Asian Review of Mechanical Engineering
ISSN: 2249-6289 (P) Vol.11 No.1, 2022, pp.33-39

DOI: https://doi.org/10.51983/arme-2022.11.1.3331

A Comprehensive Review and Comparative Study of Various Rib Configurations Used in Rectangular Duct for Heat Transfer Enhancement

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(Received 22 February 2022; Revised 20 March 2022; Accepted 18 April 2022; Available online 22 April 2022)

Abstract - **This research study provides a comprehensive review of various heat transfer enhancement techniques that are being used by various researchers for enhancing heat transfer rate and overall thermal performance factor of the heat exchangers. Based on the present review study, it can be concluded that intensive study has been carried out by various researchers to determine the effect of various rib geometries on the heat transfer enhancement and friction factor characteristics of rectangular duct. The enhancement in the heat transfer rate is obtained by introducing the blockages or restrictions in the fluid flow path by providing various rib turbulator configurations. This research paper puts highlights on the various heat transfer enhancement techniques are used for increasing overall thermal performance factor in the heat exchangers. Introduction of ribs as flow disturber results not only into increase in heat transfer surface area but also into increased turbulence, recirculation of working media, viscous effect and secondary flow that results into swirl. The interruptions or blockages created by ribs provided in the flow channel results into increased pressure drop and disruptions in boundary layer development. Provision of ribs also causes secondary flow which ensures enhanced thermal contact between working fluid and surfaces of the flow channel. This results into increase in heat transfer coefficient and thermal performance of heat exchanger respectively.**
Keywords: **Heat Transfer Enhancement, Overall Enhancement Ratio, Ribs, Reynolds Number, Turbulent Flow, Turbulators**

I. INTRODUCTION

Heat exchanger is a device that is used to transfer the heat efficiently between two substances or mediums i.e., from one matter to the second matter. Basically, heat exchangers are the main devices that are used in the field of many engineering applications like refrigeration and air conditioning systems, thermal power industries, chemical and petroleum industries, gas turbine blade cooling systems, jet engine cooling systems, nuclear reactor cooling systems, etc. The research in the field of heat exchangers is mainly focused on design of heat exchangers that can ensure enhanced heat transfer rate and low friction during the flow. During the design of heat exchanger, design engineer primarily focuses on accurate estimation of rate of heat transfer and pressure drop that can occur during the flow of heat exchanging media through the heat exchanger. The increased cost of material and electricity or energy has created many challenges in the design of heat exchangers. The most challenging factor is to make compact heat exchanger which ensures that the heat transfer rate is high, and rate of power consumption is low. The enhancement in heat transfer rate can be achieved through creation of artificial disturbances in the flow path of the fluid. But these artificial disturbances introduces resistance to flow, increase in pressure drop which ultimately increases the pumping power requirements and results into high operational costs. Heat transfer enhancement can be achieved through various techniques like active techniques, passive techniques and combination of these two, etc.

Use of these techniques results into increased convective heat transfer coefficient and overall thermal performance of heat exchanger. Active techniques of heat transfer enhancement involve use of mechanical aids, use of electrostatic fields, surface fluid vibrations, etc. whereas the various passive techniques of heat transfer enhancement includes artificial inserts like helical twisted tapes, wire coil inserts, baffle plates, surface roughners like fins or ribs (having square, circular, triangular, rectangular or pentagonal cross section), additives like nano fluids etc.

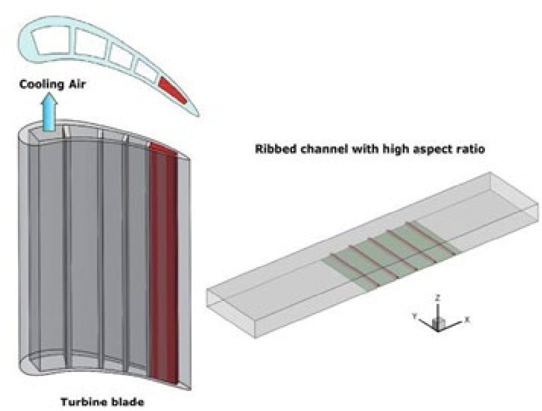

Fig. 1 Cooling of Internal Passage of Turbine Blade using Rectangular Ribs

Sometimes combination of active and passive techniques is used to attain the required objective of enhancement in heat transfer. Among active and passive techniques, active techniques are more economical as compared to passive techniques. Inserts like rib turbulators are the most commonly used active heat transfer enhancement technique employed in various rectangular and square shaped channels of heat exchangers.

