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# Thermal performance enhancement in cross flow by vortex generators: A Review

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Abstract. The passive mode of enhancement in the heat transfer applications has been widely used since decades. The method is more popular due to the non-requirement of any prime mover for energy interaction. The fluid flow interaction in any heat exchanger defines the thermal performance of the device. The cross-flow heat transfer experiences the flow through the tube array and fins. The fin-and-tube heat exchangers are widely used in many fields such as air-conditioning, refrigeration, automobile, process industry, etc. The winglets are the projected area over the fins and the tube surface in order to impart flow turbulence as the fluid flow over the tube surface. Over last decades, numerous researchers have proposed the different methods for the heat transfer enhancement with the increased turbulence. This study presents the comprehensive review of most of the research on heat transfer augmentation with the use of vortex generators. The study also suggests the measures for understanding the design consideration of the cross-flow heat exchanger so as to fabricate the better model of the future cross-flow heat exchanger.

Keywords. cross flow, vortex generator, heat transfer.

#### 1. Introduction

As of present energy crisis, the fuel prices are ever increasing, there is a need to conserve the available resources with improved efficiency. The gas-to-liquid process heat exchangers are most frequently used in recent industrial application such as air conditioning and refrigeration systems, space heating, electronic cooling, petrochemical, and food processing applications. The flow in most of the cases lies in the category of one fluid mixed, other un-mixed. In unmixed fluid usually flows through the tubes, where as the mixed fluid passes through the tube array or cylinders. The tube side fluid is usually the hotter so as to exchanger the heat with the colder fluid. In order to increase the surface area for the heat transfer, the hotter fluid is allowed to pass through the number of small tubes. This causes the colder fluid to pass through the tubes array, thereby generating the turbulence to enhance the heat dissipation rate. So the turbulence generation on the mixed zone fluid is the primary source of increasing the heat transfer [1].

The turbulence generation is prominently created by passive modes in case of any heat exchangers. The passive modes are subjected to the class of heat exchanger, fluid involved in heat transfer. The

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passive modes involve the use of various cross-section of the cylinder, use of corrugate tubes, provision of the fins over the tubes, and provision of the winglet in the form of vortex generator to increase the turbulence so the heat transfer is increased. Amongst the different passive modes, the provision of the winglets is one of the most effective as numerous researchers make use of the winglet to enhance the heat transfer. The winglets are the short extended surface in the form of fin directly mounted or attached on the tube or the fin surface. The winglets cause the opposition to the mean fluid flow and thereby increases the flow turbulence in the zone of heat transfer. The flow opposition generated the vortex and hence the winglets are prominently termed as vortex generators. In this present study, the comprehensive review of heat transfer augmentation is carried out by different researchers across the globe in last two decades by the use of the winglets. The present study acts as a guideline for the design engineer so as to understand the key aspects in use of the winglets for the heat and fluid flow applications.

#### **1.1. Passive enhancement methods:**

With the non requirement of the external power source, the passive enhancement methods employed for the heat transfer augmentation by generating the additional turbulence became more popular in recent times. Some of them make use of the different types of the fin surface such as helical fin, plain fin, and wavy fins. The majority of the researchers prefer the use of the winglets for the enhancement process. The most commonly used winglets are rectangular, trapezoidal, delta winglets. The details about the different winglets on the heat transfer enhancement process are presented in the following sections.

#### 2. Use of Winglets for enhancing thermal performance

The winglets are the short extended fin like surface projected over the tube surface or on the fins aimed at creating the turbulence with the minimum rise in the pressure drop. The area of the winglet reduces along its length. This results in lower pressure drop for the cross flowing fluid. As the fluid flows over the winglet the swirl is generated in the working fluid resulting in the development of the vortex which results in increased turbulence. The pioneer work in the field of use of winglets for the heat transfer enhancement is performed by Edwards and Alker [2] in 1974 which makes use of cubes and delta winglet vortex generators. The rise in the thermal enhancement is reported along with no rise in the pressure drop characteristics. The schematic representation of the delta winglet is as shown in the figure 1. The arrangement of the winglets with the direction of the fluid flow results in the two main classifications of the winglets as Common flow up (CFU) and common flow down (CFD).



