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A Detailed Review on Passive Methods of Heat Transfer Enhancement

Chetan P. Vora[1], Virang H. Oza[2], Nilesh Bhatt[3]

Research Scholar, Gujarat Technological University, Ahmedabad, India[1]

Department of Mechanical Engineering, Shri Labhubhai Trivedi Institute of Engg. and Technology, Rajkot, India[2]

Professor and Head, Department of Mechanical Engineering, L D College of Engineering, Ahmedabad, India[3]

Abstract: Heat transfer enhancement techniques are widely used in areas such as process industries, air conditioning and refrigeration system, heat recovery process, chemical reactors etc. Passive techniques, where inserts are used in the flow passage to augment the heat transfer are advantageous compared to the active techniques, because they are simple to manufacture, cheap and they can be easily employed in an existing heat exchanger. Presently passive methods are most popular to enhance the heat transfer in heat exchanger. A wide range of inserts are used, particularly when turbulent flow is considered. This paper presents a critical review on different passive heat transfer augmentation techniques such as twisted tapes, wire coils, fins and ribs, which are the most commonly used passive heat transfer augmentation tools.

Keywords: Baffles, Fins, Heat Transfer Enhancement, Ribs, Twisted Tape, Wire Coil.

I. INTRODUCTION

Energy demand increasing by leaps and bounds, and fossil fuel is depleting. Looking towards the present energy scenario, the utilization of energy in effectively and improved way to enhance the heat transfer in heat exchanger plays a vital role. Heat exchangers have an important role in numerous industrial and engineering applications. The present requirement is to design an effective heat exchanger, which can save energy, space, and material.
Significant efforts have been given in last decade to develop heat transfer augmentation techniques in heat exchanger in order to reducing size and cost of the system. By introducing a disturbance in the fluid flow passage, heat transfer rate is increased. Some inserts can be placed in the fluid flow passage to enhance the heat transfer rate and this reduces the hydraulic diameter of the flow passage which creates flow blockage, but it may increase the pumping power. Hence, it is necessary to achieve a required heat transfer rate at economic pumping power [1].

II.HEAT TRANSFER ENHANCEMENT METHODS

Heat transfer augmentation techniques are widely developed to improve the thermal performance of heat exchangers. These techniques are classified as: Active methods, Passive methods, and compound methods. Passive methods are used to increase heat transfer rate by increasing the surface area, roughness, and changing boundary conditions. Inserts are used in flow passage to enhance the heat transfer rate in passive method. In active method external power input is used to enhance the heat transfer. Nano sized, high thermal conductivity metallic powder can be added in the fluid to increase heat transfer rate in active method. Because of simple manufacturing and easy to apply in existing heat exchanger, passive methods are more popular compared to active methods. Two or more techniques like active and passive methods may be employed simultaneously to enhance the heat transfer in compound methods. Present study mainly deals with passive methods of heat transfer enhancement.

III.INSERTS

Some kind of inserts are placed in flow passage to augment the heat transfer rate. Several type of inserts are fins or corrugated surfaces, twisted tape, wire coils, ribs etc. Heat transfer enhancement in fluid flow by providing inserts is mainly due to flow blockage. Flow blockage increases the pressure drop and hence increases viscous efforts due to reduced free flow area. It also increases flow velocity.

A. Twisted tape

Twisted tapes are metallic strips twisted as per desired shape and dimensions. It is inserted in the flow passage to augment the heat transfer. It is used with less friction factor. It enhancing heat transfer by producing swirl into the heavy flow which disturbing the boundary layer at the tube surface due to rapidly changes in the surface geometry. It include turbulence and swirl flow due to the change in the geometry, which provide better results of heat transfer coefficient and

