Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 08, August - 2025

Review of Thermal Analysis for Banks of Tubes with Vortex Generator

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***Abstract*— Enhancement of forced convection occurs when the heat transfer rate is increased, and the pressure penalty is reduced in the fluid flow across banks of tubes in heat exchangers using a longitudinal vortex generators (LVGs) arrangement. Different shapes of vortex generators for flow through banks of the tube heat exchanger are used. This review contains experimental and numerical studies interested in the heat transfer rate of banks of tubes with longitudinal vortex generators (LVGs), studied under laminar and turbulent flow conditions. This paper also includes the thermo-hydraulic performance parameters of vortex generators with tube banks for fluid flow in the duct, which are studied experimentally and numerically. This paper interests researchers that focus on the rate of heat transfer in banks of the tubes.**

***Keywords*— vortex generators; banks of tubes; heat exchanger**

I. INTRODUCTION

In the industrial field, fluid flows over banks of tubes in ducts are crucial and useful in many industrial processes. Banks of tubes are widely employed in various engineering works, such as cooling, heating processes, the chemical industry, nuclear system cooling, food processing, electronics cooling, automobiles, petroleum, and aerospace. There is a propensity for fluid to flow more rapidly along the refined duct wall, thus reducing the tube banks' flow velocity. It is good to deal with the increase in the rate of heat transfer gained by using longitudinal vortex generators of many shapes, sizes, and arrangements, such as longitudinal, curved, transverse, inclined, etc., for flow in the duct, as explained carefully by Tiggelbeck et al. [1]. In any case, understanding the various states that predict how flow conditions transition from one composition to another is crucial for conducting research on new types of tube heat exchanger banks. These permitted determining the performance properties of devices to avoid any potential problems. Working fluids like air, water, and ethylene glycol are usually used in many engineering processes like heating and cooling processing. Several methods are utilised to enhance the rate of heat transfer; a low heat transfer rate of these working fluids prevents enhancement in performance. The enhancement rate of heat transfer is one of the essential tools in saving energy in heat transfer processes. The performance enhancements in the heat transfer rate of heat exchangers increased the overall heat transfer coefficient and led to the use of a small size and low cost of the heat exchanger. This paper reviews numerous previously published studies focusing on vortex generators with various designs, locations, and heat transfer techniques. Additionally, the thermal performance of banks of tube heat exchangers is intended to identify areas that should be investigated in the industry's future and facilitate means for researchers to study this field.

II. CONCEPT OF LONGITUDINAL VORTEX GENERATORS (LVGS)

Vortex generators are utilised to increase the rate of heat transfer, which is promised to work on the airside. Longitudinal vortex generators like horizontal wings and vertical winglets are generated to swirl flow into the fluid flow throughout the duct, causing the rate of thermal energy to enhance as shown in 'Figure 1'. Vortex generators can be fixed on a bottom wall of the duct. Swirl flow is generated when fluid flows pass over the LVGs and the tubes because of the separation of the boundary layer for fluid flow on the surface of the vortex generator [2].

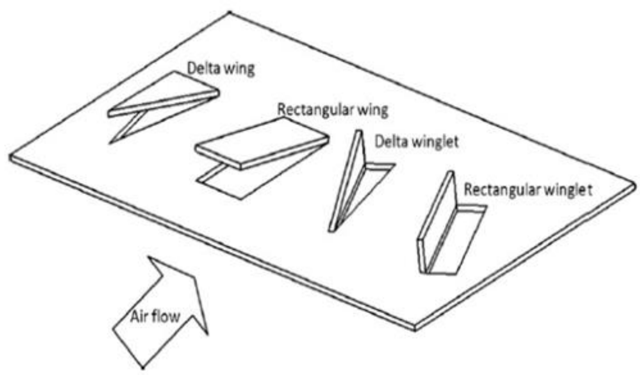

Fig. 1. Schematic diagrams of four common LVGs [2].

Finding a novel design of heat exchangers is used to increase the rate of heat transfer, which is taking the interest of researchers because of its enormous technological significance. It is widely agreed to receive that the increased rate of heat transfer acquired by using obstacles by vortex generators winglets (VGW) of different shapes, sizes and arrangements (rectangular, trapezoidal, delta and curved trapezoidal) [3], as illustrated in 'Figure 2'.