Fig. 1 shows the application of active technique of heat transfer enhancement in turbine blade. In this application the internal cooling passage of turbine blade is provided with rectangular cross section ribs inside the rectangular channel.

II. VARIOUS RIB CONFIGURATIONS USED IN RECTANGULAR DUCT FOR HEAT TRANSFER ENHANCEMENT

Many researchers have carried out experimental and theoretical studies on heat transfer enhancement in rectangular and square ducts provided with various arrangements of geometrically different rib Turbulators. This study focuses on revision of the past studies carried out in the field of heat transfer enhancement in rectangular duct roughened with various rib turbulators.

Wong [1] *et al.,* conducted experimental and numerical research for investigation of forced convection and flow friction characteristics of turbulent air flow through a rectangular duct which is provided with cross-ribs having square cross section mounted on bottom surface of the duct. Uniform heat supply was given to the bottom surface only and a constant flow with Reynolds number 12,380 was maintained. The variation in forced convection and flow friction is studied by changing the angle from 30° to 120°formed by the ribs. Through experimental investigation it was observed that highest heat transfer coefficient is obtained for angle between 60° and 70°.The numerical study is carried out with k-Ɛ model to study the forced convection and flow friction characteristics of rectangular duct provided with cross ribs (Fig. 2). The results of numerical study were found in line with those of experimental results with variations in the range of 2-10% on lower side.

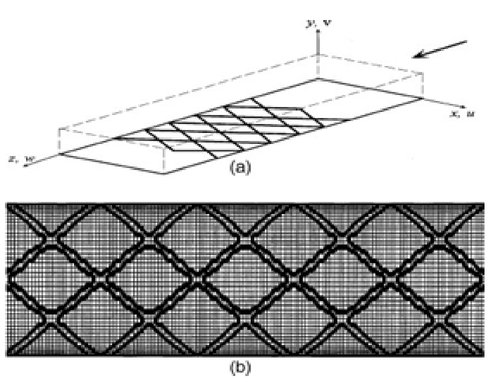

Fig. 2 a) Coordinate system used for Numerical study
b) Computational Grid for Cross rib angle=60° [1]

Yuan [2] *et al.,* carried out experimental study to investigate the effect of winglet provided in rectangular duct on heat transfer and friction factor. It was observed that duct with winglets (Shown in fig. 3) shows enhanced thermal performance as compared to duct provided with disturbances in transverse direction for Reynolds number ranging from 5000 to 47000. The Nusselt number ratio (Nu/Nuo) varies between 1.7 to 3.5 and 2.7 to 6.0 for same pumping power and same mass flow condition respectively. Based on the experimental results the following correlations are obtained for Nusselt number and friction factor.

- $Nu=0.0884\ Re^{0.7593}$
- $f=0.0971\ Re^{0.0629}$

Based on comparison of the results from experimental data and correlation data the deviation from experimental data is 3.7% and 5.8% for friction factor and Nusselt number respectively.

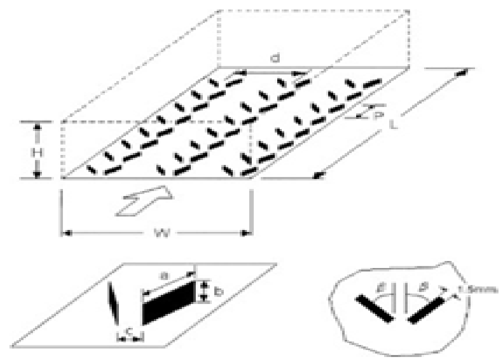

Fig. 3 Test Duct Structure [2]

Ahn [3] *et al.,* carried out simulation and experimental thermal and aerodynamic performance investigation of turbulent flow through a channel roughened with square and semicircular ribs. Large Eddy Simulation (LES) technique was used to study heat transfer enhancement phenomenon in rib roughened channel. Based on the results it was observed that the channel roughened with semicircular ribs shows enhanced overall thermal performance (by 5%) as compared to channel roughened with square ribs at the same flow conditions. The results of this study are given in Table I.