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Nusselt number. Simultaneously it increases pressure drop. Pitch and twist ratio are the main design parameters of twisted tape. Several researchers have worked on heat transfer enhancement using twisted tape insert. Murugesan et al. [2] done experimental investigation on heat transfer and friction factor characteristic of turbulent flow in a tube fitted with trapezoidal-cut twisted tape insert. They compared the results of plain tube with the tube fitted with trapezoidal cut twisted tape. Trapezoidal-cut twisted tape for twist ratio 6.0 and 4.0 for turbulent flow have been used. Significant increase in heat transfer coefficient and friction factor was observed for tape with trapezoidal-cut. Sarada et al. [3] investigated the augmentation of turbulent flow heat transfer in a horizontal tube by means of varying width twisted tape inserts for air as the working fluid. It was observed that for full width of 26 mm the enhancement of heat transfer with twisted tape inserts compared to plane tube varied from 36 to 48% and for reduced width of 22 mm it was varied from 33 to 39%. It was also concluded that for reduced width of 22 mm, 61% of material saved and the performance was 1.32-1.39 times compare the plane tube. Patil and Babu [4] presented a review of heat transfer enhancement in a circular tube and square duct with twisted tape and screw tape inserts. The result shows twisted tape insert is more effective. At the same mass flow rate the twisted-tape is more popular than the helical screw-tape having a higher heat transfer rate because of lower pressure drop and simplicity of manufacturing. Square duct has high surface to volume ratio hence heat transfer of square tubes was found considerably higher than the circular tube. Salman et al. [5] carried out numerical investigation of the heat transfer and friction factor characteristics of a circular tube fitted with V-cut twisted tape insert with twist ratio as 2.93 and different cut depths as 0.5, 1, and 1.5 cm for laminar flow. Their results showed that heat transfer enhancement increases with the Reynolds number and decreases with twist ratio made by the classical and V-cut twisted tape inserts. It was also concluded that V-cut twist tape provides better thermal contact between surface and fluid which leads to high heat transfer coefficient. Salam et al. [6] worked on heat transfer enhancement in tube using rectangular-cut twisted tape insert and concluded that heat transfer enhancement efficiency increased with the increase of Reynolds number. Figure 1 shows rectangular-cut twisted tape. Their result showed that Nusselt number in the tube with rectangular-cut twisted tape inserts were 2.3 to 2.9 times higher with the increase of friction factor by 1.4 to 1.8 times compared to smooth tube. Chakole et al. [7] investigated the enhancement of turbulent flow heat transfer in a horizontal tube by means of varying width twisted tape inserts with air as working fluid. It was concluded that twisted tape inserts provides 36 to 48% heat transfer enhancement compared to plain tube. Lower value of twisted tape width provides lower friction factor and Nusselt number.

Figure 1 Rectangular-cut twisted tape [6]

Bhattacharyya et al. [8] investigated the influence of center-trimmed twisted tape on heat transfer rate, friction factor, and thermal enhancement efficiency. Swirl flow generates inside the circular duct with the use of center-trimmed twisted tape. It was found that significant enhancement of heat transfer obtained in the center-trimmed twisted tape compared to plain twisted tape. It was also observed that with decrease in twist ratio the friction factor heat transfer and thermal enhancement efficiency increases.

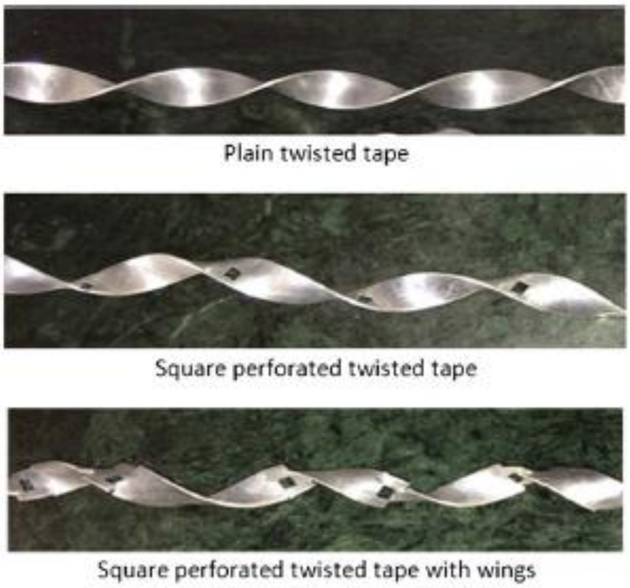

Figure 2 Photographs of twisted tapes [10]

Hussein [9] presented heat transfer enhancement in tube using six types of twisted tape like normal, regularly spaced, triangular-cut, rectangular-cut, semicircular-cut and drilled. It was found that modified twisted tapes more turbulence was created during the swirl of fluid and provides higher heat transfer rate compared to plain twisted tape. Their result showed that heat transfer process in tube with twisted ribbon provider drilled was more efficient than other form of twisted tape. Suri et al. [10] carried out experimental investigation of heat transfer and fluid flow behaviour in a heat exchanger tube in multiple square perforated twisted tape with square wing inserts. Multiple square perforated twisted tape provides better heat transfer as well as they were thermo-hydraulically better compared to without multiple square perforated twisted tape inserts. Figure 2 shows plain, square perforated, and square perforated with wings types twisted tapes.