Furthermore, vortex generators are called turbulence surfaces or obstacle surfaces, responsible for promoting the convective rate of heat transfer techniques in banks of tube heat exchangers [4, 5]. The design and location of the obstacle surface play a substantial impact on the performance of the bank of tubes by enhancing the heat transfer rate and reducing pressure drop in fluid flow through the duct [6, 7]. Instruments of swirl flow are used to increase the heat transfer rate in HXs [8].

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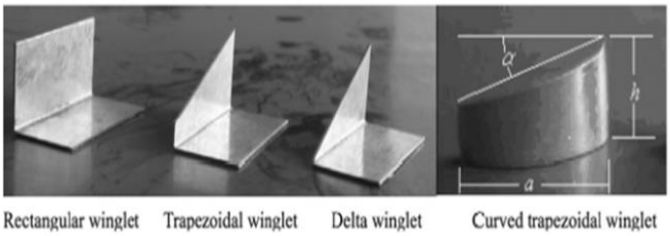

Fig. 2. Different shapes of vortex generators winglets [3].

III. HISTORY OF USE VORTEX GENERATORS (VGS)

Heat transfer to or from banks of tubes (or bundles) of heat exchangers in cross flow is relevant to numerous industrial applications. The thermo-hydraulic performance enhancement of heat exchangers is a significant interest of researchers and designers. Recently, various techniques have been developed to enhance the thermal performance of tube banks in heat exchangers. These technologies are called active technicality, passive technicality and compound technicality [9-12]. Active technicality incorporates utilising outer energy to increase thermo hydraulic performance in heat exchangers. For instance, augmenting the blending stream rate by (a) scraping or revolving the surface, (b) wavy surface heat transfer, (c) the limit layer, and creating an additional stream, (d) using a magnetic and electric current to produce constrained convection, consequently augmenting mass blending of cold and hot fluid, and introducing identical fluid to the source section of HXs, etc. These technicalities increment the surface area for heat transfer fins utilising the assistance of extensive surfaces, for example, sinusoidal fins [13, 14], punctured fin surfaces and miniature fin tubes [15], offset strip fins [16], wavy herringbone fins [17], wavy fins [18], plane fins [19], louvre fins, etc. [20-24]. Ashwin et al. evaluated flow parameters in terms of quality factor, which refers to the term quality factor with slight variation. It also shows the ratio between the coefficient of heat transfer to the evident loss in pressure, Nusselt number, and vortices. The results highlight the importance of improving heat transfer rates. The flow becomes faster in passages generated by the vortex winglet pairs and the region; eventually, the circular pipe increases the flow rate [25]. Torii and Kwak suggest a new technique that can increase the heat transfer rate but still cannot decrease the pressure drop in the banks of tubes in heat exchangers. When using circular pipes in a comparatively slash Reynolds number flow rate, use kinds of longitudinal vortex generators like delta winglets [26]. Paisarn et al. investigated experimentally for heat exchanger thermo-hydraulics in the various angles of attack by using winglets for upward and downward flow. The testing was accomplished for Reynolds numbers in the area from 2000 to 9000 and the heat flux 0.5 to 1.2 W/ m^2.K. Experiences were performed with different heat fluxes and different air flow rates. It was performed that the flow rate of air mass rises that produced a higher heat transfer rate. Thermo-hydraulic performance with the wavy surface was 3.5 times greater than the common duct, and pressure loss was 5 to 6 times higher than the common duct [27].

