Heat Transfer Enhancement Through A Rectangular Channel With Turbulators- A Review

Sanjeev Kumar[1], Dharmendra Rathore[2]
[1, 2] Dept of Mechanical Engineering
[1, 2] Bagula Mukhi College of Technology, Bhopal (M.P), India

Abstract- *Turbulators and different obstruction used in the path of air passage through channel used to increases the heat transfer either by breaking the laminar sub layer or by increasing the turbulence in duct passage for air flow. Several types of turbulators elements were used extensively to improve the heat transfer characteristics in this equipment. The roughness elements of two dimensions, three dimensions and of irregular shapes were used by various investigators. This paper presents the review of enhancement of air channel. This paper is an attempt to summarize and conclude the investigations involving using small height elements and small surface protrusions on channel walls as artificial roughness elements of various geometries and its effect on heat transfer and friction factor through experiments.*

Keywords- Heat transfer, Pressure Drop, CFD.

I. INTRODUCTION

The initial efforts on using turbulators for improving heat transfer characteristics were confided with the areas of nuclear reactors, gas turbines blades, pipes carrying fluids and compact heat exchangers. Several types of turbulators elements were used extensively to improve the heat transfer characteristics in these equipment. The roughness elements of two dimensions, three dimensions and of irregular shapes were used by various investigators. The concept of artificial roughness was first applied by Joule [1] to enhance heat transfer coefficients for in-tube condensation of steam and since then many experimental investigations were carried out on the application of artificial roughness in the areas of cooling of gas turbine, electronic equipment, nuclear reactors, and compact heat exchangers etc. Nunner [2] was the first who developed a flow model and likened this model to the temperature profile in smooth tube flow at increased Prandtl number. The proposed flow model predicts that roughness reduces the thermal resistance of the turbulence dominated wall region without significantly affecting the viscous region. The argument was quantified by using the Prandtl analogy and replacing Pr by $(f/f_s)P_r$. This model predicts that value of St/Sts decreases with increase in Prandtl number. The proposed flow model also predicts that St/Sts, is independent of the roughness type. A friction correlation for flow over sand-grain roughness was developed by Nikuradse [3]. Based on law of the wall similarity, Nikuradse presented the pressure drop results in terms of roughness function R and roughness Reynolds number e+. Dipprey and Sabersky [4] developed a heat-momentum transfer analogy relation for flow in a sand-grain roughened tube and achieved excellent correlation of their data. The concept proposed by Dipprey and Sabersky was so common and it can be applied to any roughness for which law of the wall similarity holds. Prasad and Mullick [5] were the first who introduced the application of artificial roughness in the form of small diameter wire attached on the underside of absorber plate to improve the thermal performance of solar air heater for drying purposes. After Prasad and Mullick's [5] work a number of experimental investigations of solar air heater involving roughness elements of different shapes, sizes and orientations with respect to flow direction have been carried out in order to obtain an optimum arrangement of roughness element geometry [6-9]. Effect of various parameters on the thermo-hydraulic performance of artificially roughened solar air heater through CFD approach can be obtained in Ref. [10-19]. The aim of present study is to review the effect of various turbulators geometries on the flow and heat transfer through the rectangular channel."

II. GEOMETRICAL PARAMETERS OF TURBULATORS

The key dimensionless geometrical parameters that are used to characterize artificial roughness are:

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.

Relative roughness height (e/D): Relative roughness height (e/D) is the ratio of rib height to equivalent diameter of the air passage.

Angle of attack (α): Angle of attack is inclination of rib with direction of air flow in duct.

Aspect ratio: It is ratio of duct width to duct height. This factor also plays a very crucial role in investigating thermo-hydraulic performance.

III. APPLICATION OF TURBULATORS IN RECTANGULAR CHANNEL

Ahn [20] investigated on five different types of roughness element (Fig. 1) in rectangular duct with e/DH =0.0476, P/e=8, and W/H=2.33, to understand the comparative thermo-hydraulic performance due to these elements. They concluded that the triangular rib has the highest heat transfer capacity and Nusselt number is higher in the case of square and triangular ribs when compared to semicircular ribs. The square ribs have the highest friction factor.