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The prominently used winglets over the fin surfaces are delta wing, rectangular wing, delta winglet and rectangular winglets as shown in the figure 2. Amongst them, rectangular and delta winglet offers less resistance to the cross fluid. Biswas et al [3] make use of the pair of common flow down configuration of delta winglets to enhance the heat transfer rate along with the overall reduction in the size of the heat exchangers. The schematic representation of the heat exchanger is as shown in the figure 3. Liou et al [4] make use of the flow pattern by using the Laser-Doppler velocimeter with the flow Reynolds number is maintained constant at 12000. The various winglets used are delta wing, delta winglet with common flow up and common flow down arrangements, along with oblique, and broken V-shaped configuration. The delta winglets result in the better heat transfer enhancement. Hence the majority of the researchers prefer the delta winglet over other vortex generators. The flow visualization by the use of dye injection is studied by Jerry Lo et al [5] in case of annular and delta winglet vortex generators in fin-and-tube heat exchanger applications. The development of the longitudinal vortices is observed with the increased intensity as annular vortex height is increased. The longitudinal vortex generators that creates swirling motion to the cross fluid which causes the turbulence. The direct comparison of the common flow up and common flow down configuration has been made by Torii et al. [6] for delta winglet vortex generators in case of fin tube heat exchangers. The schematic layout is as shown in the figure 4. The cross fluid Reynolds number is varied from 250 to 2100. The higher enhancement in the Nusselt number along with pressure drop is reported for the common flow up type geometry orientation. The in-line and staggered tubes represent heat transfer augmentation 10-20% and 10-30% respectively.





The extension of the use of the delta winglet with the circular tubes is performed by Biswas et al. [7]which makes use of the elliptical tubes rather than circular tubes to prevent the greater pressure drop. The use of the elliptical tubes prolongs the separation of the fluid along with a minimizing in the size of the wake at the cylinder downstream. The oval tube with winglet orientation is as shown in the figure 5. The increment in the Nusselt number of the order of 40% is observed with the use of the two delta winglet pair. The lower angle of attack, the winglet has significant lower pressure drop with higher enhancement in the heat transfer rate. Feng Gen et al. [8] similarly makes use of the delta winglet in case of the tubular tubes so as to reduce the pumping power by using the mass transfer analogy which makes use of naphthalene. The cross fluid Reynolds number is varied from 250 to 3000 with three different fin thickness ( $T_p$ ) as 4,5, and 6 mm is used as shown in the figure 6. The pumping power increases with the reduction in the thickness if the fin. The smaller thickness of fin results in the higher Nusselt number enhancement is observed.





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Li Li et al. [9] studied the experimental and numerical performance of the finned flat elliptical tubes. The flat fins are rectangular in shape and individual to each tube to accommodate more number of vortex generators over the fin surface. The Reynolds number is varied from 1000 to 12000. The pressure drop is relatively low than thin continuous fin surface. C B Allison et al. [10] performed the experimental analysis for estimation of the effects of delta-winglet vortex generators in case of fin and tube radiator as indicated in the figure 7. The flow visualization study is performed by impinging dye with Reynolds numbers of 2600, 3400 and 4600. It is found that vortex generator, the flow is guided on the surface of the tube to increase the localized velocity gradients and Nusselt numbers. Jin Leu et al. [11] performed the thermal and flow simulation for the plain fin tube heat exchanger with the use of rectangular block type vortex generators. The three different attack angle of 30°, 45°, and 60° is used with Reynolds number ranging from 400 to 3000. The experimentation was performed with infrared thermovision. The block vortex generators causes reduction in fin area, along with best heat transfer enhancement at 45° attack angle. The orientation of the vortex generators are as shown in the figure 8.





Li Li et al. [9] performed computational analysis on the fluid flow and heat transfer rate for the finand-tube heat exchanger with three different vortex generators as rectangular vortex with zero attack angle, rectangular vortex with non zero attack angle, and delta vortex with non zero attack angle. The fins are individual to each tube as shown in the figure 9. The Reynolds number were varied from 500 to 2800 with results indicating that the Nusselt numbers is enhanced up to 20% for longitudinal vortex generators. The winglets in form of delta showed the best heat transfer performance. Zdanski et al. [12]investigated the effect of delta winglet type vortex generators on flow of air over in-line tube bank. The punched delta winglets are placed at the upstream of the tubes in in-line tube banks. The vortex generators generates the turbulence in the oncoming air prior to the entry in the tube bank which results in higher heat transfer. The layout of the tube bank with vortex generators is as shown in the figure 10. The overall increment in the Nusselt number of the order of 30% is estimated.