IV. GEOMETRY ANALYSES OF VORTEX GENERATORS

A. Mathematical model

In recent years, numerous numerical studies have been conducted to analyse the impact of longitudinal vortex generators (LVGs) on the effectiveness of tube banks in heat exchangers. The impact of various kinds of longitudinal vortex generators is archived based on the modern numerical research on the heat transfer rate and pressure drop of the heat exchanger. Chu et al. conducted 3-D numerical studies to analyse the heat transfer rate and fluid flow composition in banks of elliptic tube heat exchangers using obstacle turbulence. The solution of general governing equations is accomplished through the use of a CFD code and the application of boundary conditions. To promote the precision of the simulation products, the mesh points around the wall of tubes and the surface of vortex generators are smooth. For the Reynolds number instituted on the hydraulic diameter in the area from 500 to 2500, it was found that the intermediate Nusselt number for three rows of banks of the elliptic tube heat exchanger using augmented was 13.6–32.9% above the baseline case; however, the pressure drop also increased by 29.2%–40.6%. Three geometrical characteristics – the position of the obstacle (turbulence upward stream and downward stream), a row of banks of elliptic tubes (the number of the row was n = 2, 3, 4 and 5), and angles of attack (α = 15°, 30°, 45° and 60°) – were also researched for characteristics optimisation. The longitudinal vortex generators with the position of downward stream, minimum tube row number and angles of attack α = 30° give the better performance of heat exchangers by enhancement in heat transfer rate [28]. Gholami et al. researched numerically the solution with the wavy rectangular winglet of continuity, momentum, and energy equations resolving by using Fluent ANSYS 14. The effect of the Reynolds area between 400 and 800 with longitudinal wavy rectangular winglets at a 30° angle was investigated. The results indicated that the turbulence created by the rectangular wavy obstacle can improve the heat transfer rate of tube heat exchangers while maintaining a reasonable pressure drop and enhancing thermo-hydraulic performance. This raise is more critical for the case of the wavy obstacle turbulence upward stream arrangement [29]. Wanling et al. also studied the impact of three different shapes of longitudinal obstacle turbulence, such as rectangular, trapezoid, and delta winglets, on thermo-hydraulic performance numerically and the swirling flow rate of the banks of the tube heat exchanger. The results indicated that the overall average Nusselt number (Nu) increase is related to the pressure drop caused by the growth of the Reynolds number. Under the corresponding pumping power restrictions, this study found that the optimum configuration of the longitudinal obstacle turbulence is the delta winglet for the research cases [30]. Mohammad and Ashiqur presented a 3-dimensional numerical study for thermo-hydraulic performance in fluid flow across banks of circular and elliptic pipes HXs and used longitudinal obstacle turbulence. The heat transfer rate and pressure drop are measured numerically using CFD ANSYS FLUENT 15. The study found that under laminar flow conditions, the Reynolds number (Re) ranged from 500 to 850, and that the geometric shape of the tube had a greater effect on enhancing the heat transfer rate. The heat transfer rate rises by 13 % when the angle of attack changes from 15º to 25º. However, pressure drop rises by 62 % and 40 % for the circular and elliptic pipes, respectively [31]. The authors concluded that using wavy obstacle turbulence in upward stream arrangements, specifically the longitudinal Delta winglet as an obstacle, yielded good results in their numerical studied [29, 30]. Other researchers improved heat transfer rates while increasing pressure drop by using obstacle turbulence within the duct, as illustrated in 'Figure 3' [28, 31].

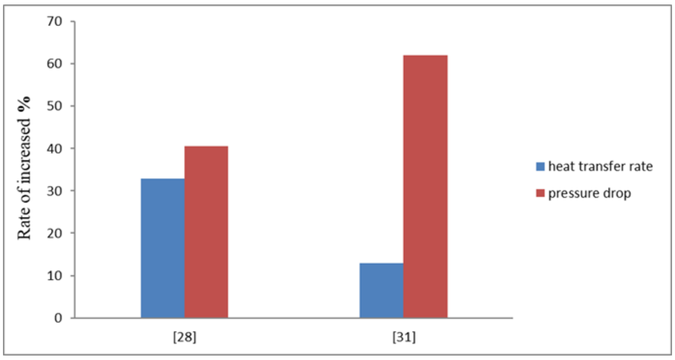

Fig. 3. Comparing results between [28] and [31] in the numerical study.

B. Thermal analysis experimentally

Zhou and Ye studied experimentally by comparing traditional delta winglets and curved trapezoidal winglets (CTW) and longitudinal rectangular obstacle turbulence, delta obstacle turbulence and trapezoidal obstacle turbulence. It found that Delta obstacle turbulence pairs produced the best execution in the transitional flow region and laminar; however, curved trapezoidal winglets produced a higher heat transfer rate in the turbulent flow region [32].

Zdanski et al. presented experimentally the influences of vortex generators of the Delta obstacle turbulence on the thermo-hydraulic performance in series banks of the tube. The effects of the following characteristics on the thermo-hydraulic enhancement were estimated as the main target of this study, the X dimension from the bank of tubes to the vortex generators. The experimental procedures compared the current outcomes to correlations that have been empirically established in the literature review. The actual outcomes indicate that the Nusselt number (Nu) increased by nearly 30% when utilising longitudinal vortex generators (LVGs). Furthermore, the pressure loss across the pipe banks was increased and reached nearly 40% [33].