Bhattacharyya et al. [11] designed twisted tape turbulator for heat transfer enhancement at different entrance angle in a solar heater. The twisted tape insert has a better thermo-hydraulic performance. It was also found that the large entrance angle and small twist ratio can augment the heat transfer rate, but increases the flow resistance due to higher turbulence intensity. It was suggested that twisted tape insert is convenient to fabricate and use and can be widely used in heat transfer augmentation of turbulent flow. Yousif and Khudhair [12] studied on heat transfer enhancement in a tube fitted with twisted tape insert. It was concluded that the effect of twisted tape is greater in the turbulent than in laminar flow. Some of the twisted tape augmentation methods were summarized. Heat transfer rate increases in full length twisted tape but friction factor also increases, while low friction factor and Nusselt number observed in short length twisted tape. Twisted tape with uniform pitch performs better than gradually decreasing pitch. It was also summarized that centrally located loose fit twisted tape gives better results. Baffled twisted tape with holes provides better heat transfer rate due to increase of turbulence, which also increases friction factor.

B. Wire coil

Figure 3 shows a typical configuration of a wire coil [1]. A wire coil is the helical coil spring which functions as non-integral roughness. It has some advantages like simple manufacturing, easy installation, easy to remove, and low cost. Wire coil mixes the flow in the viscous sub layer near the wall quite effectively and hence it is more effective in a turbulent flow compared with twisted tape. Wire coil cannot mix the bulk flow well and hence it is not effective in laminar flow. While twisted tape cannot properly mix the flow in viscous sub layer and hence it is not effective in a turbulent flow but effective in laminar flow.

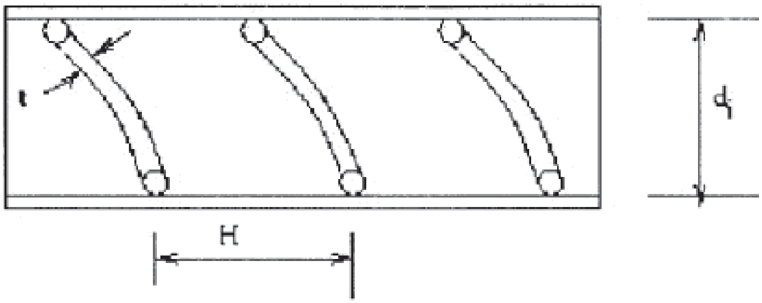

Figure 3 Wire coil [1]

The wire coil is easy to manufacture. It is also easy to insert and remove from tube and hence it justifies its usage in heat transfer enhancement. Some other advantages of wire coil inserts can be their low cost, they don't change mechanical strength of original plain tube. Some researchers worked on wire coil insert to enhance heat transfer. Nephon [13] studied the heat transfer characteristics and the pressure drop of the horizontal double pipe with coil-wire inserts. It was concluded that the heat transfer rate and heat transfer coefficient depend directly on the mass flow rates and effect of coil-wire insert. With increase in Reynolds number heat transfer decreased. Garcia et al. [14] **s**tudied on three wire coils of different pitch inserted in a smooth tube in laminar and transition regimes. It was found that the heat transfer enhancement obtained with the wire coils will be reasonably higher than the one obtained with the twisted tapes. Gunes et al. [15] experimentally investigated the heat transfer and pressure drop in a tube with wire coil insert in turbulent flow regime. The experiments were carried out with three different pitch ratio and two different ratio of equilateral triangle length side to tube diameter at some distance. With the increase of Reynolds number, wire thickness, and the decrease of pitch ratio the Nusselt number increases. The use of coiled wire inserts leads to a significant increase in heat transfer and pressure drop compared to the smooth tube. Biswas and Salam [16] Carried out experimental investigation in a circular tube fitted with wire coil insert with air as working fluid to measure tube side heat transfer coefficient, friction factor, heat transfer enhancement efficiency for turbulent flow. Heat transfer coefficient for the tube with wire coil insert was higher compared to that of plain tube by 1.5 to 2.3 times at same Reynolds number. Heat transfer enhancement efficiency was increased with increase of Reynolds number in the range of 1.3 to 2.6. Shashank et al. [17] investigated double pipe heat exchanger with wire coil insert of three different materials as copper, aluminium, and stainless steel with different pitches. Their result showed that coil wire insert provides major effect on heat transfer and friction factor. Higher friction factor obtained at lower coil wire pitch. It was also concluded that copper insert provides higher heat transfer enhancement compared to aluminium and stainless steel insert. Valmiki [18] studied heat exchanger with helical wire coil insert in plain tube to improve the heat transfer and the overall thermal performance. Experimental work was done with copper and aluminium wire coil inserts by varying pitch of 1, 2, and 3 cm respectively. It was concluded that wire coil inserts performs better than plain tube to enhance high heat transfer rate. It was also concluded that copper wire coil provides better than aluminium wire coil to obtain higher heat transfer.