TABLE I COMPARATIVE RIB PERFORMANCE [3]

Factor	Square	Semicircle
Nut/Nu0	2.49	2.56
Q/Q0	3.29	3.28
f / f0	11.4	9.97
$(Q/Q0)/(f/f0)^{1/3}$	1.46	1.52

Wang [4] *et al.,* experimentally investigated the heat transfer and friction characteristics in a square duct roughened on one wall by ribs of various shapes like square, trapezoidal, triangular, etc. the various operating parameters considered for this study were as below.

TABLE II PARAMETERS FOR EXPERIMENTAL STUDY [4]

Operating Parameter	Values
Rib height to duct hydraulic diameter ratio	0.1
Rib pitch to height ratio	8-15
Reynolds number	8000-20000

From experimental study was observed that trapezoidal ribs having decreasing height in the direction of flow give higher heat transfer coefficient and friction factor as compared to other ribs. Square and triangular shaped ribs showed almost similar performance in terms of heat transfer and friction factor characteristics.

Aharwal [5] *et al.,* carried out experimental study for investigation of thermal performance factor of a rectangular duct provided with split ribs having square cross section inclined at 60° as shown in fig. 4. Table III depicts the various operating parameters that were used during this experimentation.

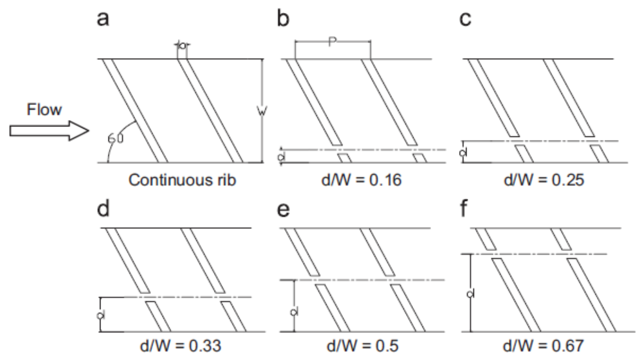

Fig. 4 Split rib arrangements with variation in gap position [5]

TABLE III OPERATING PARAMETERS FOR EXPERIMENTAL STUDY [5]

Operating Parameter	Values
Relative roughness pitch (P/e)	10
Relative roughness height	0.0377
Duct aspect ratio (W/H)	5.87
Reynolds number (Re)	3000-18000
Angle of attack (a)	60°
Relative gap position (d/W)	0.167–0.5
Relative gap width (g/e)	0.5–2

Based on the experimental study carried out for rectangular duct with and without ribs, it was observed that inclined ribs having gap shows rise in Nusselt number and friction factor in the range of 1.48 to 2.59 times and 2.26-2.9 times respectively as compared to duct without ribs. Highest Nusselt number and friction factor was obtained for inclined ribs having relative gap width of 1.0 and relative gap position of 0.25.

Eiamsa-ard [6] *et al.,* conducted numerical investigation of thermal performance characteristics of a channel provided with seven ribs on bottom wall of the channel. The ribs used were having shape like concave, convex, wedge, concave-concave, concave- convex rib, etc as shown in fig. 5.

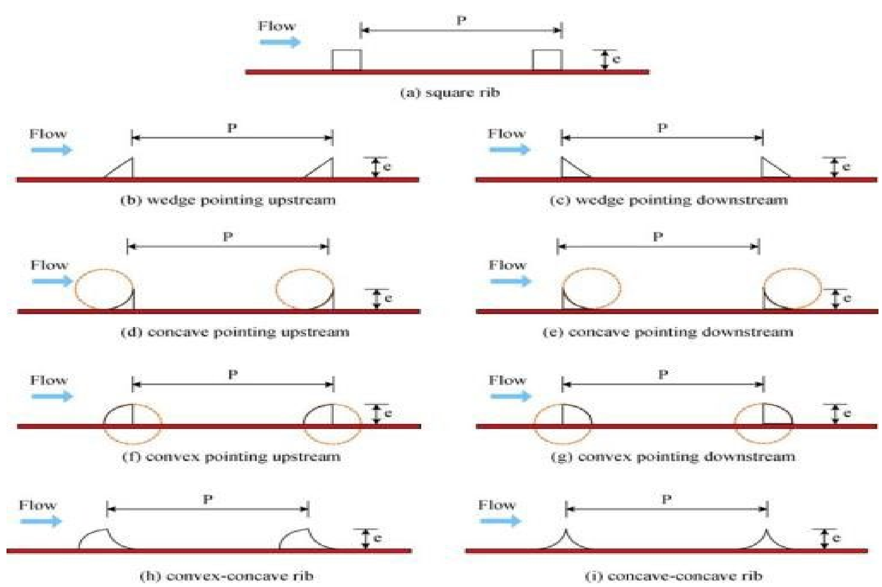

Fig. 5 Configuration and arrangements of Various Ribs [6]

The results of the simulation indicated that the rib having convex-concave surfaces shows highest overall thermal performance factor of 1.19 on account of higher Nusselt number and lower friction factor at Reynolds number of 10000. The Thermal Enhancement Factor (TEF) of various shaped ribs in as shown in fig. 6.