Babak Lotfi et al. [13] investigated the thermo-hydraulic performance of the smooth wavy fin-andelliptical tube heat exchangers with the rectangular trapezoidal, angle rectangular, and curved angle rectangular winglet. The layout of the vortex generators is as shown in the figure 11 with cross flow Reynolds number from 500 to 3000 with attack angle from 15° to 75°. The Colburn j factor and friction factor f are used in the estimation of the thermo-hydraulic performance of the heat exchangers. The curved angle rectangular winglet pair with smaller attack angle indicates the best thermohydraulic performance.



Zhou et al. [14] experimentally investigated the heat transfer augmentation with plane and curved winglet type vortex generators having punched holes as indicated in figure 12. The rectangular, trapezoidal and delta vortex generators with and without holes are selected for experimentation. The effects of punched hole diameter and location of the performance of winglets were used for estimation of the performance of a heat exchanger using dimensionless parameters. The punched holes improve the thermo-hydraulic performance of the system and decrease the overall flow resistance for all cases. Gholami et al. [15] numerically investigated the heat transfer augmentation and pressure drop characteristics for fin-and-tube compact heat exchangers with wavy rectangular winglet-type vortex generators. The effect of Reynolds numbers for the wide range from 400 to 800 and the effect of attack angle of 30° of wavy rectangular inlets are also estimated. The orientation is as shown in the figure 13. The results indicates that using wavy-up rectangular winglet has the better heat transfer performance and rectangular winglet. The usage of wavy-up rectangular vortex generator results in a uniform increase in the heat transfer performance and pressure drop in proportion to other cases.





Anupam Sinha et al. [16] performed simulation study in case of the fluid flow across fin and tube type heat exchanger having rectangular vortex generators for in-line and staggered configuration as indicated in the figure 14. The cross flow Reynolds number is varied from 200 to 1500 along with the different attack angle of the winglets. The swirl motion generates the strong vortex and intensifies the rate of heat transfer. The attack angle of 162.5° indicates the higher span wise Nusselt number.



Wenjin Wang et al. [17] performed the CFD investigation on the finned-tube heat exchanger with rectangular winglet having an accessory trapezoidal wing at the inlet as indicated in the figure 15. The tubes are arranged in the staggered arrangement with the fluid Reynolds number is from 500 to 2500 respectively. The results are compared with the rectangular winglets. Both heat transfer and pressure drop are increased in case of rectangular winglet with trapezoidal wing relative to that of the rectangular winglet pair by the order of 5%. With the increased attack angle enhancement in heat transfer of the order of 20% is observed with the pressure penalty of 30% over the rectangular winglets. In order to avoid the complex vortex generators researchers also make use of the obstacles in the form of vortex to generate the necessary turbulence for the incoming fluid, as Hosseini et al. [18] experimentally and numerically simulated the different vortex generators in form of wave, broken, and sinusoidal obstacles with cross Reynolds number from 20000 to 200000. The turbulent fluid will dissipate more heat compared to streamline fluid. The different geometry sections for turbulence generation are indicated in the figure 16. The wave and sine obstacles have a higher potential for heat transfer enhancement compared to the broken obstacles. Similarly, the vortex size and intensity both increases as the flow pass over the cylinder arrays compared to the broken obstacles.



Figure 15. rectangular winglet with trapezoidal wing obstacles.



Wang et al. [19] investigated the numerical performance tube bank having circular tubes and fin with interrupted annular groove over fin surface fins and compared with that of the plain fin. The length of the radial groove and the circumferential locations are the key aspects affecting the conjugate heat transfer. The orientation of the tube bank with annular fins is as shown in the figure 17. The use of the annular groove aimed at guiding the cross fluid across the tubes along with a reduction in the size of the wake region. The results show that as the length of the annular groove increases, friction factor increases drastically. There is an average 35% increase in the friction factor, with 10% to 40% increase in Nusselt number for Reynolds number ranging from 600 to 2500. The annular groove has a better thermal performance at higher Reynolds number rather than lower Reynolds number, as frictional forces are more significant at lower Reynolds number. Some of the authors [20,21] also make use of the tube cross-section and longitudinal fins so as to make the flow vortex to enhance the heat transfer rate.



The table 1 briefly summarizes the work in case of the vortex generators for the cross flow fluid flow heat exchangers with respect to the flow Reynolds number, tube arrangement, and their key finding. The table also provides the guidelines for the field engineer to select the exact vortex generators considering the heat transfer and penalty in the pumping power for the cross fluid.

**Table 1.** The summary of the work carried by the different researchers with the use of the winglets or vortex generators for the thermal performance enhancement.