C. Ribs

Heat transfer enhancement can also be possible by adding ribs to the wall of internal flow channels. Many researchers have studied the influence of ribs in the channel for improvement of heat transfer. The effect of different rib heights on the impinging flow and heat transfer was studied by Gau and Lee [19]. In their experimental work Reynolds number varies from 2500 to 11000, the slot width-to-height ratio varies from 1.17 to 6.67, and nozzle-to-plate spacing varies from 2 to 16. It was found that with the increase of the slot width-to-rib height leads to that the wall jet can separate from the rib, reattach to the next one and recirculate inside the cavity. This reattachment and recirculation of flow can considerably enhance the heat transfer at the location of ribs. Kamali and Binesh [20] developed a computer code to perform a numerical simulation for optimizing the shape of two-dimensional channel with periodic ribs mounted on the bottom wall to enhance turbulent heat transfer. Their results showed that the chamfered rib-groove roughness ducts were more efficient as compared to chamfered repeated ribs without grooves. Abdulrazzaq et al. [21] carried out numerical simulation on heat transfer enhancement in channel by triangular ribs of different angles. In their investigation triangular ribs with three angles of 60°, 90°, and 45° and Reynolds number in the range of 20000 to 60000 at constant surface temperature were studied. Their results showed that greatest enhancement of heat transfer was found in the triangular rib with 60° angle at Reynolds number of 60000 as compared to other types of ribs. Figure 4 shows different triangular rib geometry. Heat transfer and friction factor characteristics of steam flow in ten different rectangular channels with ribs on two opposite walls was investigated by Shi et al. [22]. With the increase of Reynolds number, the friction factor ratios of steam in all ribbed channels was increased. The maximum heat transfer attended by the highest friction factor occurred at rib angle of 60° due to the higher rib angle included secondary flow swirls at 60° in channels. With the increase of width of the ribbed wall higher flow disturbance occurs and hence average Nusselt number and friction factor increases with increasing the channel aspect ratio. Liu et al. [23] applied turbulence promoters to enhance heat transfer in internal flow channels. Their study employed with heat transfer distribution in a square channel with turbulence promoters like orthogonal (90°), continuous angled (45°), discrete angled (45°), V-shaped, and inverted V-shaped rib configuration. For all kind of turbulence promoters adding grooves between the ribs enhance the heat transfer. It was found that the discrete angled configuration of grooved ribs revealed the maximum heat transfer enhancement and thermal performance, while it was minimum for the orthogonal configuration. Figure 5 shows configuration of ribed-surfaces and ribbed-grooved surfaces.

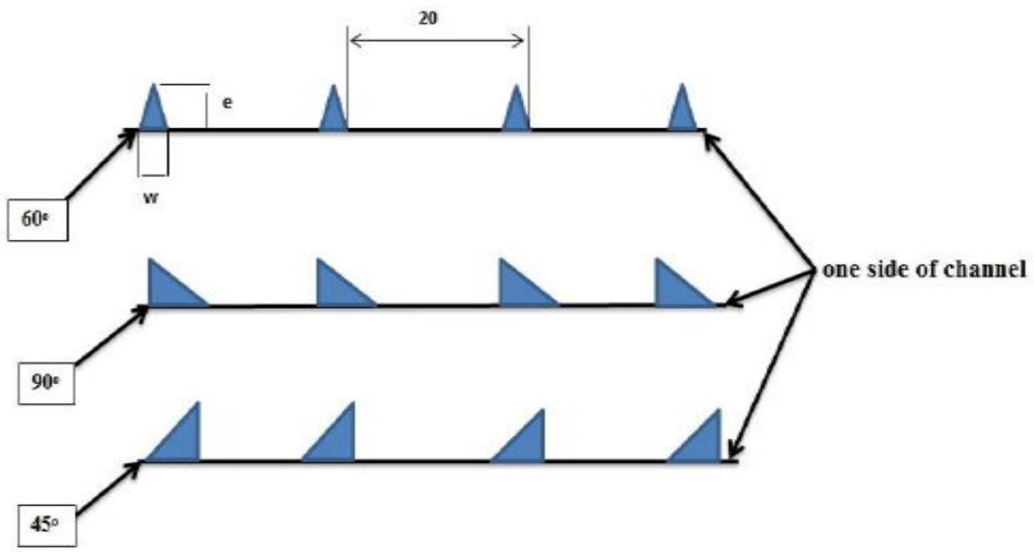

Figure 4 Different triangular rib geomentry [21]