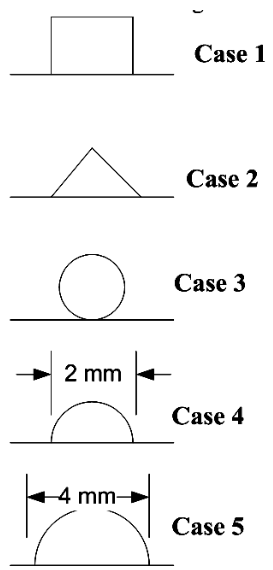

Fig. 1. Different geometries

Chandra et al. [21] investigated the effect with varying number of with transverse ribbed walls with the parameters Re = 10,000 to 80,000; P/e = 8; e/DH = 0.0625; L/Dh = 20 for fully turbulent flow in square channel. They concluded that one ribbed wall has the heat transfer increase of 2.43–1.78 (40% improvement) for Re = 12,000 to 75000, with two opposite ribbed walls the increment was 2.64 to1.92 (6% improvement), three ribbed walls has the increment of 2.81 to 2.01 (5% improvement) and with four ribbed walls, an increment of 2.99 to 2.12 (7% improvement). The maximum increase in the friction factor was found to be 9.50 with four sided ribbed walls and minimum with one ribbed wall of 3.14. They also compared the performance factor {(Str/Stss)/(fr/fss)} of four cases and concluded that, it is highest at 1.78–1.17 for one wall ribbed surface. Tanda [22] investigated for heat transfer coefficient distribution in rectangular channel with transverse continuous, transverse broken and V-shaped broken ribs with the parameter's W/H = 5; α = 45 or 60. Liquid crystal thermography was applied to the study of heat transfer from the ribbed surface. He found the maximum performance of continuous transverse ribs, 45 V-shaped ribs and 60 V-shaped ribs at the optimum value of P/e = 13.3, transverse broken ribs with P/e = 4 and 8 give the higher heat transfer augmentation. Transverse broken ribs with P/e = 4 and 13.3 gives best thermal performance and transverse continuous ribs again with P/e = 4 and 8 gives lesser heat transfer increment. Andallib et al. [23] investigated the heat transfer and flow characteristics in the entrance section of a rectangular channel with one and two solid ribs at the bottom surface. They used hot wire anemometry (HWA) and resistance thermometry (RTD) for measuring the velocity and temperature and Liquid crystal thermography (LCT) to trace temperature profiles, heat transfer coefficient evaluation and Nusselt number calculation. The various parameters used are Re = 2.09 x 10^4; P/e = 10. They compared the results of experimentation and theoretical energy balance and found similar performance under the given range of data selected. Won and Ligrani [24] compared the thermo-physical characteristics in channels with parallel and cross rib turbulators on two opposite surfaces with the parameters Reynolds number based on channel height = 480 to 18300; W/H = 4; α = 45; e/D = 0.078; P/e = 10. They found that Nusselt number is almost same for crossed and parallel-ribs, local. Nusselt number for parallel-ribs are significantly higher than crossed-rib and pressure loss is higher in central part of the channel. Wang and Sunden [25] performed investigation of heat transfer and fluid flow in rectangular channel with broken V-shaped up ribs using crystal thermography (LCT) and particle image Velocimetry (PIV) techniques using the parameters e/Dh of 0.06; P/e was kept to 10; α = 60; W/H = 1/8. They concluded that the performance in heat transfer is higher than the continuous ribs bur with more friction loss. Liu et al. [26] investigated on heat transfer increment in a solar air heater with the absorber plate roughened by extended surfaces geometry. Prasad and Mullick [27] investigated on solar air heater with protruding wires on underside of the absorber plate. They found improvement of 9% (from 63% to 72%) in plate efficiency for Reynolds number of 40,000. The plate efficiency is 44.5% higher in cross corrugated sheet with protruding wire than plane galvanized iron sheet. Gupta, Solanki and Saini [28] investigated the thermo-physical effect of transverse wire roughness on absorber plate on heat and fluid flow characteristics in transitionally rough flow region ($5 < e+ < 70$) for rectangular solar air heater ducts with the parameters Reynolds number (Re) = 3000 to 18000 for a duct aspect ratio (W/H) = 6.8 to11.5, relative roughness height (e/D) = 0.018 to 0.052 and relative roughness pitch (P/e) = 10. They concluded that the heat transfer increased up to 1.8 times than that of smooth solar air heaters at α = 60 and friction factor by 2.7 at α = 70 for the range of parameters investigated. Saini and Saini [29] investigated for fully turbulent flow with expanded metal mesh as artificial roughness element. They used rectangular duct with W/H=11; Relative longways length (L/e) = 25 to 71.87; Relative short way length (S/e) = 15; e/D = 0.012 to 0.039 as different parametric values for Re = 1900 to 13000. They concluded that the maximum values of Nusselt number and friction factor occurs at angle of attack of 61.9 and 72. They also developed the correlation for Nusselt number and friction factor. Gupta et al. [30] investigated on optimum design and operating conditions in artificially roughened solar air heater using the parameters e/D = 0.023 to 0.05; Re = 4000 to 18000; Solar intensity (I) = 400 to 1300 W/m^2; α = 60. The optimum design conditions were determined and correlation was developed for Reynolds number using the parameters selected for investigations. Ekkad and Han [31] investigated on two pass square channel solar air heater with rib tabulators with parameters Re = 6000 to 60000; e/DH = 0.125; P/e = 10; α= 90 parallel, 60 parallel, 60 V, and 60 broken V shaped ribs. They investigated on thermo-physical characteristics and secondary flow before the 1800 turn, in the turn region, after the turn, and the downstream in the second pass through the channel. They concluded that Nusselt number ratios in the second pass to be 2 to 3 times higher than that for the first pass and the 60 parallel, 60 V. Also 60 broken V ribs gives high heat transfer rate in the first pass and 60 broken V ribs giving slightly better heat transfer, while, 60 parallel ribs give higher heat transfer in the turn and second pass respectively. Verma and Prasad [32] investigated for optimal performance parameters in the form of Reynolds roughness numbers e+ and thermal efficiency $\eta_{thermal}$ for the artificially roughened solar air heaters using the parameters Re = 5000 to 20 000; m = 0.01 to 0.06 Kg/sec; P/e = 10 to 40; e/D = 0.01 to 0.03 and e+ = 8 to 42. They found out the optimal value of e+ opt = 24 at which $\eta_{thermal}$ = 71%, thus significant increase in heat transfer using artificial roughness in solar air heaters. Singh et al. [33] investigated the heat and fluid flow characteristics of solar air heater with discrete V down ribs as roughness elements with the parameters Re =3000 to15000; relative gap width (g/e) = 0.5 to 2; relative gap position (d/w) = 0.20 to 0.80; P/e = 4 to 8; α = 30 to 75 and e/Dh = 0.015 to 0.043. They also developed the correlations for Nu and f for the given range of parameters selected. The maximum increase in Nusselt number and friction factor calculated is 3.04 and 3.11 at the optimum values of parameters d/W = 0.65, g/e = 1.0, P/e = 8.0, α = 60 and e/Dh = 0.043. Momin et al. [34] investigated the effect of V-shaped ribs as roughness elements on the underside of the absorber plate of solar air heater with geometrical parameters as Re=2500 to 18000; e/DH=0.02–0.034; α=30 to 90; p/e =10; W/H = 10.15. They found the increase in heat transfer and friction of 2.30 and 2.83 than smooth duct at α= 60, also in comparison to inclined ribs the enhancement was in heat transfer was 1.14. They also found out the correlation for Nusselt number and friction factor for the V shaped ribs. Karwa [35] investigated the thermo-physical behavior of roughened solar air heater with transverse, inclined, V continuous and V discrete ribs with α = 60 for inclined and V patterns; Re = 2800 to 15000; R (e+) = 17 to 90. He also developed heat transfer and friction factor correlation based on the law of wall similarity and heat momentum transfer analogy. He found the increase in heat transfer of 65% - 90%, 87% - 112%, 102% - 137%, 110% - 147%, 93% - 134% and 102% - 142% respectively whereas the increase in friction factor for the ribs were 2.68 – 2.94,3.02 – 3.42, 3.40 – 3.92, 3.32 – 3.65, 2.35 – 2.47 respectively. Sahu and Bhagoria [36] investigated the heat transfer coefficient in the solar air heater using 90 broken integral transverse ribs on absorber plate with the parameter’s W/H = 8; Re = 3000 to 12000; P/e = 6.67, 13.33, 20; e/D = 0.0338 and I= 750–880 W/m^2. They concluded that maximum heat transfer and efficiency 83.5% occurs at P/e =1.33. They find considerable increment in heat transfer and with friction factor. Jaurker at al. [37] investigated the thermo-physical characteristics of rib grooved artificial roughness in rectangular solar air heater duct with the parameters Re = 3000 to 21,000; e/D = 0.0181–0.0363; P/e = 4.5–10; relative groove position ratio (g/p) = 0.3 to 0.7. They also developed the correlations for Nusselt number and friction factor. They concluded that rib-grooved duct with P/e = 6.0 and g/p = 0.4 the maximum value of the Nusselt number is 2.75 and with P/e = 6.0, g/p= 0.4 e/D = 0.0363, the maximum value of the friction factor is 3.61. Mittal et al. [38] Investigated the effect of various types of roughness element on absorber plate of the solar air heater with the parameter’s W/H = 10; e/D = 0.02 to 0.04; P/e = 10; Re = 2000 to 24000 to find out the effective efficiency using the correlations for heat transfer and friction factor developed by various investigators for the range of parameters they used. They concluded that the inclined ribs with low values e/D have high effective efficiency for Re > 12000, expanded metal mesh has better effective efficiency for Re < 12000 and effective efficiency of smooth solar air heater is higher than the solar air heaters with roughness for very high Reynolds number. Karmare and Tikekar [39] investigated the effect of solar air heater roughened with metal grit ribs with parameters e/Dh = 0.035 to 0.044; P/e = 12.5–36; relative length of grit (l/s) = 1.72 to1 and Re = 4000 to 17000. They also developed correlation for Nusselt number and friction factor within the range of parameters selected. They concluded that within the range of parameters selected the optimum values of parameters are l/s = 1.72, e/Dh = 0.044, P/e = 17.5 which gives optimum performance.