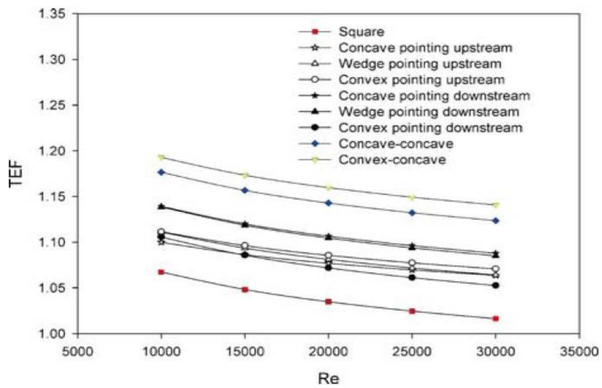

Fig. 6 Thermal Enhancement Factor (TEF) for different shaped ribs [6]

Tanda [7] *et al.,* conducted experimental investigation of heat transfer enhancement in a rectangular duct (having aspect ratio of 5) provided with ribs inclined at 45°angle on one and two surfaces of the duct. During the experimentation the Reynolds number was varied from 9000 to 35000, rib height to hydraulic diameter ratio (e/D) was maintained at 0.09, and rib pitch to height ratio was varied from 6.66 to 20 (in 4 steps) respectively.

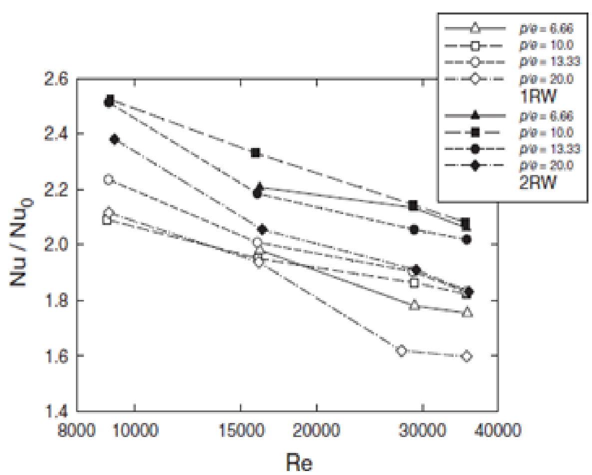

Fig. 7 Variation of Nusselt Number ratio Vs Reynolds Number for One ribbed wall and Two ribbed wall channel [7]

From the study it was observed that highest thermal performance factor was obtained for rib pitch to height ratio of 10 when inclined ribs were provided on two walls of the duct. The thermal performance factor value was found to be in the range of 1.02 to 1.20. Similarly, the rectangular duct with inclined ribs provided one wall showed highest thermal performance for rib pitch to height ratio of 13.33.

Chamoli [8] *et al.,* carried out the experimental investigation to study effect of V-shaped perforated baffled ribs (shown in Fig. 8) on the heat transfer and friction factor characteristics of rectangular duct.

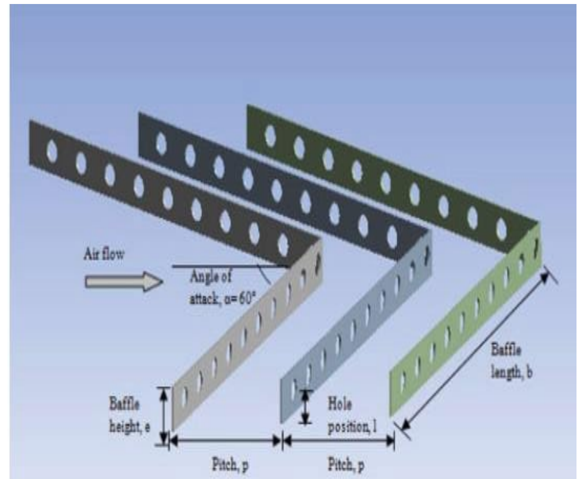

Fig. 8 Various configurations of V-shaped baffle plate having perforations [8]

The experimental study was performed for rectangular duct having aspect ratio of 10 and the operating parameters maintained during the study were like relative roughness height of 0.4, roughness pitch ranging from 2 to 4, Reynolds number ranging from 3800 to 19000, angle of attack=60° respectively.