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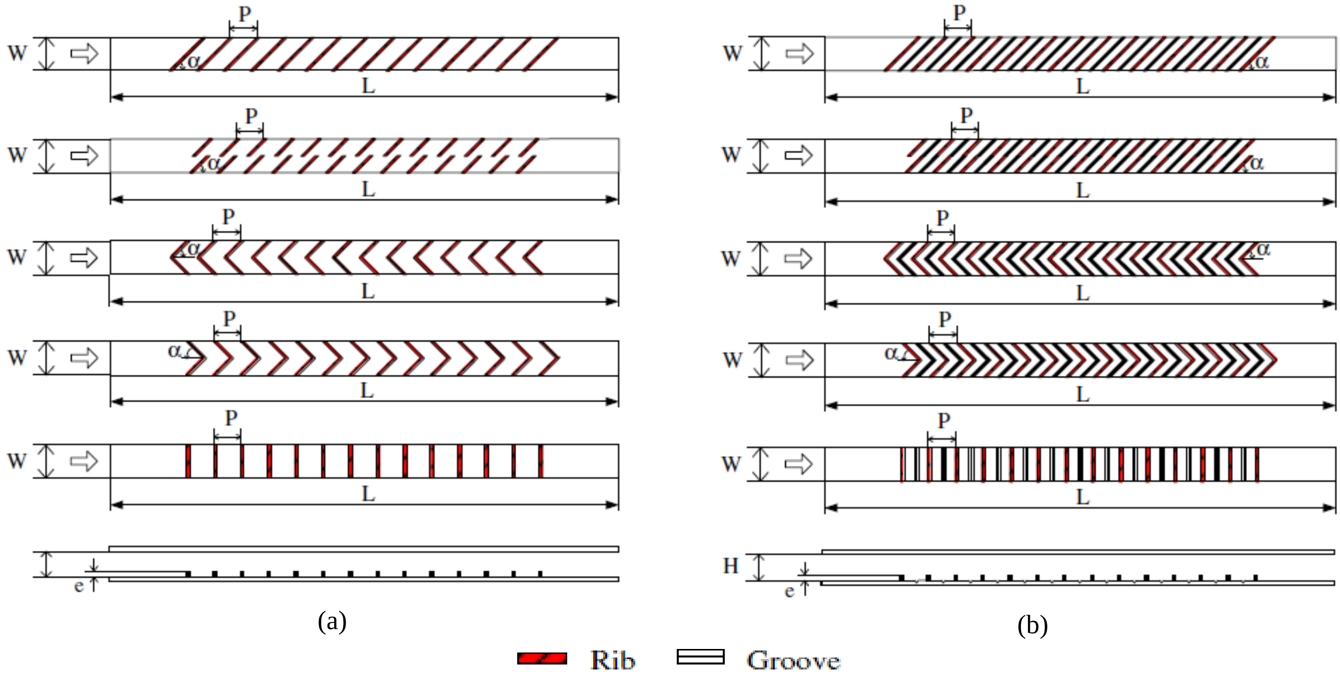

Figure 5 (a) Configuration of ribbed surfaces (b) Configuration of ribbed-grooved surfaces [23]

Jedsadaratanachai and Boonloi [24] presented thermal performance analysis, flow visualization, and heat transfer characteristics in a round tube heat exchanger with wavy V-rib. The wavy V-rib disturbs the thermal boundary layer near the tube wall and provides better fluid temperature distribution and hence heat transfer rate and thermal performance were enhanced. The convective heat transfer process between orthogonal air jet impingement on a smooth, horizontal surface and a roughened uniformly heated flat plate was studied by Alenezi et al. [25]. Maximum heat transfer rate was obtained with the rib height which matches the velocity boundary layer thickness at the rib location. Too high a rib provides a lower heat transfer rate as compared to the no rib case. Maximum heat transfer enhancement of 15.6% was found at the optimum rib height and location.

D. Baffles

The local heat transfer coefficient leading to higher heat transfer with the use of baffles which completely makes the change of flow field. By using the baffles arrangement, heat transfer is increased but the pressure drop of the flow also increased due to the decreased flow area or flow blockage. Several researchers have worked on heat transfer enhancement using baffles. Dutta and Dutta [26] presented effects of baffle size, perforation, and orientation on internal heat transfer enhancement for both solid and perforated baffles. With a decrease in the angle of baffle and increase in the perforation density the friction factor ratio decreased. In perforated baffles, heat transfer enhancement considerably decreased with a decrease in the angle of attack. Inclined baffles were studied along with the combination of jet impingement techniques by Khan et al. [27]. Their work deals with experimental investigation of heat transfer with turbulent flow in a rectangular channel with inclined solid and perforated baffles combined with rib. Solid baffle provides better performance than that with high perforations but worse than low perforations. A device combined ribs with baffles was a viable solution. The baffle provides the largest distribution in flow whereas the ribs created the least.

