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# A review on improving thermal-hydraulic performance of fin-and-tube heat exchangers

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**Abstract.** Fin-and-tube heat exchangers are one of the most common type of heat exchangers that are normally used in sectors that require small size and light weight but high heat transfer capabilities. Compact fin-and-tube heat exchangers experiences high convective thermal resistance at the air-side due to the thermo-physical properties of air. Thus, the purpose of this paper is to provide an overview of research works that are relevant to improving thermal-hydraulic performance at the air-side of fin-and-tube heat exchangers. This paper covers a variety of parameters such as tube parameters like tube arrangement, tube shapes and tube inclination angles; extended surfaces such as different shapes of fins and different parameters of vortex generators like attack angles, shapes and locations. Overall, for most modifications there was increment in heat transfer but accompanied with a pressure drop penalty. However, this varies for different combinations of parameters thus this review is to help understand how every mentioned parameters influences the thermal-hydraulic performance.

## 1. Introduction

Heat exchangers are devices that transfers heat energy between two fluids which are at different temperatures. This device is used in many fields such as heater and air-conditioning systems in a household or vehicle; chemical processing and as well as for power plants. There are many types of heat exchangers such as shell-and-tube heat exchanger, plate heat exchanger and compact fin-and-tube heat exchanger whereby their usage depends on the application.

Compact heat exchangers (CHEs) are normally used where weight and volume are a matter of interest. CHEs has an efficient heat transfer for a given small volume because a large surface area is obtained by attaching thin plates or fins closely to the walls separating the working fluids. In compact fin-and-tube heat exchanger, both fluids are normally in cross-flow configuration whereby they move perpendicular to each other. This produces high turbulence thus generates high heat transfer. Performance and efficiency of heat exchangers are measured through the amount of heat transfer using least area of heat transfer and pressure drop where both represents cost and power requirements of a heat exchanger respectively.

Compact fin-and-tube heat exchangers normally experiences high pressure drop which in return consumes a lot of energy. Besides, the thermal resistance experienced are the air-side convective thermal resistance, wall conductive thermal resistance and fluid-side convective thermal resistance. Due to thermo-physical property of air, the air-side convective thermal resistance is the highest thus enhancement of heat transfer should be focused on the air-side. With this in mind, the purpose of this review is to summarise experimental and numerical investigations on the thermal-hydraulic performances of fin-and-tube heat exchangers. This review is focused on different tube parameters and extended surfaces such as fins and vortex generators (VGs) for thermal-hydraulic improvements.



## 2. Effects of tube parameters on thermal-hydraulic performance

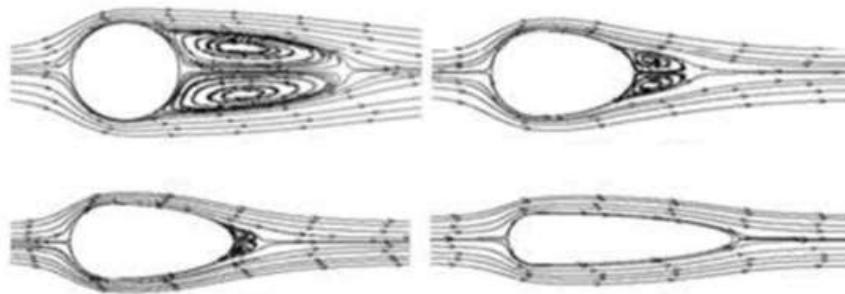
Tube parameters such as its arrangements, shapes and inclination angle normally influences the flow and thermal behaviour of the flowing fluid. These parameters are emphasized because they are closely related to the air-side thermal-hydraulic performance and since this part of the heat exchanger experiences the most thermal resistance, modifications to these parameters might be useful.

### 2.1. Tube arrangement

Tube arrays such as inline and staggered are known to produce different flow separations and fluid re-circulation. This was observed by Zhang et al. [1] where they found that the inline and staggered arrays of tubes have different performances. In the case of multiple tubes arrangement, the reduced gap between adjacent fins increased the velocity and temperature gradients resulting in a significant increase in heat transfer and pressure drop. This is more significant for staggered tubes arrangements as the gap is even smaller. This allows staggered tube arrays to distort the temperature profiles of the approaching fluid significantly. Kim et al. [2] stated that the staggered tube arrays yields higher enhancement of the heat transfer due to increment in velocity that intensifies turbulence. Their experiment showed that heat transfer coefficient of the staggered tube alignment was 10% higher than that of the inline tube arrays. Bhuiyan et al. [3] have also noted that higher heat transfer and pressured drop is observed in all flow ranges in staggered case.

