughness geometry is generally considered to be simple, an innovative and economic technique for improving thermal performance of solar air heater. Several studies have been carried out to determine the effect of shapes, position, and height of protrusions on heat transfer and friction characteristics of solar air heater duct for the range of parameters. This technique is gaining importance among the researchers since long time and a number of researches are still going on and has further future scope. This paper presents the detailed review of various researches made on artificial roughness geometries summarizing their consequences.

Keywords **—Artificial roughness, Ribs, Solar air heater, Turbulators, Rectangular Duct.**

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I. INTRODUCTION

Fossil fuel sources are confined and so the present scenario of energy consumption and growth are not sustainable in the longer term. The energy demand for different application can be achieved by picking up solar energy efficiently. One of the most applications of solar energy is to produce warm air for domestic and industrial uses. In industrial applications, this warm air can be used for preheating furnaces or evaporating in dryers. On the other hand, in construction industry, it can be adopted to provide a portion of heating requirements of interior spaces. On this basis, during the recent years, an extensive deal of research has been done on solar heaters. Solar air heater (SAH) is a device in which energy from sun is captured by absorbing surface and the thermal energy is extracted by the air flowing over it. SAH is the cheapest way of solar energy conversion and used for various applications as space heating, drying of crops, and other industrial applications. A typical SAH is simply designed and requires less maintenance. However, they have poor heat transport between absorber and fluid due to development of laminar sublayer which results in a lower efficiency. The heat transfer coefficient can be significantly improved by disrupting the laminar sublayer and inducing turbulence adjacent to the absorber plate by providing artificial roughness. However, it is done at the cost of extra pressure drop which upturns the pumping power requirements. In these pieces of research, performance of various types of solar heaters has been investigated, ending up with remarkable advances in this scope. The performance of solar air heater is low due to low convective heat transfer coefficient between absorber plate and flowing air because of presence of a viscous sub-layer. Improvement in heat transfer process is essentially required for thermal energy systems to solve the global energy problem, which can facilitate enhanced heat transfer rate, compactness i.e. significant reduction in weight and size, longer life and ultimately to get better performance. Most of the thermal systems, particularly gas turbine blades operate at higher inlet temperature to ascertain higher efficiency. Thus, efficient cooling is very much desired. As a result, various heat transfer enhancement techniques (active/passive) have been proposed to improve the internal cooling of thermal systems such as cooling of gas turbine blades, combustor wall and electronic components, nuclear reactors, compact heat exchangers and solar air heater. Applications of heat transfer enhancement concepts can be found in gas turbine air foils, solar air heaters, electronic cooling, etc. A common technique to enhance heat transfer is by installing turbulence promotors (‘‘rib turbulators”) on the smooth walls. The rib turbulators generate secondary flows which increase near-wall shear in the vicinity of the ribs and these secondary flows also interact with channel side walls to increase turbulent transport of energy from relatively hotter walls by forming vortex or vortices.

II. ARTIFICIAL ROUGHNESS AND ITS IMPLICATIONS

Generally, thermal performance of smooth absorber plate is considered to be low because of low convective heat transfer coefficient. Sub laminar layer is developed over absorber plate which acts as thermal resistant to flowing air. For enhancing the heat transfer rate, sub laminar layer is broken/disturbed by creating local turbulence which is achieved using artificial roughness. Artificial roughness is created underside of absorber plate by means of small height wires attached to absorber plate in repeated nature. As the air flows over roughened surface, separation and reattachment are occurred in between the consecutive ribs leading to local wall turbulence and thereby improving the convective heat transfer coefficient of absorber plate. Secondary recirculation flows further help to improve to enhance the heat transfer rate as it promotes the mixing from heated surface to core flow. Enhanced heat transfer is also associated with increased pressure drop in term of friction factor which is unfavourable. So, it becomes necessary to minimize the pressure drop penalty because extra energy for creating turbulence is needed which comes from the blower, resulting high pumping power requirement. This problem can be solved by keeping the rib height small in comparison to duct height. Small height roughness creates the turbulence on the surface and it does not disturb the core flow.

Alam and Kim [1] proposed that roughness parameters such as ribs arrangement, shape of wires, rib pitch and rib height effect the heat transfer and friction factor. Various rib arrangements have been investigated and some arrangements are transverse ribs, angled ribs, V-ribs, W-ribs, multi V-ribs, rib with groove, staggered ribs, chamfered ribs and discrete ribs.

Zhang et al. [2] investigated the usefulness of placing convex dimples upstream ofgrooves on the improvement of the thermal performance and to address the effects of convex dimplespanwise arrangements and its number on the heat transfer and friction characteristics in the convex dimple-grooved channel.

III. METHOD TO INVOKE ARTIFICIAL ROUGHNESS

Convex Dimples with Grooves:

Zhang et al. [2] in their paper carried out an experimental investigation to reveal the usefulness of placing convex dimples upstream of grooves on the improvement of the thermal performance and to address the effects of convex dimple spanwise arrangements and its number on the heat transfer and friction characteristics in the convex dimple- grooved channel. Additionally, a study on the transverse-protrusion-grooved channel is conducted to serve as a contrast, and three spanwise positions of the convex dimple as well as two convex dimple numbers are considered. The results indicate that compared with transverse protrusions, placing convex dimples upstream of grooves can produce counter-rotating vortex pairs which cause an upstream movement of the flow reattachment. In addition, vortexes shedding from convex dimples can transport the cooler central core flows to the near-wall region and wash up the hotter flows trapped inside the groove region in upward and spanwise directions, which causes significantly higher streamwise, spanwise and downward velocities. Replacing transverse protrusions with convex dimples can enhance heat transfer rate, except the case with convex dimples which are too close to side walls. All cases with convex dimples provide the significantly lower friction loss but higher thermal performance factor than that of the case with transverse protrusions. Additionally, for the convex dimple number studied here, increasing the number of convex dimples leads to a significant increase in Nusselt number as well as thermal performance factor but a slight increase in friction factor. Besides that, the spanwise shift of convex dimples shows complex results. Fig. 1 illustrate the geometry of the roughness profile.