Author and year	Nature of study	Winglet type	Re range	Tube orientation	Co-relations / Evaluation criteria
Biswas et al. [3] 1994	numerical	Delta winglet pair	Re=500 and 1000	staggered	Nusselt number enhancement ratio, Nu/Nu <sub>o</sub>
Liou et al. [4] 2000	experimental with LDV	Multiple winglets	12000	N/A	Nu=0.023 Re <sup>0.8</sup> Pr <sup>0.4</sup>
Jerry Lo et al. [5] 2002	experimental	multiple	500	staggered	Flow visualization with dye injection
Torii et al. [6] 2002	experimental	Delta winglet	300-2500	Inline and staggered	Colburn factor, j=Nu/Re.Pr <sup>0.33</sup>
Biswas et al. [7] 2003	numerical	Delta winglet	1000	staggered	Contour plots
Feng gen at al. [8]	experimental	Delta winglets	1076 1121 1136	staggered	Nu=Sh(Pr/Sc) <sup>n</sup>
Li Li et al. [9] 2015	numerical	Rectangular and delta	500-3000	Single tube	$j = Nu/RePr^{0.33}$

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Allison et al. [10] (2007)	experimental	Delta winglet pair	600-1400	staggered	Flow visualization techniques
Zdanski et al. [12]	experimental	Delta winglet	300-1300	inline	Nu=0.26557Re <sup>0.608</sup> C <sub>L</sub> $\left(\frac{P}{D}\right)^{0.075}\cos(\alpha)^{-0.448}$
Lotfi et al. [13]	numerical	rectangular trapezoidal, angled and curved	500-3000	staggered	$j = \frac{h}{\rho.u^2.C_p}.Pr^{2/3}$
Zhou et al. [14]	experimental	Punched rectangular, trapezoidal	1000- 21000	Plate surface	$j = \frac{Nu}{Re.Pr^{0.33}}$
Gholami et al. [15]	numerical	rectangular	400-800	In-line	Nu=hD/k
Anupam Sinha et al. [16]	numerical	Rectangular pair	200-1500	Inline and staggered	Quality factor, $Q = \frac{\frac{Nu}{Re.Pr^{0.33}}}{\frac{f}{8.00}}$
Wenjin Wang et al. [17]	numerical	Rectangular with built up edge	500-2500	staggered	Nu=hD/k
Hosseini et al. [18]	experimental and numerical	Sine, wave, broken obstacles	20000- 200000	staggered	Nu=hD/k and Contour plots

# **3** Conclusion

Based on the above literature survey on cross flow enhancement using vortex generators carried by the different authors the following key points are concluded.

- The vortex generators in the form of the winglets are the small projected fin-like structure mounted to generate the fluid flow turbulence on the shell side fluid. The delta vortex generators are the most commonly used vortex generators.
- The delta type vortex generators have the least obstruction in the cross flow fluid in case of the tube bank. The vortex generators can be separately mounted or punched from the base fin surface material.
- The punched vortex generators are usually not preferable as the boundary layer over the fin surface gets distracted. The wavy fin surface further enhances the thermal performance rate along with the requirement of the pumping power.
- The rectangular vortex generators are also preferred due to its capability of forming the secondary fluid flow along with mean stream flow.

# 4. Future design consideration

The following aspects leads to the design and development of the future cross-flow heat exchanger considering the above literature survey in case of the passive mode of thermal performance enhancement.

- The most commonly used vortex generators are delta, rectangular, curved delta, and curved rectangular, and trapezoidal vortex generators. Amongst these, the delta vortex generators offer the least resistance to the fluid flow.
- The curved delta winglets offer the improved overall thermal performance as the fluid is guided along the curved vortex generators over the tube surface and hence the pressure drop is reduced substantially.
- To reduce the pressure drop, the alternate use of the winglet pair is preferred rather than the continuous vortex assembly. The vortex generators are very much required in case of the inline configuration of the tube bank.
- The study related to the punched delta vortex generators with punched holes on the vortex generators are yet to be performed. This may results in the lower pressure drop as compared to the other configurations as fluid can pass through the multiple holes along with increased turbulence.
- As the turbulence generation is the main aspect in heat transfer enhancement, the fin, and the vortex generators may be of a different material from the base material of the tube surface.
- Use of the multiple holes on the winglets can be used if the height of the winglets is significantly higher or fin pitch is smaller. Furthermore, in case of more number of rows, the height of the winglets can also be reduced along the direction of the flow to reduce the higher pressure drop.

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