Webb et al. [40] covering a wide range of e/Dh ratio with P/e values of more than 10 was used in his experiments in flow through pipes where the ribs were aligned normal to the main stream direction. Firth and Mayer [41] investigated heat transfer and friction factor performance of four different types of artificially roughened surfaces with square transverse rib, helical rib, trapezoidal transverse ribs and three-dimensional surfaces in gas cooled reactor. The experiments conducted with roughness in one wall of absorber plate, two walls and four walls. The roughness element in one wall is favored by most of the investigators as discussed below in the range of Re = 3000 to 30000. Different correlations for heat transfer and friction factor were developed based on the experiments done by different investigators. Bhargava and Rizzi [42] demonstrated that the efficiency of solar air heaters can be increased by increasing the channel depth along length. Adel A. Hegazy R. [43] optimized the channel height of different types of solar air heater. J. C. Han, L. R. Glicksman and W. M. Rohsenow [44] investigated the effects of rib shape, angle of attack and pitch to height ratio on friction factor and heat-transfer on symmetric and staggered ribs. They found that the ribs at 450 of attack angle have better performance than at 900 attack angle and sand grain roughness. J. C. Han and J. S. Park [45] investigated on the combined effects of the rib, angle-of-attack (α = 90,60,45 and 30) and the channel aspect ratio (W/H = 1, 2 and 4) on the heat transfer coefficient in short rectangular channels (L/D = 10 and 15) with two opposite rib-roughened walls. They concluded that the highest heat transfer and the highest-pressure drop can be obtained at α = 60' in the square channel; the highest heat transfer and pressure drop occur at α = 90 with W/H = 4 in the rectangular channel and the values of highest heat transfer and pressure drop differs marginally at α = 60 for W/H = 2. The Heat transfer and friction correlations were also obtained for the surface. Shou-shing hsieh et al. [46] investigated effects of aspect ratio (W/H) = 1, 2, Reynolds number (Nu) 63.5 < Re < 254 and the initial boundary layer thickness on low speed forced convective heat transfer near two-dimensional transverse ribs. They also derived the correlation for average Nusselt number. Ying-Jong Hong et al. [47] investigated for turbulent flow on staggered ribs in a square duct with two opposite rib-roughened walls using the parameters e/DH = 0.19; p/e = 5.31 and Re= 13000 to 130000.The temperature distribution and correlations between Nusselt number and Reynolds number was established. The heat transfer rate was calculated to be 2.02-4.60 times higher than fully developed turbulent flow in smooth duct for Re = 13000. Jenn-Jiang Hwang and Tong-Miin Liou [48] investigated the thermo-hydraulic performance for a low aspect ratio channel with staggered slit ribs on top and bottom walls with the parameters β1= 24%, 37%, 46%; p/e = 10,15 20. W/H = 0.081; Re = 10000 to 50000.They concluded that the arrangement of ribs gives a higher heat transfer enhancement with lower pressure drop for the same solid rib height and spacing. Also, the friction factor decreases with an increase in rib open area ratio. They also developed the general friction and heat transfer correlations have been developed. Xiufang Gao and Bengt Sunden [49] investigated the heat transfer and pressure drop in a rectangular duct with staggered ribs of parameters aspect ratio (W/H) = 1 to 8; relative roughness height (e/DH) = 0.06; angle of attack (α) = 60; Reynolds number (Re) = 1000 to 6000.They observed that secondary flow causes span wise variation of heat transfer coefficient along the rib length and reattachment occurs between two ribs. They concluded that the V downstream ribs induce highest friction factor then V upstream and then parallel ribs with least friction factor. Also, V downstream has stronger secondary flow and gives higher heat transfer when compared to V upstream and parallel ribs and parallel ribs has better performance at higher Reynolds number than V upstream. Akira Murata, Sadanari Mochizuki [50] investigated on laminar and turbulent flow with transverse or angled rib turbulators of 600 or 900 in a square channel. They concluded that heat transfer is highest in front of the rib and laminar flow has lesser effect on flow field with ribs than turbulent flow as a result the velocity and temperature profiles have lesser differences than turbulent case. S. W. Ahn [51] investigated on five different types of roughness element in rectangular duct with e/DH =0.0476, P/e=8, and W/H=2.33, to understand the