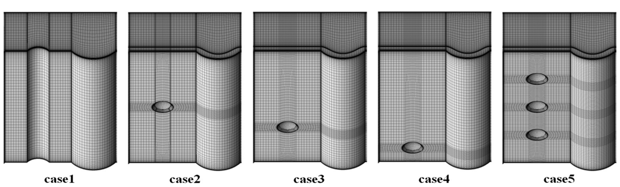
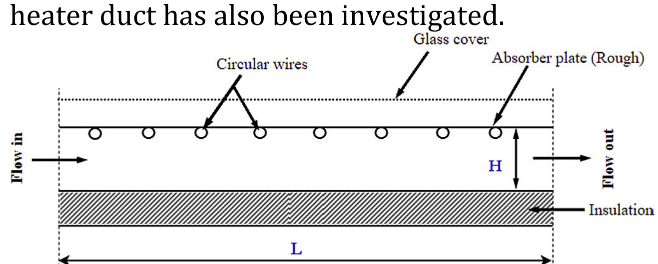


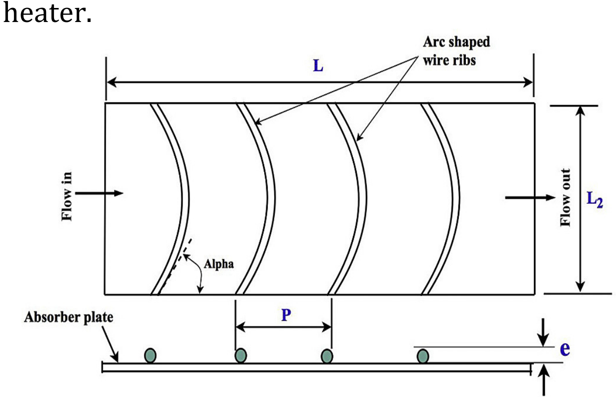
Fig. 1. Convex Dimples with Groves

WireRibs:

Sahuand Prasad [3] carried out a comprehensive investigation on thermal and thermohydraulic performance of solar collector for heating air having circular wire rib roughness in the form of arc shape on the back side of absorber plate as shown in fig. 3. A mathematical model incorporating the operating and system parameters has been developed and the results have been computed by using MATLAB for specified range of these parameters. A conventional solar air heater working under similar conditions has also been considered for the purpose of comparison. At rib height-to-duct hydraulic diameter ratio =0.0422 and flow-attack-angle =0.3333 the values of maximum thermal and effective efficiencies were found to be 79.84% and 75.24% respectively for the range of parameters used in the investigation. Further, the thermal efficiency, obtained in the present work has been compared with those obtained for other roughness geometries available in the literature for common roughness parameters and operating parameters to validate the results. Optimization of different parameters of wire roughness for optimum thermohydraulic (effective) efficiency of solar air heater duct has also been investigated.



(a) Roughened absorber plate solar air heater.



(b) Arc shape absorber plate with wire rib roughness.

Fig. 2. Wire ribs

Rectangular Ribs:

Kumar et al. [4] in their experiment monitored the enhancement of thermal performance of solar air heater. rectangular geometry of ribs is considered over the absorber plate. The fluid flow characteristics and heat transfer in ribbed triangular duct (with an apex angle of 60°) SAH is analysed using computational fluid dynamics (CFD). The roughened side ofduct is subjected to a constant heat flux of 1000 W m^{-2}, whereas, roughness elements are adiabatic in nature. The three-dimensional model of SAH is developed and numerical simulations are carried out by developing CFD code with the help of finite volume method. The numerical simulations are performed on commercial ANSYS Fluent 12.1 software.

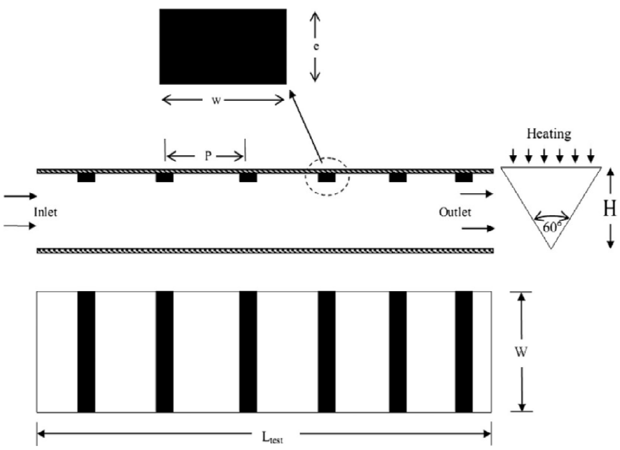


Fig. 3. Rectangular ribs

A new roughness parameter called rib aspect ratio (e/w) is introduced in this study and its effect on friction factor (f) and Nusselt number (Nu) is investigated along with relative roughness height (e/D) and relative roughness pitch (P/e) for the Reynolds number ranges from of 4000 to 18,000. The values of rib aspect ratio (e/w), roughness height (e/D) and relative roughness pitch (P/e) range from 0.25 to 4.0, 0.02 to 0.04 and 5 to 15, respectively. A considerable increase in friction factor (f) and Nusselt number (Nu) is observed due to rectangular rib in comparison to smooth one. A significant enhancement in Nu and f is observed by using rectangular rib roughness and it is shown in Fig.3 respectively. The maximum enhancement in Nusselt number (Nuenh) is seen in case of P/e value of 10 in comparison with smooth duct SAH. With increase ofP/e ratio from 5 to 10, Nuenhvalue increased. But with increase in P/e value beyond 10 to 15, Nuenhstarted decreasing. Nu increased by 2.70 times the smooth duct SAH in case of P/e value of 10, whereas, minimum enhancement of 2.02 is observed for P/e value of 15.

V - Shaped Ribs:

Ravi and Saini [5] in their work constructed an experimental setup consisting of a double pass solar air heater duct provided with discrete multi V-shaped and staggered rib as artificial roughness on both sides of the absorber plate has been designed and fabricated. The parameters of interest investigated experimentally, cover a wide range of Reynolds number (*Re*) from 2000–20000, relative staggered rib pitch (*p'/p*) from 0.2–0.8, relative staggered rib size (*r/e*) from 1–4 and relative roughness width (*W/w*) from 5-8. Experimental data related to heat transfer, pressure loss and thermohydraulic performance has been determined. Substantial improvement has been obtained with some penalty of friction losses. Discrete multi V-shaped and staggered rib geometry significantly enhances both Nusselt number and friction factor as compared to smooth surface. The increment in Nusselt number lies between 2.91 and 4.52 with the increment in friction factor from 2.08 to 3.13 as compared to smooth DPSAH. The maximum value of Nusselt number has been found correspond to *r/e* =3.5, *p'/p*=0.6 and *W/w*=7 whereas the maximum value of friction factor has been observed at *r/e* =3.5, *p'/p*=0.6 and *W/w*=8. Substantial enhancement in thermohydraulic characteristics has been obtained with staggered rib piece in the central rib region of discrete multi V- shaped ribs. Maximum value of thermohydraulic performance has been observed corresponding to a relative staggered rib pitch of 0.6, relative staggered rib size of 3.5 and relative roughness width of 7. Roughness geometry of V – shaped rib is shown in fig. 4.