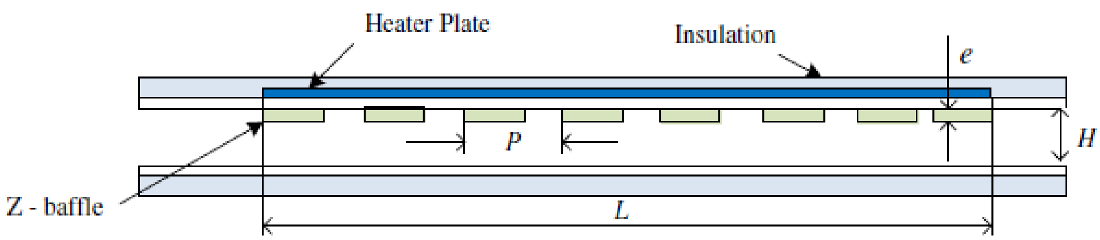

Figure 6 Test section with Z-baffle [30]

Numerical investigation of laminar heat transfer in a three dimensional isothermal wall square channel with 45° inclined baffles was carried out by Promvonge et al. [28]. It was concluded that enhancement factor of the 45° baffle provides higher than that of the 90° baffle for all Reynolds numbers and baffle heights. Promvonge and Kwankaomeng [29]

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investigated periodic laminar flow and heat transfer in a channel with 45° staggered V-baffles. Nusselt number and friction factor values found to be increased with the rise in the V-baffle height. Their result showed that the optimum thermal enhancement factor was around 2.6 and 2.75 at baffle height of 0.15 times of the channel height for the V-baffle pointing upstream and of 0.2 times for the V-baffle pointing downstream respectively.

The influence of Z-shaped baffles on heat transfer augmentation in a rectangular channel was investigated experimentally by Sriromreun et al. [30]. It was found that the in-phase 45° Z-baffles provides better Nusselt number, friction factor, and thermal performance as compared to the out-phase 45° Z-baffle. It was also observed that the presence of Z-baffle yields to an extensive increase in friction loss compared with the smooth channel without baffle. Figure 6 shows test section and Figure 7 shows in-phase and out-phase Z-baffle arrangement.

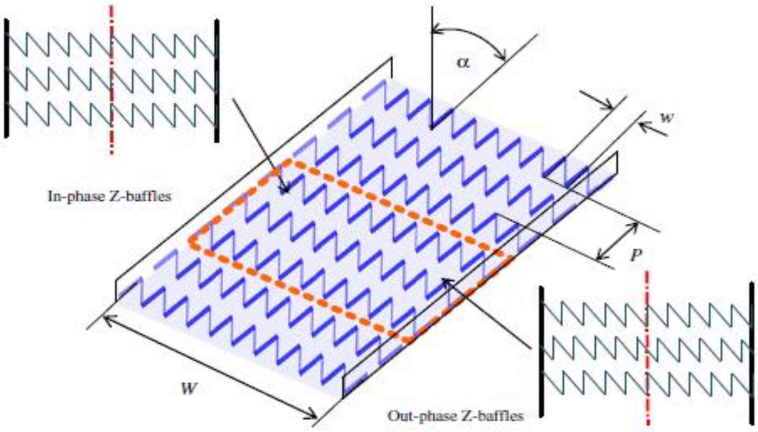

Figure 7 In-phase and Out-phase Z-baffle arrangement [30]

Ameru [31] investigated effect of corrugated baffles on the flow and theraml fields in a channel heat exchanger. The straight baffle found to be better than the corrugated baffle in terms of increase in heat exchange, since the vortex size region, in which there were wider molecular exchanges. Their result showed that overall performance factor was increased from 1.27 to 1.53 when corrugation angle was increased from 0° to 45°, in comparision with unbaffled channel.

E. Fins or corrugated surfaces

Heat transfer can also be increased by attaching thin strips of metal called fin. Fin increases effective area of surface. It is one of the heat exchanging devices that are employed comprehensively to increase heat transfer rates.