Prasopsuk et al. conducted an experimental study on the effect of longitudinal rectangular winglets on the thermal effectiveness of heat exchangers (HXs) at Reynolds numbers ranging from 4100 to 26000. It accomplished that longitudinal rectangular winglet kind LVGs produce increased thermo-hydraulic efficiency as contrasted to the case without used LVGs with an increase in pressure loss in the duct [34].Zhang et al. also studied experimentally for normal fin surfaces with 12 longitudinal obstacle turbulence of delta winglets over each tube in banks HXs. Experiments involving four rows of tube heat exchangers with actual geometric shapes were conducted to compare the overall properties of a suggested fin design with those of circular tubes and wavy fins. Furthermore, the circular tube heat exchangers have six rows of circular tubes with two wavy fins. The distance between the fins was 2.117mm and 2.54 mm, which used twelve and ten surfaces wavy and two rows of the suggested fin with the circular tube heat exchanger surfaces with five rows of the circular tubes at the same distance between fins. The design incorporated twelve and ten longitudinal turbulence obstacles, respectively. The velocity entrance of the airflow is in the range of 1.5 m/s to 7.5 m/s, while the water flow rate is constant at a specific value at each air entrance velocity. The testing result showed the thermo-hydraulic performance and pressure drop increased by longitudinal obstacle turbulence for banks of the tube heat exchanger, which used a fin with the five rows of banks of the tube with a normal fin surface. The design can replace the six rows of wavy surface fins with two rows of standard surface fins. Furthermore, the longitudinal vortex generators increased the Nusselt number for two cases that used the fin surface and the wavy fin surface [35].Abdulkerim et al. demonstrated the effect of three dominant characteristics on tube heat exchanger banks' thermo hydraulic performance and pressure drop experimentally. These are fin surfaces, such as those with louvred or wavy surfaces. The surface of the fins is stepped by the number of rows of banks in the tube. This research specifically used three wavy surfaces and five louvred surface fins; a round of banks of tube heat exchanger prototypes was a fabrication. The pressure drop and thermo-hydraulic performance of these HXs were carried out at a wind tunnel in ambient conditions. The outcomes showed the side of pressure loss and the performance of the thermo-hydraulic of WFBTAHXs and LFBTHXs fin surfaces for the various numbers of rows of banks of the tube and airflow entrance velocities. It is results that pressure loss and the performance of the thermo-hydraulic of the louvred fins of banks of the tube heat exchanger are greater than pressure loss and the performance of the thermo-hydraulic of the wavy fins of banks of tube heat exchangers for all the stats which were researched. The performance of the thermo-hydraulic of louvred fins of banks of the tube heat exchanger is greater by 16.4–6.9%, 28.5–18.3% and 25–11.7% than the performance of the thermo-hydraulic of the wavy fins of banks of the tube heat exchanger for the cases of 2 rows of banks of the tube, three rows of banks of the tube and four rows of banks of the tube, respectively. Furthermore, the pressure losses of the wavy fins of the tube heat exchanger banks are significantly lower than those of the louvred fins of the tube heat exchanger [36].[32, 34] showed when Delta winglets, curved trapezoidal winglets, and rectangular winglets were used. [33, 36] show enhancement of the Nusselt number when using delta winglets, louvred fins, and wavy fins, concluding better results with delta winglets through the duct in the experimental studies, as shown in 'Figure 4'.

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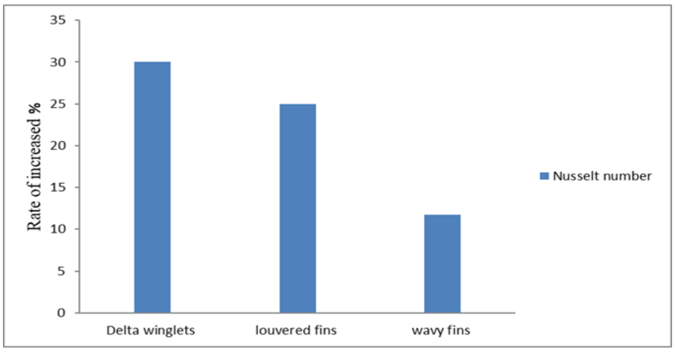

Fig. 4. Comparing results between [33] and [36] in the experimental studies.