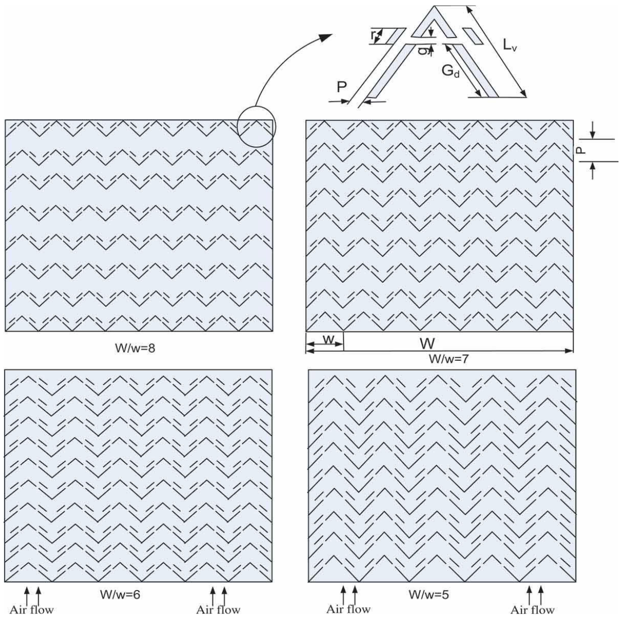
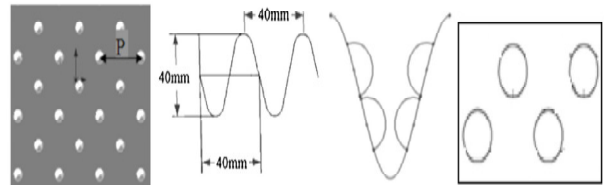


Fig. 4. V shaped ribs

Different Surface Shapes:

Li et al. [6] carried experimental investigation on the absorber surface of the collector whose shape was made up to provide better heat transfer surfaces was presented. In the study four types of air solar collectors: sinusoidal corrugated plate, protrusion plate, sinusoidal corrugated and protrusion plate and a base flat-plate collector are presented.In their work, the aim was to increase the solar air collector efficiency using passive method in air collectors. When comparisons were made among the four collectors, the same time of days with the same radiation was used for all collectors. Collector performance tests were conducted on days with clear sky condition. The collector efficiency increased with increasing mass flow rate of fluid. The thermal efficiency of type-III is the highest among the four types under the same mass flow. The efficienciesof collectors increased approximately 1.08-fold in type-II, 1.31-fold in type-III, 1.23-fold in type IV compared to the flat-plate (type-I) collector. Different surface shapes are shown in fig. 5.



A. Type IIB.TypeIII C. Type IV

Fig. 5.Different surface shape

C Shaped Ribs:

Gabhane et al. [7] carried out an analysis in which the thermal and hydraulic performance of Double Flow Solar Air Heater (SAH) roughened with multiple C-shape rib was investigated experimentally. Three rib angles were used for different rib geometries with varying pitch distance, an angle of attack and Reynolds number. Multiple C-shaped ribs in double flow arrangement provides better heat transfer than other arrangements. Correlations were developed for Nusselt number, friction factor, Stanton number and Thermohydraulic performance parameter to increase the usefulness of result. Following Conclusions have been made (a) Double flow Solar Air Heater performs better over singleflow arrangement.(b) Multiple C-shape arrangement on both sides of absorber gives more heat transfer than scattered C-shape roughness. (c) Three roughness angles and five pitch distances are used for investigation. i.e. fifteen roughness models investigated.(d) Maximum Nusselt number was 415 obtained for relative roughness pitch of 24, roughness angle of 90˚and 15,000 Reynolds number. (e) This roughness arrangement gives friction factor of 0.031 with 3.48 Thermohydraulic performance parameter. (f) Statistical correlations were developed for Nusselt number, friction factor, Stanton number and thermohydraulic performance parameter which gives maximum average deviations below 12% with reasonable accuracy. Roughness geometry is shown in fig. 6.

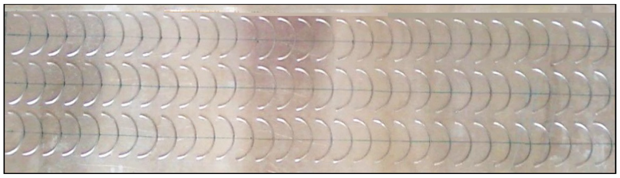


Fig. 6. C shaped

Square Ribs:

Singh and Singh [8] Carried out an investigation of the thermal and hydraulic performance of solar air heater duct roughened with non-uniform cross-sectioned square wave profiled transverse rib on ANSYS Fluent 15.0. The 3-D investigation considered parameters as relative roughness pitch 4–30 and Reynolds number 3000–15,000, while relative roughness height has been fixed as 0.043.

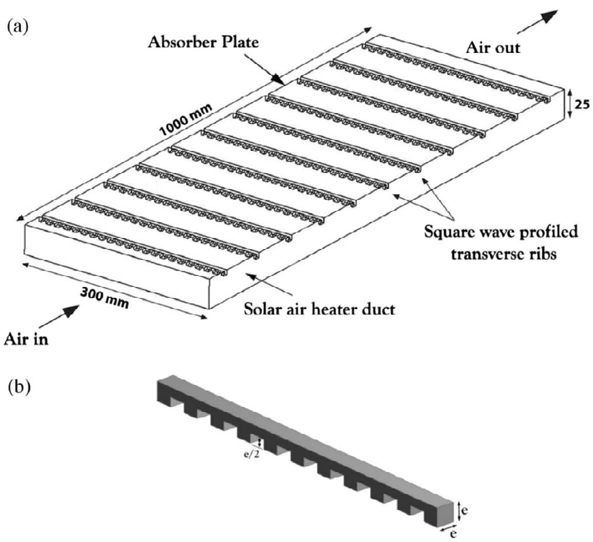


Fig. 7.Square shape rib

The turbulence model RNG k-ε with enhanced wall treatment and one periodic length was selected for analysis. The CFD methodology has been validated with the experimental results available in literature. The maximum augmentation in Nusselt number and friction factor over smooth duct was found to be 2.14 times and 3.55 times respectively at relative roughness pitch of 10 and Reynolds number of 15,000. The heat transfer and fluid flow process are discussed and visualized using streamlines and contours. The maximum thermohydraulic performance parameter was observed to be 1.43 at relative roughness pitch of 10 and Reynolds number of 12,000. The thermohydraulic performance for the nonuniform rib was also observed to be more than uniform cross-sectioned rib. Square profile of ribs is shown in fig. 7.