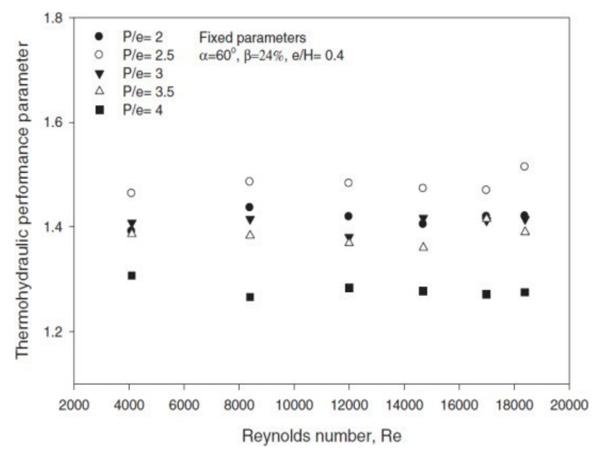

Fig. 9 Variation in Thermo hydraulic performance factor with respect to Reynolds number [8]

Based on the experimental study it was observed that the configuration having relative roughness pitch of 2.5 and open area ration of 24% shows highest Nusselt number and thermo hydraulic performance (as shown in Fig.-9). The duct with baffled plates showed maximum enhancement in the heat transfer and friction factor up to 2.57 and 5.96 times respectively when compared with the smooth duct under same conditions.

Yemenici [9] *et al.,* performed experimental study to investigate effect of concave, convex and ribbed surfaces (as shown in fig. 10) on overall heat transfer enhancement in a rectangular channel.

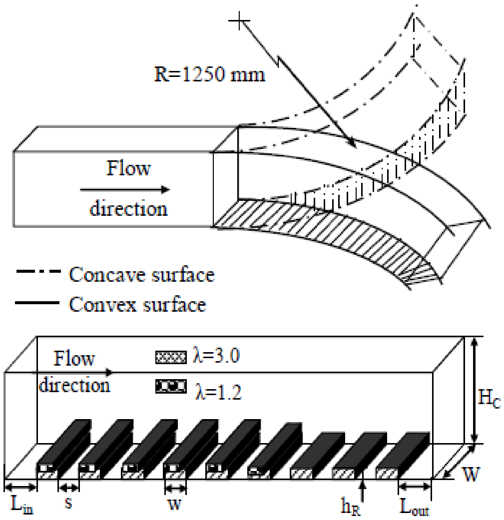

Fig. 10 Concave, Convex and Ribbed Surface [9]

From the study it was observed that ribbed surface with same heated area as that of concave and convex surfaces showed highest heat transfer enhancement in comparison with other configurations. The details of result are as shown in table IV.

TABLE IV DETAILS OF HEAT TRANSFER ENHANCEMENT FOR VARIOUS CONFIGURATIONS [9]

Type of Surface	**Type of Flow**	**% of Heat Transfer Enhancement**
Concave surface	Laminar	Increased by 55%
	Transitional	Increased by 30%
	Turbulent	Increased by 20%
Convex surface	Laminar	Decreased by 25%
	Transitional	Decreased by 20%
	Turbulent	Decreased by 15%
Ribbed surface	Laminar	Increased by 160%
	Turbulent	Increased by 120%

Shukla [10] *et al.,* conducted computational study to investigate effect of continuous and broken ribs on heat transfer augmentation in a channel. The researcher used three RANS based turbulent models (standard k-Ɛ model, RNG k-Ɛ model and realizable k-Ɛ model) for computational study and the results obtained were compared with available experimental data.

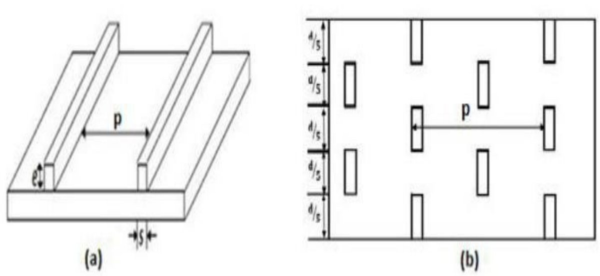

Fig. 11 Rib Configurations (a) 90° continuous ribs (b) 90° broken ribs [10]

The operational parameters and related details are given in table V.