V. VORTEX GENERATORS PERFORMANCE ANALYSIS

The thermo-hydraulic performance of obstacle turbulence (vortex generators) and fluid flow was studied numerically and experimentally in a woody duct with constant heat flux fitted with two vortex generators, square and circular, to increase thermo-hydraulic performance. The location of obstacle turbulence was in two positions, Xd = 2 cm and Xd = 1 cm, with the same area. These locations from the edge of the heater were studied under Reynolds numbers in the area from 32,000 to 83,000. The influence of vortex generators is solved by ANSYS Fluent 6.3 with the (k–ε) turbulent model. Heat flux was constant and equal to 43.09426 kW/m² for all values of the Reynolds number. The numerical and experimental outcomes show that using VGs increases the heat transfer rate. The numerical results indicated that the heater using obstacle turbulence provided a 27% increase in electrical energy efficiency. The experimental results indicated that heat exchanger performance with a distribution coefficient of heat transfer and pressure loss of fluid flow across electrical heaters using obstacle turbulence was recorded and contrasted with the flow across heaters without using obstacle turbulence. The results showed that pressure loss at the duct exit increased by 133.3%–300% when using square winglet obstacle turbulence and increased by 166.7%–400% when using circular winglet obstacle turbulence. Furthermore, heat transfer rate increased 1.3%–1.94% using square-type winglet obstacle turbulence, and heat transfer rate increased by 2.186%–3.75% when using circular-type winglet obstacle turbulence [37].

The cooling process for a hot rod was carried out using obstacle turbulence of longitudinal triangular and rectangular winglets in experiments in a wind tunnel to enhance thermo-hydraulic performance over the hot rod. Results showed that for the case of in-series banks of tube type. Under flow conditions with Reynolds number areas from 350 to 2100. Heat transfer is enhanced by 10 to 20%, while the pressure loss in the duct decreases from 15 to 8%. While for the case of staggered banks of tube type with the same Reynolds number area, the heat transfer rate increases by 10 to 30%, corresponding to a reduction in pressure loss from 55 to 34% [38].Performance was evaluated for using FLUENT 6 and found that the impacts of winglet height (hw), relative positions (ΔX or ΔY), and extension angle (θ) of longitudinal winglet obstacle turbulence on heat transfer increased and reduced pressure loss. That studied the downward flow and upward flow winglet configuration and banks of tube heat exchangers.

The underflow condition had a water flow Reynolds number of 5×10^2, while the airflow Reynolds number ranged from 1.85×10^3 to 9.7×10^3. A winglet height bank of tubes was fixed as 5 mm, 7.5 mm and 10 mm. The downward flow extension angle for longitudinal winglet vortex generators is fixed as 0°, like in the case without vortex generators, and from 5° to 45° for clockwise upward flow and anticlockwise downward flow. While for upward flow, longitudinal winglet vortex generators are fixed at −5°, −10° and −15° upward flow. Results presented an increase in extension angle for case CFDW. In this scenario, CFUW enhanced the heat transfer rate by installing longitudinal winglet vortex generators at locations ranging from +5° to +45°. These results, which cause an augmentation in the heat transfer coefficient of nearly 34 to 48%, compared with the case that does not use vortex generators. The lower pressure drop values for banks of tubes with downward flow gained at -5°C CFDW and +15°C CFUW compared with the case do not use vortex generators. For banks of tubes with upward flow, the heat transfer coefficient rises by increasing the extension angle nearly from 0° to −5°, and the values of the heat transfer coefficient for the extension angle changing from −5° to −15° have no essential variations. Pressure loss increases with winglet height, which has a negligible effect on the heat transfer. Moreover, the optimal location and angle of attack for winglet vortex generators were examined in four cases related to the optimal design of heat exchangers [39].

[37, 38, 39] show the performance of HXs with used square winglets, circular-type winglets, triangular winglets, rectangular winglets, winglet height, relative positions, and tube arrangements to enhance the Nusselt number through the duct in the experimental studies and compare results in 'Figure 5', 'Figure 6', and 'Figure 7'.