Prismatic Ribs:

Sharma et al. [9] presented an experimental study of detailed heat transfer and flow field characteristics in a rectangular duct having different types of truncated prismatic ribs on the bottom surface. The truncated prismatic ribs are manufactured by tapering the square rib from both the sides up to the center to provide rib height at the ends of 0, 2, 4, 6 and 8mm. Experimental heat transfer results using transient liquid crystal thermography (LCT) are reported along with the mean flow field results using particle image velocimetry (PIV) at a rib pitch-to-height ratio of 10. The heat transfer effectiveness of proposed rib configurations is evaluated by examining the surface and spanwise-averaged Nusselt number distribution. From the experiment it has been observed that the local heat transfer distribution is found to be axisymmetric and shows 2-dimensionality in heat transfer distribution for all rib configurations. The mapping of augmentation Nusselt number indicates the footprints of reattachment, separations and recirculation bubble in terms of spatial HTC distribution, except at Re=9400. Among the studied rib configurations, truncated prismatic rib with $ep/e = 1/4$ yields the highest overall averaged augmentation Nusselt number, about 25.15% higher than those with the square ribs at Re=58,850. Truncated prismatic rib with $ep/e = 0$ provides a better performance in friction factor ratio, about 54.65% lower than those with the square ribs.

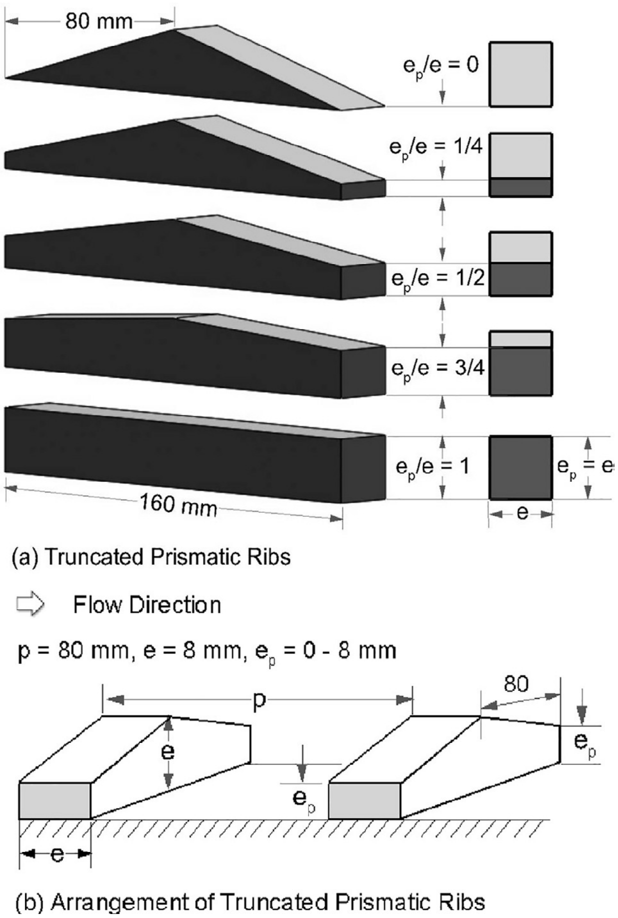


Fig.8. Prismatic rib geometry

Helical Profile of Surface:

Heydari andMesgarpourb [10] presented the effect of helical channelling on the performance of a solar heater is investigated both experimentally and numerically. The innovation of their research was designing a triangular cross-section channel, in such a way to establish a helical air flow through the air heater, in which the flow exchanges heat with the bottom and the top of the absorber plate. Once finished with measuring various thermal parameters of the system experimentally at two different flowrates, overall heat transfer coefficient and thermal efficiency of the system are calculated. The improvement of thermal performance for the present solar air heater with helical path was investigated and it was indicated that thermal efficiency of the system is improved 14.7%, 8.6%, 75% and 47% in compared with simple duct, double pass-finned plate, Smooth surface absorber plate with helical path and porous surface absorber plate with helical path respectively. Roughness geometry is shown in the fig. 9.

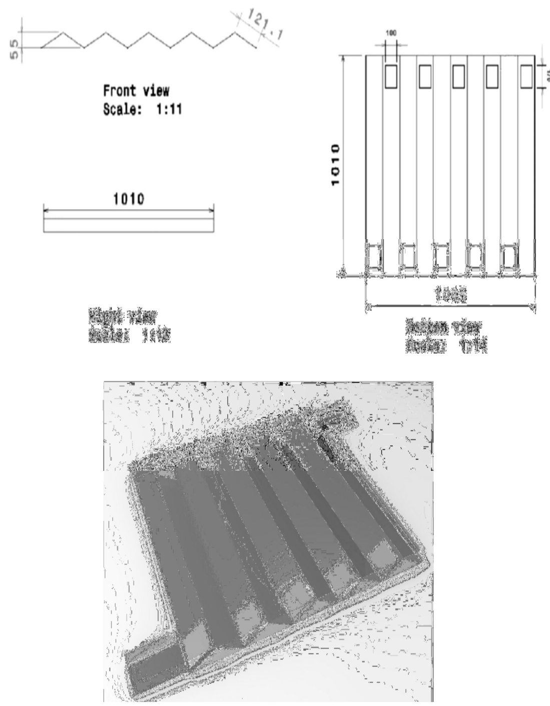


Fig.9. Helical Geometry

Criss Cross Ribs:

Singh et al. [11]in their paper presented the findings from experimental and numerical study of heat and fluid flow in a straight square duct featuring rib turbulators in a criss-cross pattern formed by 45˚angled rib turbulators. Two ribbed configurations with criss-cross pattern, Inline and staggered, have been studied where the baseline case was smooth duct with no heat transfer enhancement feature. Detailed heat transfer coefficients were calculated using transient liquid crystal thermography by employing 1-D semi-infinite conduction model. Heat transfer and pressure drop measurements were carried out for Reynolds number ranging from 30,000 to 60,000. Some of the findings that were made are, the friction factor for the inline configuration was relatively lower than the staggered configuration. The thermal hydraulic performance of both the inline and staggered configurations were similar to each other and the values changed from ~1.2 to ~1.5 for Reynolds number ranging from 30,000 to 60,000.