### 2.2. Tube shape

Tube shapes influences fluid flow across it as different shapes produce different wake regions created by the boundary layer separation at the rear of tube. This can result in large pressure drop and vigorous vibrations. Besides, different shapes of tube are believed to produce swirls and vortices at varying intensity. Zhang et al. [4] conducted a numerical study on different shapes of tubes and their simulation resulted in Figure 1 where it shows that flow separation is lower for wider tubes. Smaller flow separation will reduce the pressure drop and increase heat transfer.

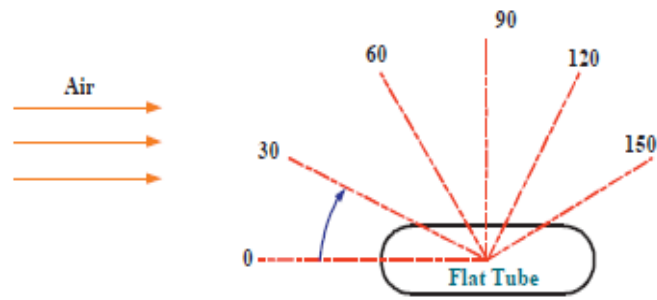


**Figure 1.** Comparison of streamlines produced by tubes of different widths [4].

In addition, Horvat et al. [5] conducted a study to understand the local heat transfer and fluid flow conditions in different tube shapes namely wing, elliptical and cylindrical tubes. Their numerical study further verifies the fact that different tube shapes influences flow separation. Besides, they concluded that ellipsoid tubes produces the lowest drag followed by wing tubes and cylindrical tubes. This is in line with the hypothesis that wider tubes produces smaller wake region. Furthermore, Tahseen et al. [6] mentioned that flat tube heat exchangers has smaller air-side pressure drop and improved air-side heat transfer coefficients in comparison to the round tube heat exchangers. This is due to smaller wake region for flat tubes compared to circular tube.

### 2.3. Tube Inclination Angle ( $\beta$ )

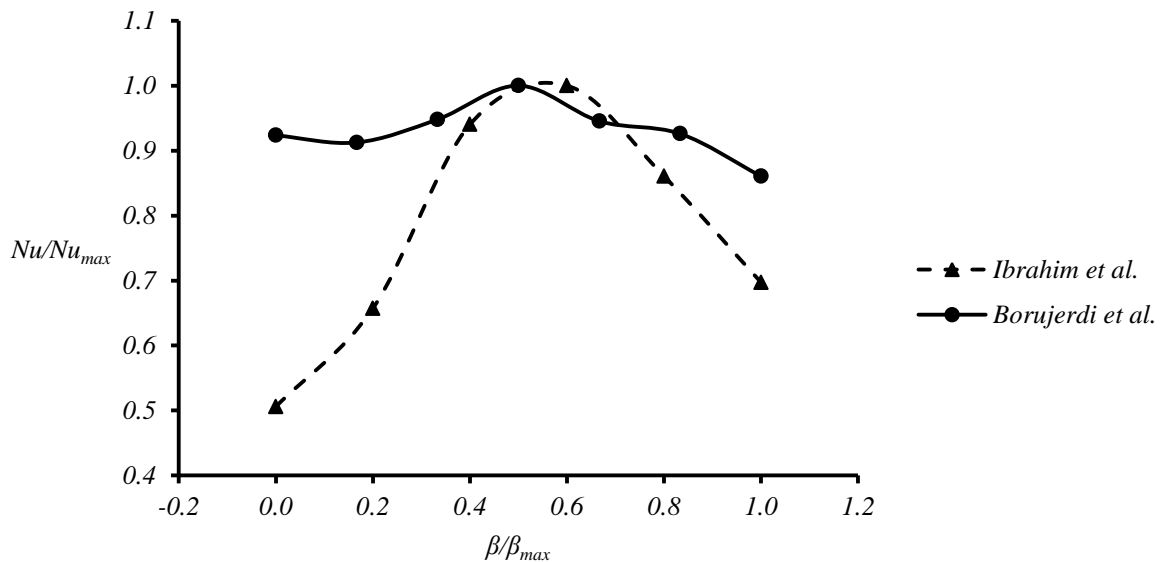
Another good way to enhance thermal performance is to induce vortex. This can be done by adjusting the inclination angles of the tubes as shown in Figure 2.