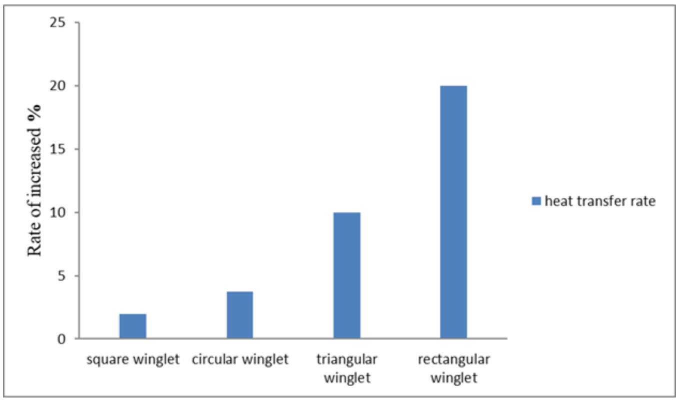

Fig. 5. Heat transfer rate increased with used square, circular, triangular, and rectangular winglet.

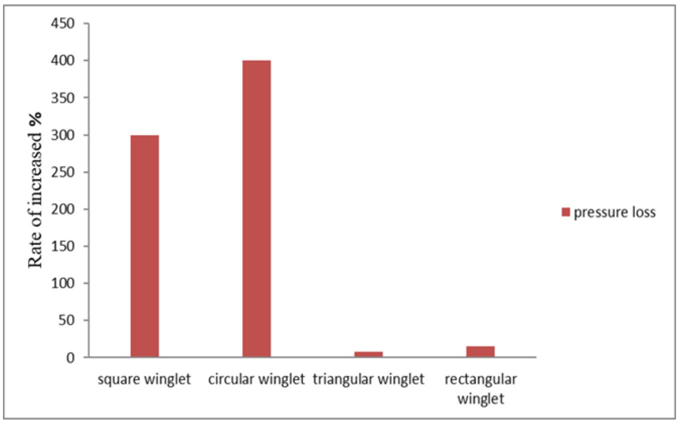

Fig. 6. Pressure drop increased with used square, circular, triangular, and rectangular winglet.

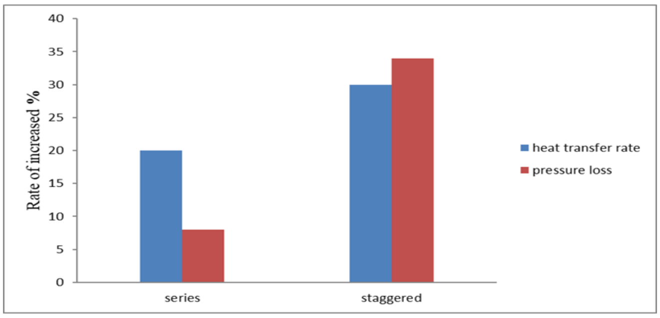

Fig. 7. Comparing results between series and staggered banks of tube.

VI. IMPACT OF LVGS ON THERMO-HYDRAULIC PERFORMANCE

The effect of using obstacle turbulence (vortex generators) with banks of tubes (HXs) on augmentation in thermo-hydraulic performance and recorded the best correlation methods of obstacle turbulence on heat transfer surfaces and contrast performance of banks of pipes in circular and elliptic shapes with and without using longitudinal winglet vortex generators, the effect of location and shape with many longitudinal winglet vortex generators, etc. It was understood that when banks of tubes of circular and elliptic shapes were placed without using any types of longitudinal winglets or vortex generators. Airflow started at a very high velocity and high Nu number. Subsequently, the air velocity and Nusselt number decreased as the thickness of the boundary layer on the duct wall increased. Vortex motions induced by vortex generators build up the best fluid mixture, increasing the heat transfer rate. However, the fluid's velocity is very low for downward flow areas where the decreased heat transfer rate becomes visible. For single-row duct banks of tubes in circular and elliptic shapes and a pair of wing vortex generators, an 81% increase in the heat transfer rate can be obtained by comparing it with the channel work without vortex generators.