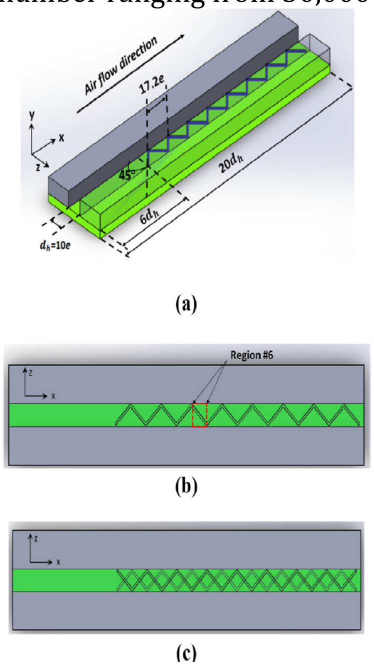


Fig.10.Criss crossribs

Pin Fins:

Sivakumar et al. [12] carried out a study on thermodynamic analysis of a forced convection solar air heater using pin-fin absorber plate and compared it with the standard flat absorber plate. The results showed that the pin-fin absorber plate hasabout 17°C higher outlet air temperature when compared to the flat absorber plate. The energy efficiency as well as exergy efficiency of a forced convection solar air heater using pin-fin absorber plate was also found to be much higher as compared to flat absorber plate. The pressure drop of pin-fin absorber plate was found to be about 60% higher compared to the flat absorber plate due to the presence of drag resistance. They concluded that forced convection solar air heaters using pin-fin absorber plate is having significant performance improvement in thermodynamic performance with minimum pressure drop across the air heater duct. The experimental arrangement is shown in figure 11.

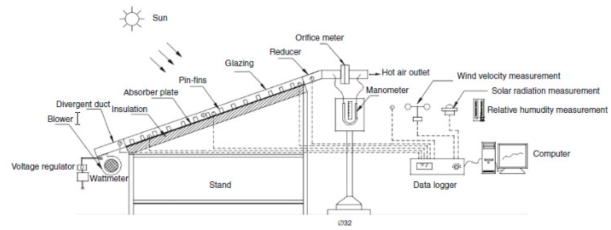


Fig. 11. Experimental setup of the pin fin absorber plate

Longitudinal Intersecting Ribs:

ChabaneZhang et al. [13] carried out detailed numerical investigation of a stationary high-aspect-ratio rib-roughed rectangular cooling channel with longitudinal intersecting ribs near the gas turbine blade trailing edge region. For the configuration without longitudinal intersecting ribs, a dominant secondary flow is generated near the intersecting region between the angled rib and the side wall, where high heat transfer augmentation region exists. However, the velocity of the secondary flow rapidly decreases along the angled rib. The high heat transfer region is almost absent in the lower part of the cooling channel. Through adding more longitudinal intersecting ribs on the bottom channel wall, more secondary flows are generated from the intersecting corner between the longitudinal ribs and the angled ribs. The area of high heat transfer regions is enlarged on the bottom channel surface, and the area-averaged heat transfer augmentation also increases as compared to the configuration without longitudinal intersecting ribs. Unfortunately, the pressure loss also increases with an increase in both the number of longitudinal intersecting ribs and the Reynolds number. The angled rib-roughened cooling channel with two sets of longitudinal intersecting ribs shows the best overall thermal performance in the Reynolds number range from 10 000 to 30 000.

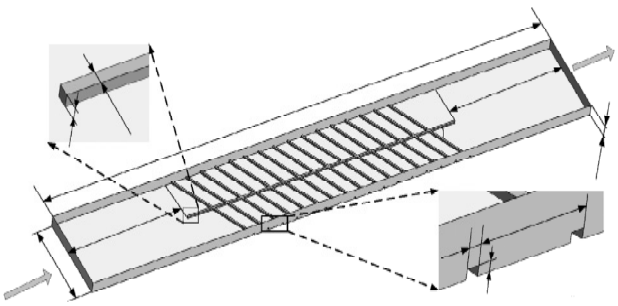


Fig. 12. Longitudinal intersectingribs

Transverse Rectangular baffles:

Chabane et al. [14] investigated the outcome of arrangement of transverse rectangular baffles perpendicular to the air stream. Authors added the baffles in the following order: for mode 1, six baffles were installed on the entry of the air stream; for mode 2, another six baffles were installed in the centre of the air stream; and for mode 3, six baffles in the end of air stream. They concluded from the results that not only adding baffles increases the thermal efficiency of the solar collector but also the placement has an impact on the thermal efficiency, temperature different, outlet temperature, and the absorber plate which states that adding baffles create more turbulence. By creating more turbulence, the heat transfer will increase between the absorber plate and the air below the absorber and that will lead for enhancing the heat exchange between the air and the absorber which will in turn lead to a better thermal efficiency. Fig. 13 shows the arrangement of rectangular baffles.

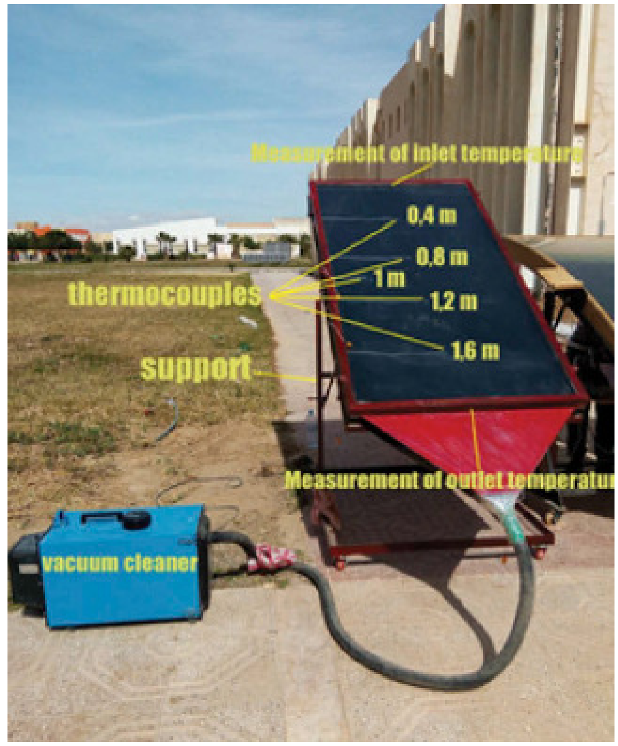


Fig.13. Transverse rectangular baffles

Wavy Fin Absorbers:

Priyam and Chand [15] examined the thermal performance of wavy finned solar air heater. The effect of mass flow rate, fin spacing and insolation on thermal efficiency and air temperature rise of wavy fin solar air heaters are investigated. Authors conducted a study to evaluate the thermal performance of wavy fin absorber solar air heater. They found that the wavy fin solar air heater with the lower fin spacing performs better than higher fin spacing due to the enhanced heat transfer area by narrowing the channel. Also, the lowest mass flow rate leads to higher temperature difference. They reported that the maximum efficiency of 69.55% has been found for the mass flow rate 0.0158 kg/s and fin spacing of 2 cm. They examined the effect of insolation for the various fin spacings and the improved thermal performance of wavy fin solar air heater has been found due to the improved surface conductance of finned absorber plate.

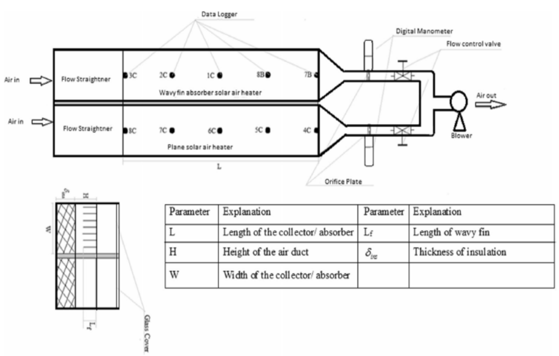
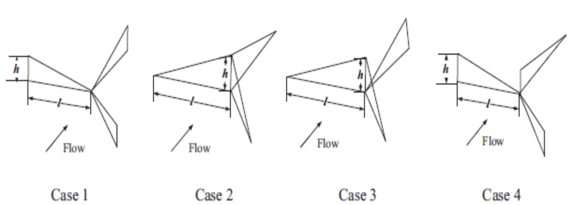


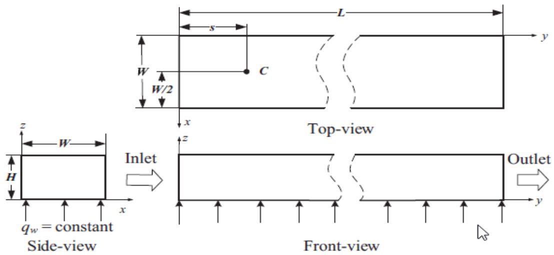
Fig. 14. Wavy fin absorber

Rectangular Channel withCombined Delta Winglet Inserts:

Liu et al. [16] conducted an experiment to study flow and heat transfer characteristics in a rectangular channel with combined delta winglet vortex generators. Authors used numerical methods to study the effects of the arrangement of winglets, rotation angle of the combined winglets and spacingbetween delta winglets on heat transfer and friction factors. The maximum Nusselt number ofthe channel is enhanced by 92%, however the friction factor is increased by 178% compared to that ofa smooth rectangular channel.The best geometry isexhibited by Case 1 because the largest volume of the swirl is generated.Authors concluded that both of the Nusselt number and friction factor first decrease and thenincrease with the rotation angle.The Nusselt number in rectangular channels fitted with thecombined delta winglet inserts is larger than that in smoothchannels due to vortices generated. Compared to plain channels, the maximum Nusselt number is increased by 92%, 81%, 76%, and 75% for Case 1, Case 2, Case 3, and Case 4, respectively.



(a) Physical model of four kinds of composite winglets.



(b)Three views of rectangular channel

Fig. 15. Rectangular channel with combined delta winglet

Trapezoidal Ribs:

Ali et al. [17] conducted an experimental study of flow over array of trapezoidal-ribs transversely placed on the wider bottom surface of the rectangular passage. Authors intended to study the profound impact of taper angle variation (0 to 20°) on the flow mechanism, its impact on the surface heat transfer distribution at a typical Reynoldsnumber of 42500 and subsequently on heat transfer improvement. As compared to square rib, trapezoidal rib provides higher heat transfer rate.Trapezoidal ribs provide higher heat transfer just behind the rib than that of square rib, and vice-versa at farther downstream locations. The square rib provides the lowest pressure drop penalty, which is around 5.48 times more than smooth duct and about 5.84 % lower than that of trapezoidal rib with $\alpha = 5^{o}$. The ribs with smaller taper angle, i.e., $\alpha = 5^{o}$ provide outstanding effectiveness in terms of overall thermohydraulic performance. Rib configuration is shown in the fig. 16.

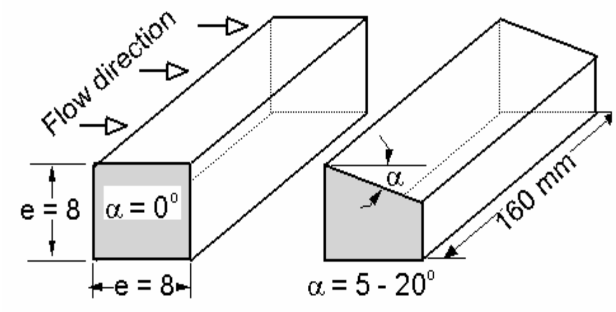
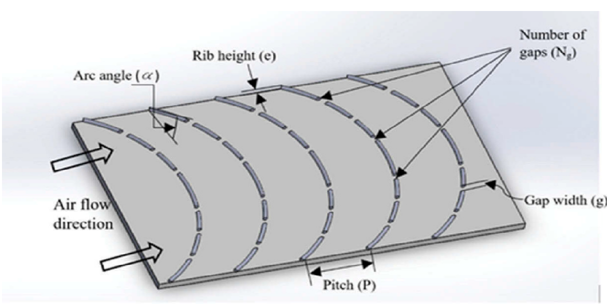


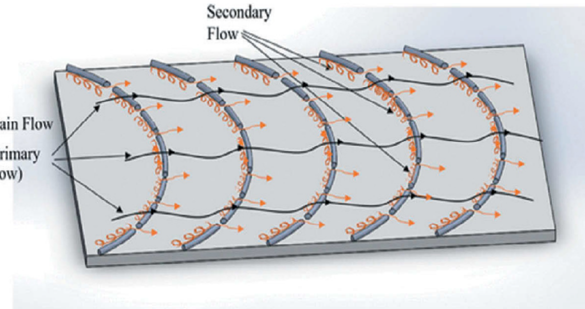
Fig. 16. Trapezoidal rib configuration

Arc Shaped Ribs:

Jain et al. [18] studied the heat transfer augmentation in a solar air heater (SAH)using arc-shaped ribs with multiple gaps. Multiple gaps in arc-shaped ribs areused to enhance the heat transfer by interrupting the growth of the boundarylayer. Authors observed that multiple gaps allow secondary flow to pass through the gaps, whichsuppresses the boundary layer thickness and enhances the heat transfer.Number of gaps in arc-shaped ribs pattern significantly affects the heat transfer and pressuredrop. Absorber surface roughened with the multiple gaps arc shaped geometry gives better heat transferthan the one, roughened with continuous arc-shaped ribs.For roughened SAH duct, the heat transfer and pressure drop arefound to be 274% and 169% higher than that for smooth SAH duct at Number of gaps (N_g) = 3.



(a) Multiple gaps in arc-shaped ribs.



(b) Flow pattern for proposed geometry.

Fig. 17.Arc shaped ribs

V-Ribs and Chamfer-V-Grooves:

Promvonge and Skullong [19]carried a study to investigate the influence of combined turbulence promoters(or turbulators) on forced convection and fluid flow resistance behaviours in a solar air heater duct using two turbulators which included V-ribs with punched holes and chamfered V-grooves.

Fig. 18. V ribs and Grooves

TheV-rib and the V-groove having the attack angle of 45° were mounted repeatedly on the absorber platewith their arrangements for V-tip pointing upstream and pointing downstream.The novel combined turbulators can generate longitudinal vortex generator of the mainflow that helps to increase the flow intensity and to move thecentral flow to the near-wall flow regions while the air jetpassing through the downward holecan provide the impingingflow on some area of the absorber.

Authors recommended the combined turbulators with V-up arrangementbecause they have an advantage on thermal performanceover the ones with V-down. Authors concluded that the combined punched-V-rib and chamfered-Vgrooveprovide the augmentation of thermal performance atabout 14–15% higher than the combined solid-V-rib andchamfered-V-groove and also at about 56–77% above thegroove alone.

Pentagonal Rib:

Debnath et al. [20] investigated the 2-D fluid flow and heat transfer characteristic in a roughened rectangular duct with pentagonal ribs. The influences of the Reynolds number, non-dimensional relative height, non-dimensional relative pitch on the thermal performance factor and hydraulic performance factor are discussed.Authors revealed that a secondary flow is generated just after the ribs.

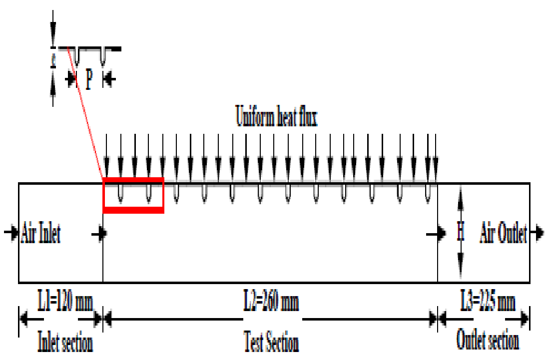


Fig. 19. Experimental Setup

Two types of vortex are generated, one is clock wise and another is anti-clockwise directed. Due to this opposite rotation of air, cold air easily come to the contact of hot wall and gained maximum amount of heat that could make the system efficient and effective. The results indicate that the Nusselt number increases with the increase in P/e and decrease in e/D, while, an opposite trend is observed for the friction factor. They concluded that the maximum enhancement of Nusselt number by 70% and the friction factor by 67.2% have been obtained at the investigated parameters. The maximum enhancement of Nusselt number by 70% and the friction factor by 67.2% have been obtained at roughness height ofe/D = 0.045, Roughness pitch ofP/e = 8, for all the investigated parameters.

V-Shped Slit Rib:

Zheng et al. [21] conducted a study on the concept for improving thermal performance ofchannel cooling by placing the V-shaped slit ribs. Five different geometricalmodels were investigated, includingthe ribs with rectangular slits, V-shaped slits, anti-V-shaped slits, broken V-shaped slits andbroken anti-V-shapedslits.

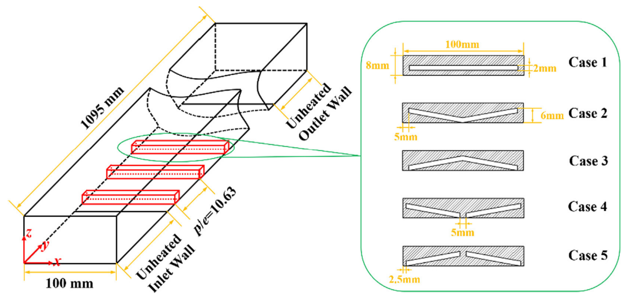


Fig. 20.Schematic diagram of V-shaped slit rib

The slitribs could reduce the area of recirculation flow and modify the flowstructures by generating the secondary jet flow to impinge on the recirculationflow directly.The thermalperformance index, which comprehensively evaluates thethermal performance of channel cooling, shows the thermal performance in thechannels with broken slits is inthe highest level due to the increased heat transfer enhancement and limited increase of pressure loss penalty. Authors stated that broken anti V-shaped slits give thehighest value of thermal performance index at lowReynolds numbers, whilebroken V-shaped slits presents the highest level of thermalperformance index at high Reynolds numbers. The diagram of geometry is shown in the fig. 20.

Three Side Concave Dimple Roughened SAH:

Kumar [22] experimentally investigated upon 1 & 3-sides concave dimple roughened ducts. Author has considered two cases comparison. They are: One side roughened duct with three sides insulation and Three sides roughened duct with one side insulation. The enhancement of 'Nu'due to provision of artificial roughnesswas strongly associated with roughness & flow parameters.Friction factor was found to decreasemonotonously as the relative roughness pitch 'p/e'increased from 8 to 12 for both the roughened ducts.Themaximum enhancement in 'Nu' for varying 'p/e', 'e/Dh' & 'e/d'was respectively found to be of the order of 2.6-3.55 times, 1.91-3.42 times and 3.09-3.94 times than one side concavedimple roughened duct for the parameters range investigated.