TABLE V OPERATIONAL PARAMETERS AND RELATED DETAILS [10]

Parameter	**Details**
Rib Configurations (Refer Fig.-11)	90° continuous attached ribs 90° continuous detached ribs 90° broken attached thick ribs 90° broken attached thin ribs
Reynolds number	10000-30000
Rib pitch to Height ratio (p/e)	10
Blockage ratio (e/d)	0.15, 0.10 and 0.08125

From the computational study it was observed that Nusselt number decreases as the Reynolds number increases for various blockages as shown in fig. 12.

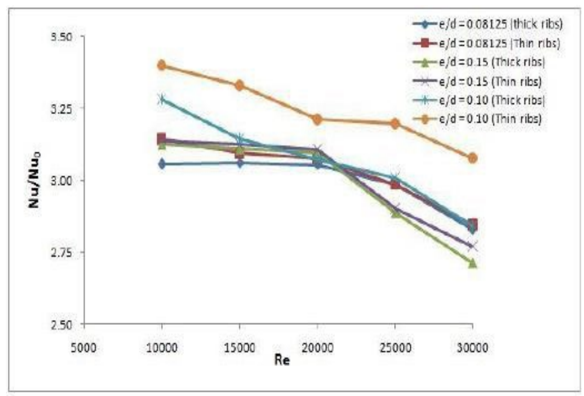

Fig.12 Nusselt Number variation with respect to Reynolds Number for various blockages [10]

Among the three computational models, standard k-Ɛ model provided better good results as compared to other two models. Also, among thin and thick ribs, the former one provided better thermal enhancement as compared to latter one. In addition to this it was observed that broken ribs provides showed performance as compares to continuous ribs.

Dewan [11] *et al.,* conducted computational study to investigate effect of rib height and thickness on heat transfer enhancement in a rib roughened channel. The researcher used standard k-Ɛ model along with its two sub types viz. RNG k-Ɛ model and realizable k-Ɛ model for computational study.

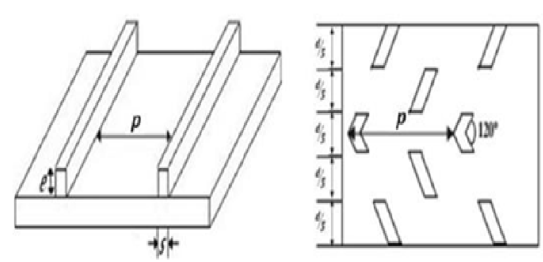

Fig. 13 Rib Configurations- 90° continuous ribs and 60° V-shaped broken ribs [11]

The operational parameters and related details are given in table VI.

TABLE VI OPERATIONAL PARAMETERS AND RELATED DETAILS [11]

Parameter	Details
Rib Configurations (Refer Fig.-13)	90° continuous attached ribs, 60°V-shaped broken ribs
Reynolds number	10000-30000
Rib pitch to Height ratio (p/e)	10
Blockage ratio (e/d)	0.15, 0.10 and 0.08125

Based on the present computational study in case of all the configurations it was observed that Nusselt number decreases as the Reynolds number increases for various blockages as shown in fig.14.The maximum heat transfer was observed for 90° attached ribs at p/e= 10. The decrease in heat transfer rate against increase in blockage ratio was observed for 60° V-shaped broken ribs.

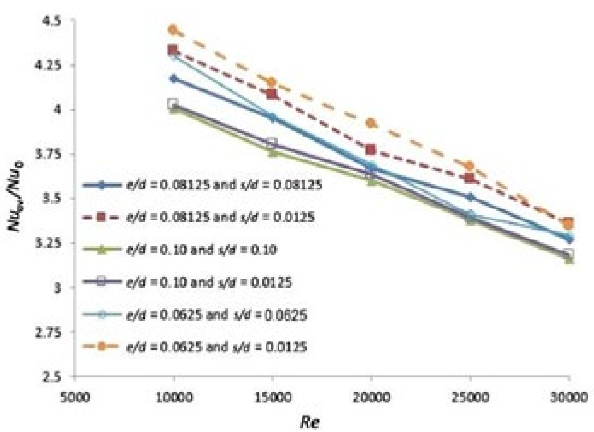

Fig. 14 Nusselt Number variation with respect to Reynolds Number for various blockages [11]