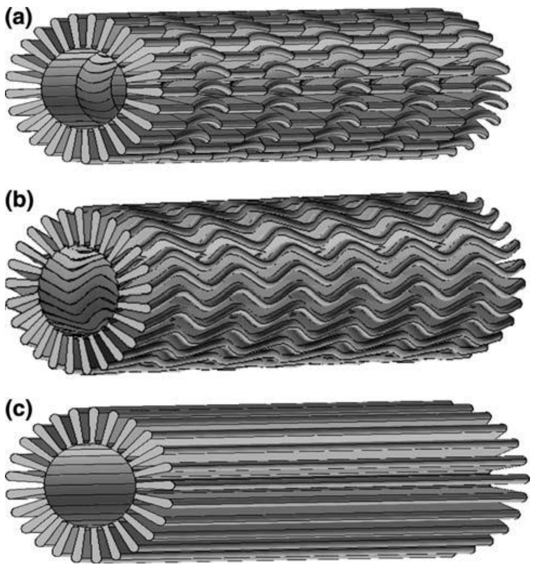

Figure 8 (a) interrupted wavy fin (b) sinusoidal wavy fin and (c) plain fin [36]

The heat flow through the fin is by conduction and hence the temperature distribution in a fin will depend upon the fin material and the surrounding fluid. The rate of heat transfer depends on the surface area of the fin. One of the effective way to enhance the convective heat transfer rate is by increasing the surface area of heat transfer and increase the

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turbulence in fluid flow by using fins or corrugated surfaces [32,33]. Wang et al. [34] carried out experimental study on the heat transfer and friction characteristics of typical wavy fin-and-tube heat exchangers. It was found that the wavy fin heat transfer characteristics does not depend on fin pitch. Their result showed that heat transfer coefficients for wavy fin geometry found to be 55% to 70% higher as compared to plain fin at the penalty of 66% to 140% of the friction factor. Pressure drop and heat transfer characteristics of turbulent flow was studied by Yu and Tao [35] in annular tube with wave-like longitudinal fins using air as the working fluids. It was observed that wave plays a vital role in the heat transfer enhancement. Strong heat transfer enhancement found with the wave fin compared to smooth tube due to reduction of hydraulic diameter and the insertion of the blocked inner tube, which reduces the intersection angle between the velocity and the temperature gradient. Turbulent pressure drop and heat transfer characteristics in tubes with three different kinds of longitudinal wavy fins like interrupted wavy, sinusoidal wavy, and plain were analysed by Wang et al. [36]. The overall heat transfer coefficients in wavy channels were higher as compared to plain fin channel, at the penalty of larger pressure drop. Interrupted wavy fin tube enhanced heat transfer by 72% to 90%, at 2 to 4 times penalty of pressure drop.

Figure 8 shows interrupted wavy fin, sinusoidal wavy fin and plain fin. Hamdan and Al-Nimr [37] studied fully developed laminar forced convection heat transfer augmentation with the use of porous fins in parallel-plate channels. Porous fins having high thermal conductivity were attached to the inner walls of two parallel plate channels to enhance the heat transfer. Highest Nusselt number was obtained at fully filled porous duct which required the highest pumping pressure. It was found that with the using porous fins required less pumping pressure with comparable high heat transfer enhancement. Numerical and experimental investigation was carried out by Wang et al. [38] on the flow and heat transfer characteristics in rectangular channel provided with pin fins. Several pin fins like circular, elliptical, and drop-shaped with the same cross-section areas were used in their study. The heat transfer enhancement of drop-shaped pin fin was lower than that of circular pin fins. The specific friction loss was less of drop-shaped pin fin as compared to elliptical and circular pin fins and hence it is promising option as compared to other two pin fins.

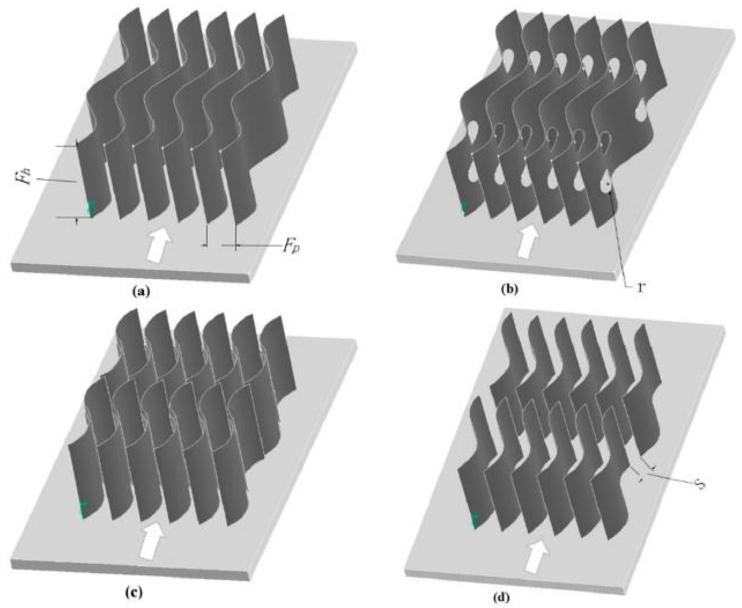

Figure 9 (a) traditional wavy fin (b) perforated wavy fin (c) staggered wavy fin and (d) discontinuous wavy fin [39]