Furthermore, when adding one pair of wings, vortex generators had increased the heat transfer rate by 147% compared to the planar channel. However, it also had reached that at Re = 1000 for four pairs of wings with vortex generators with interior wing pairs in the common flow upward stream and exterior wing pairs in the common flow downward stream with elliptical tubes. That results in a 100% greater rate of heat transfer with augmentation compared with the flow in the duct, which does not use wing pairs [40].A numerical study demonstrated the influence of obstacle turbulence on enhancing heat transfer in the tube heat exchanger banks and found a 13% augmentation in thermo-hydraulic performance compared with no used obstacle turbulence [41]. The impact of Delta winglets' obstacle turbulence on thermo-hydraulic performance also was recorded by all numerical studies. It found that flow in a duct with single winglets and paired winglets augmented thermo-hydraulic performance by 33% and 67% compared to the duct without winglets [42]. The above observed that in all cases, any types of vortex generators were used in banks of the tubes that promoted heat transfer rate in the heat exchanger. There is usually the pressure drop, which can be illustrated as follows: for the case without used vortex generators, the resistance of the flow of air in the duct results only from the friction between air particles and duct walls with tube walls. The resistance of the airflow in the duct when vortex generators were used not only results from the friction between air particles and duct walls with tube walls but also from extra resistance, which causes an increase in pressure loss through flow in the duct. The table must have a title at the top, e.g., in Table 1 (Times New Roman italic font 11 pt). When creating a table, it is recommended to use the style shown in Table 1. Visibility between rows, in case there is a larger amount of data displayed by the table, can be improved by shading in lighter shades of grey colour. Numbers written in decimal form should be separated by a decimal point.

VII. INFLUENCE OF LOCATION AND GEOMETRIC SHAPE OF WVGS ON THE THERMO-HYDRAULIC PERFORMANCE OF HXS

Different locations and shapes of winglet vortex generators are used to reach the optimum thermo-hydraulic features of the banks of the tube heat exchanger. Due to its importance, many researchers have studied this topic both numerically and experimentally. These researches interested in the winglet height, angle of attack, and shape of vortex generators by several researchers carried out in experimental work. The impact of vortex generator arrangement on pressure loss with an increase in heat transfer rate through banks of the tube heat exchanger is also carried out in numerical work. It resulted in vortex generators with a moderate angle of attack tending to have a high-pressure loss penalty with a better heat transfer coefficient, and the angle of attack was in a range between 15 ° and 25°. Numerical research was conducted on the impact of location and geometric shape of WVGs on augmentation in the thermo-hydraulic performance of longitudinal Delta and rectangular vortex generators by using several characteristic dimensions of longitudinal vortex generators: winglet height, length, and position. It resulted from increasing winglet length with the same angle of attack, which enhances the heat transfer rate. Furthermore, it concluded that the longitudinal Delta and rectangular vortex generators with longer winglets cause higher pressure loss with a better heat transfer rate. Results showed that any increase in the height of longitudinal vortex generators means a smaller area cross-section of flow in the duct. Increases in flow velocity, consequently, induce strong swirling flow and vortices. Similarly, most studies describe the impact of winglet length, height, and position on the optimum design for heat exchangers with longitudinal Delta and rectangular vortex generators.

IX. CONCLUSION

The current reviews focused on thermo-hydraulic performance for banks of the tube heat exchanger, improved by using different shapes and sizes of VGLs with varying angles of attack and their position. Vortex generators are ideal for reducing pressure loss and increasing the heat transfer rate for fluid flow through banks of tube heat exchangers in all numerical and experimental research. Present work shows a review of vortex generator designs in recent decades for their technological importance in the field of heat transfer, briefly presenting their applications, most characteristics, and development stages.VGLs play an important role in the advancement of heat transfer applications. The following is summarised for essentially resulting observations on this review:

1) More efficient thermo-hydraulic performance in a rectangular duct with obstacle turbulence than without obstacle turbulence because of low thermal properties in liquid, air, and flow, and finally an increased heat transfer rate for HXs.
2) Vortices are generated by obstacle turbulence such as rectangular and delta winglets. These vortices are induced when the fluid passes through obstacle turbulence. More turbulence in the duct induced an enhancement in thermo-hydraulic performance in the fluid flow.
3) With an increase in airflow velocity and vortices generation, that case reduces in pressure throughout the duct because of friction between air particles and duct walls with tube walls, which is inversely proportional to the airflow velocity.
4) Researchers used various angles of attack for VG's in their studies, which found the moderate angle of attack was an optimum angle.
5) Literature studies focused on the impact of various design characteristics for augmentation in thermo-hydraulic performance in multi-row banks of tube HXs with the use of a number of obstacle turbulence (vortex generators) at the specified shape and position, with circular and elliptic tube rows. Researchers use the elliptic tube row to enhance air velocity. This technique increases thermo-hydraulic performance according to a minimum increase in pressure loss.
6) Future works in this field: researchers should study novel designs for vortex generators by finding a new shape, length, height, and location. Additionally, the effects of vortex generators on the flow that causes pressure drop during air flow in the duct should be studied to determine the optimal design for these generators to increase the heat transfer rate of the heat exchanger.

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 08, August - 2025

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