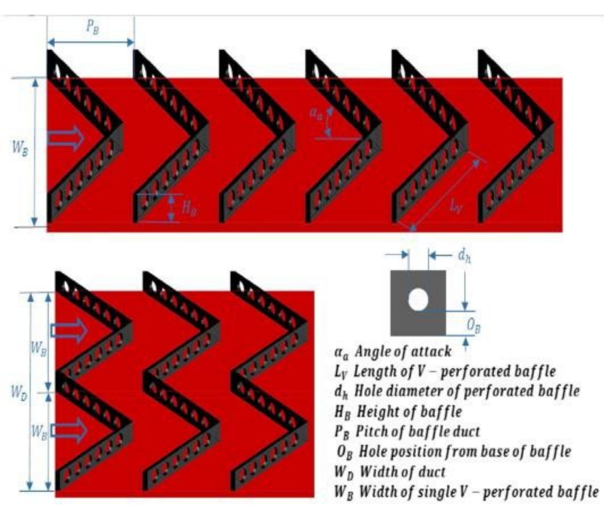

Fig. 15 Multi V-perforated baffle [12]

Kumar [12] *et al.,* carried out experimental investigation of heat transfer enhancement in a rectangular duct provided with multi V-perforated baffle having different relative baffle widths (as shown in fig.15) attached on the bottom wall of the duct.

The various parameters used in this study are given in table VII.

TABLE VII OPERATIONAL PARAMETERS AND RELATED DETAILS [12]

Parameter	Details
Aspect Ratio (WD/HD)	10.0
Reynolds number	4000-9000
Relative baffle width (WD/WB)	1.0-6.0
Relative baffle height (HB/HD)	0.5
Relative baffle pitch (PB/HB)	10.0
Relative Hole position (OB/HB)	0.44
Open area ratio (ß0)	12%

From the experimental results it was observed that the thermo-hydraulic performance of the rectangular duct is a function of relative baffle width (WD/WB) (Refer fig. 16).

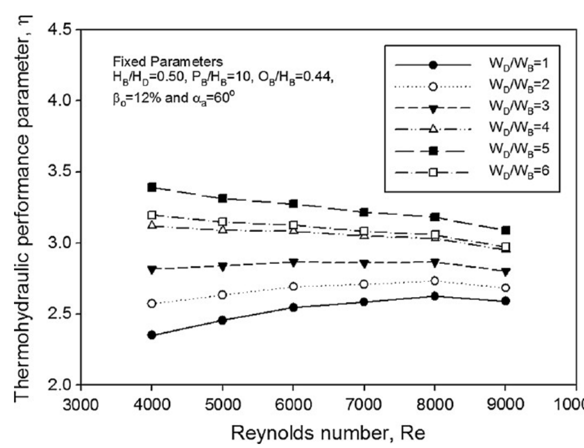

Fig. 16 Thermo-hydraulic Performance Vs Reynolds Number for Various Relative width ratio [12]

Among all the configurations tested it was observed that multi V-pattern perforated baffles gave highest thermo-hydraulic performance as compared to all other baffle shapes. Highest values of Nusselt number and friction factor were obtained for multi V-down pattern perforated baffles having relative baffle width (WD/WB) of 5.0 and 6.0 respectively.

III. CONCLUSION

Based on the present review study, it can be concluded that Intensive study has been carried out by various researchers to determine the effect of various rib geometries on the heat transfer enhancement and friction factor characteristics of rectangular duct. The enhancement in the heat transfer rate is obtained by introducing the blockages or restrictions in the fluid flow path by providing various rib turbulator configurations. Insertion of ribs into the rectangular duct not only results into improving surface area available for heat transfer but also causes turbulence and recirculation of fluid. The various geometrical parameters like rib shape, cross-section, rib height, rib length, pitch, direction of alignment and related terms like rib height to pitch ratio (p/e) has significant effect on heat transfer and friction factor characteristics. The interruptions or blockages created by ribs provided in the flow channel results into increased pressure drop and disruptions in boundary layer development. Provision of ribs causes secondary flow which ensures enhanced thermal contact between working fluid and surfaces of the flow channel. This results into increase in heat transfer coefficient and thermal performance factor of the heat exchanger respectively.

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