To enhance the heat transfer of plate fin heat exchanger three new kind of wavy plate fins namely perforated wavy fin, staggered wavy fin, and discontinuous wavy fin were introduced by Xue et al. [39]. It was found that all proposed three type of wavy fins have advantages as compared to the traditional wavy fin. In perforated wavy fins, enlarged hole strengthen the turbulence, which caused rapid mixing between the core and the fluid near the fin surface and hence thermo-hydraulic performance increased. In the staggered wavy fins, with the larger staggered ratio, the better the thermo-hydraulic performance due to the less flow turbulence at the staggered section. In the discontinuous wavy fins, the higher the distance between the discontinuous wavy fins, the better the mixing of fluid on the both sides of fins and hence higher the heat transfer enhancement. A maximum performance evaluation criteria found to be as high as 1.24 in the perforated wavy fin. Figure 9 shows the shapes of traditional wavy fin, perforated wavy fin, staggered wavy fin, and discontinuous wavy fin. Heat transfer optimization in corrugated wall channels was studied by Fabbri [40]. The performance of corrugated wall channel was compared with a smooth wall duct. A corrugated profile can only maximize the heat transfer when Reynolds number, Prandtl numbers, and the pressure drop were not too low.

IV.CONCLUSION

Following conclusion have been made from the reviewed literature of heat transfer enhancement by passive methods.

- Heat transfer augmentation techniques have been widely developed to improve the thermal performance of heat exchanger systems to reduce the size and cost of the systems. Swirl flow is the one of the way to enhance heat transfer and extensively applied to heating or cooling systems in many engineering applications. The rate of heat transfer mainly depends on the surface area, roughness, and the boundary conditions.
- Passive techniques does not require any external power, while active system requires external power. Passive techniques of heat transfer are advantageous as compared to active technique of heat transfer.
- A twisted tape with a tight twist ratio provides an improved heat transfer rate at a cost of increase in pressure drop for low Prandtl number. This is because the thickness of the thermal boundary layer is small for a low Prandtl number fluid and a tighter twist ratio disturbs the entire thermal boundary layer, thereby increasing the heat transfer with increase in the pressure drop.
- A twisted tape insert performs better in a laminar flow than any other insert, because in a laminar flow the thermal resistance is not limited to a thin region. However, twisted tape performance also depends on the fluid properties such as the Prandtl number. For the high Prandtl number the twisted tape will not provide good thermo-hydraulic performance compared with other inserts such as wire coil, because it blocks the flow and therefore pressure drop is large. On the basis of a constant pumping power, short-length twisted tape provides better performance than full-length twisted tape. For the design of a compact heat exchanger for laminar flow, twisted tape can be used effectively to enhance the heat transfer. Twisted tape in turbulent flow is effective up to a certain Reynolds number range but not over a wide Reynolds number range.
- Twisted tape and wire coil inserts are economical heat transfer enhancement methods compared to other passive methods. The heat transfer enhancement obtained with the wire coils will be reasonably higher than the one obtained with the twisted tapes. Heat transfer coefficient for the tube with wire coil insert is higher compared to that of plain tube. Copper insert provides higher heat transfer enhancement compared to other material wire coil insert.
- With the increase of the slot width-to-rib height leads to enhance the heat transfer due to the wall jet can separate from the rib, reattach to the next one and recirculate inside the cavity. Highest heat transfer enhancement is obtained in triangular rib with 60° angle. The discrete angled configuration of grooved ribs revealed the maximum heat transfer enhancement and thermal performance as compared to other types of ribs.
- A device, combining ribs with baffles was a viable solution. Solid baffle provides better results with high perforations but worse results with low perforations. In perforated baffles, heat transfer enhancement considerably decreased with a decrease in the angle of attack.
- One of the effective way to augment the convective heat transfer rate is by increasing the surface area of heat transfer and increase the turbulence in fluid flow by using fins or corrugated surfaces. Air heater with fins are more efficient than that without fin for the lower mass flow rate.

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