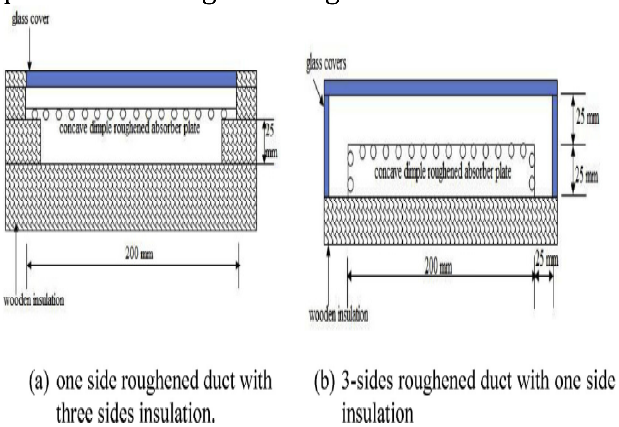


Fig. 21. Dimple Roughened SAH

Cubical Ribs:

Nanjundappa [23] investigated experimentally theeffect of cubical three-dimensional roughness configurationson the absorber surface of a solar heater to improve itsperformance. Arrangement patterns ofroughness elements on the absorber surface affects thermohydraulic performance toa greater extent. Author stated that cubical roughness elements used in this investigationproduces better heat transfer characteristics. However, this enhancementis particularly accompanied by increased pumping power due to increasedfriction.Maximum enhancement of Nusselt number is found to be 72.7% corresponds to the relativeroughness gap (w/e) of 4 and relative roughness pitch (p/e) of 10. Minimum enhancementof the friction factor is found to be 138.7% corresponds to the relative roughness gap (w/e) of 8 and relative roughness pitch (p/e) of 20. Fig. 22 shows the geometry of cubical ribs.

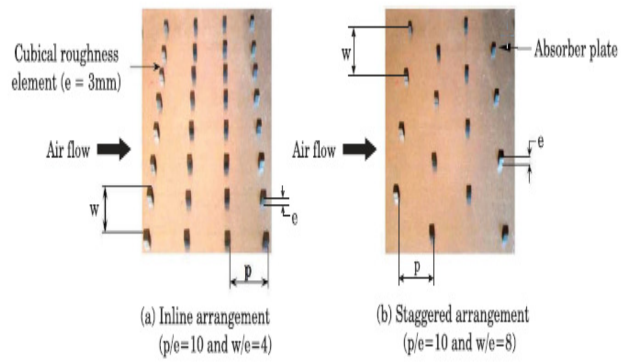


Fig.22. Cubical ribs

Discrete Multiple Arc Shaped Ribs:

Kumar et al. [24] experimentally investigated the multiple-arc shaped (three arcs) rib roughness. Remarkableimprovement in thermal performance of solar air heater is observed byvarying roughness parameters but it leads to increase in pumping power of solar air heater.Significant change in thermal and hydraulic characteristics has observedby fabricating multiple arced roughness on the heated sidecalled absorber plate of the SAH. Analysis show that the Reynolds number is more sensitiveparameter in changing Nusselt number and friction factor. The Nusselt number improved with the change of number of gaps from 1 to 3 andmaximum value obtained is 4.83 times the smooth solar air heater. The geometry of the ribs is shown in the figure 23.

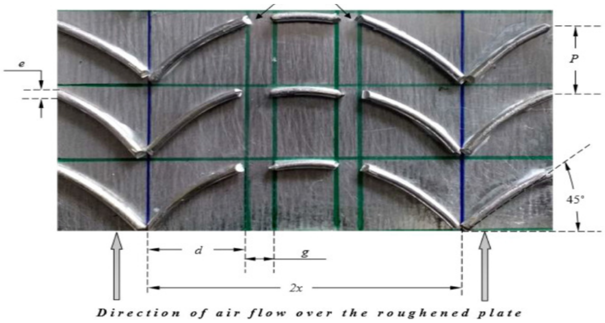


Fig. 23. Multiple arc shaped ribs

Delta Shaped Vortex Generator:

Baissi et al. [25] investigated the heat transfer and energy loss due to flow friction in the absorbersurface of a SAH channel fitted with perforated and non-perforatedlongitudinally curved delta-shaped baffles.Two cases have beendealt with perforated and non-perforated baffles.The obtained results averred a significantaugmentation in heat transfer andreduction in pressure drop. Whereas, Nusselt number (Nu) and in airflow friction (f) have reachedrespectively 6.94and 45.83 times more than smooth channel.It has been found that in case of perforated longitudinally curveddelta shaped baffles a resistance to the flow was developed especiallywhen P_1/e and P_t/b ratios became large. The maximum value of thermal enhancement factor (TEF)recordedwas equal to 2.26 and it is obtained in case of perforated longitudinallycurved delta shaped baffles with Re in the range of 11,382, and P_1/eand P_t/b are equal to 3 and 0.6 respectively.

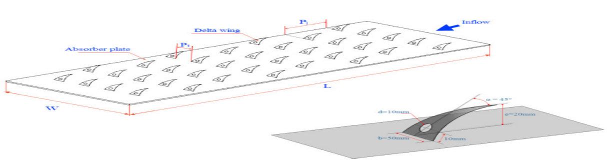


Fig. 24. Delta shaped winglets

IV. CONCLUSION

This article presents a review of the studies carried out by numerous researchers in order to enhance the heat transfer, thermal performance and thermal efficiency by the utilization of artificial roughness of different forms, contours and orientations. It is observed that the investigators have performed a lot of experimental and analytical work by implementing distinct shapes and types of artificial roughness such as wavy fin, rectangular pin fin, arc shaped ribs, pentagonal ribs, trapezoidal ribs, etc. to increase the heat transfer characteristics of solar air heater. enhancement in heat transfer with little penalty of friction. This paper is very beneficial for researchers in carrying out the experimental and numerical investigations to find out and improve the new geometries for the maximum improvement 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 application of artificial roughness leads to substantial enhancement in the heat transfer and thermal performance of solar air heater. The Nusselt number increases with the increase in Reynolds number for all the roughness geometries.
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. Several 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 forecast the thermal as well as thermohydraulic performance of solar air heaters having roughened ducts.
5. 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.

6. It came into view that the thermo-hydraulic performance is enhanced by varying the configuration of roughness from straight to pin fin, pin fin to V-rib, V-rib to arc shaped ribs and so on. It is also noticed that the creation of gap or hole in a rib roughness produces better result.
7. 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.

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