comparative thermo-hydraulic performance due to these elements. They concluded that the triangular rib has the highest heat transfer capacity and Nusselt number is higher in the case of square and triangular ribs when compared to semicircular ribs. The square ribs have the highest friction factor. P.R. Chandra et al. [52] investigated the effect with varying number of with transverse ribbed walls with the parameters Re = 10,000 to 80,000; P/e = 8; e/DH = 0.0625; L/Dh = 20 for fully turbulent flow in square channel. They concluded that one ribbed wall has the heat transfer increase of 2.43–1.78(40% improvement) for Re = 12,000 to 75000, with two opposite ribbed walls the increment was 2.64 to1.92(6% improvement), three ribbed walls has the increment of 2.81to 2.01(5% improvement) and with four ribbed walls, an increment of 2.99 to 2.12(7% improvement).The maximum increase in the friction factor was found to be 9.50 with four sided ribbed walls and minimum with one ribbed wall of 3.14.They also compared the performance factor {(Str/Stss)/(fr/fss)}of four cases and concluded that ,it is highest at 1.78–1.17 for one wall ribbed surface. Giovanni Tanda [53] investigated for heat transfer coefficient distribution in rectangular channel with transverse continuous, transverse broken and V-shaped broken ribs with the parameter's W/H = 5; α = 45 or 60. Liquid crystal thermography was applied to the study of heat transfer from the ribbed surface. He found the maximum performance of continuous transverse ribs, 450 V-shaped ribs and 600 V-shaped ribs at the optimum value of P/e = 13.3, transverse broken ribs with P/e = 4 and 8 give the higher heat transfer augmentation. Transverse broken ribs with P/e = 4 and 13.3 gives best thermal performance and transverse continuous ribs again with P/e = 4 and 8 gives lesser heat transfer increment. Andallib Tariq et al. [54] investigated the heat transfer and flow characteristics in the entrance section of a rectangular channel with one and two solid ribs at the bottom surface. They used hot wire anemometry (HWA) and resistance thermometry (RTD) for measuring the velocity and temperature and Liquid crystal thermography (LCT) to trace temperature profiles, heat transfer coefficient evaluation and Nusselt number calculation. The various parameters used are Re = 2.09 x 104; P/e = 10. They compared the results of experimentation and theoretical energy balance and found similar performance under the given range of data selected. S.Y. Won and P.M. Ligrani [55] compared the thermo-physical characteristics in channels with parallel and cross rib turbulators on two opposite surfaces with the parameters Reynolds number based on channel height (ReH) = 480 to 18300; W/H = 4; α = 45; e/DH = 0.078; P/e = 10. They found that Nusselt number is almost same for crossed and parallel-ribs, local. Nusselt number for parallel-rib are significantly higher than crossed-rib and pressure loss is higher in central part of the channel. Lieke Wang and Bengt Sunden [56] performed investigation of heat transfer and fluid flow in rectangular channel with broken V-shaped up ribs using crystal thermography (LCT) and particle image Velocimetry (PIV) techniques using the parameters e/Dh of 0.06; P/e was kept to 10; α = 60; W/H = 1/8. They concluded that the performance in heat transfer is higher than the continuous ribs with more friction loss. Several other types of turbulators elements were used extensively to improve the heat transfer characteristics [57-85].

IV. CONCLUSION

This article presents a detailed review of the experimental investigations carried out by various researchers in order to enhance the heat transfer by the use of turbulators of different shapes, sizes and orientations. On the basis of the review of the literature and comparative study of artificially roughened channel, the conclusion can be summarized as follows:

1. The use of turbulators on a surface is an effective technique to enhance heat transfer to fluid flowing in the duct. Artificially roughened channels have enhanced rate of heat transfer as compared to the smooth solar air heaters.
2. 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 duct should be made in such a way that it should transfer maximum heat energy to the flowing fluid with minimum consumption of blower energy.
3. It has been found that roughness geometries being used in ducts are of many types depending upon shapes, size, arrangement and orientations of roughness elements on the absorber plate.
4. There are several parameters that characterize the roughness elements, but for duct 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.

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