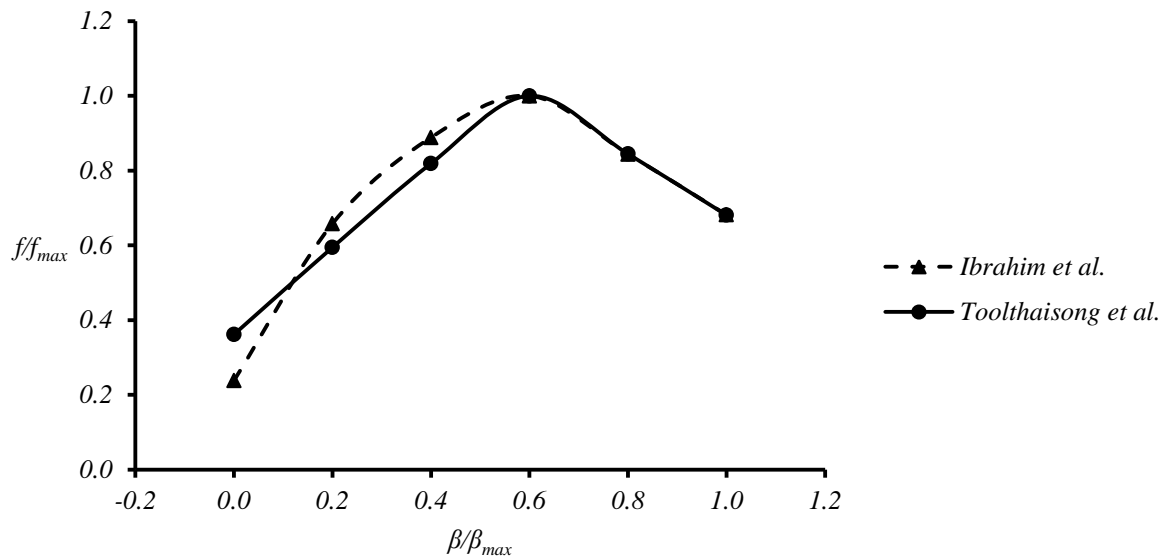
**Figure 2.** Different tube inclination angle with respect to air stream [7].

Badr et al. [8] visualised numerically on how inclined tubes effects thermal-hydraulic performances. They concluded that inclined tube produces counter-rotating flows in the wake region. This increases the flow velocity on the tube surface. Furthermore, they found out that increasing the tube inclination angle causes the gaps between the tubes to form a nozzle-like structure whereby the fluid flow velocity increases and this makes vortex formation more intense. Both of these effects enhances thermal performance. In addition, Ota et al. [9] claimed that increasing the tube inclination angle produces a violent transversal fluid motion that would increase heat transfer. However, this would increase the wake width so pressure drop would increase as well. Besides, Ibrahim et al. [10] concluded that as the tube inclination angle is increased from  $0^\circ$  to  $90^\circ$ , the heat transfer and pressure drop is increased because the nozzle-like flow and vortex formation increases. As the angle is further increased to  $150^\circ$ , the heat transfer and pressure drop reduces.

Figure 3 and Figure 4 shows the variation of normalized Nusselt number ( $Nu$ ) and friction factor ( $f$ ) respectively with normalized tube inclination angles. Both figures indicate that similar results were obtained by other authors [7, 11] whereby as the tube inclination angle is increased to  $90^\circ$   $Nu$  and  $f$  increases and as the inclination angle is increased beyond  $90^\circ$ , both  $Nu$  and  $f$  reduces.



**Figure 3.** Variation of normalized  $Nu$  against normalized  $\beta$ .



**Figure 4.** Variation of normalized  $f$  against normalized  $\beta$ .

In general, in terms of effectively distorting air flow in such a way that thermal-hydraulic performance improves, it is understood that staggered tubes produce more intense vortex and swirls whereby it increases heat transfer and pressure drop. Besides, it was also found that wider tubes produce smaller wake regions. Thus, elliptical and flat tubes were identified as effective tube shapes due to their larger aspect ratio. Finally, heat transfer and pressure drop increase as the tube inclination angle is increased to  $90^\circ$  and further increment in the angle reduced the heat transfer and pressure drop.

### 3. Effect of fins on thermal-hydraulic performance

Fins are known to increase heat transfer due to extended surface. To further enhance heat transfer, different shapes could be used to effectively distort fluid flow. However, to avoid large heat transfer area per volume, compactness was focused while ensuring efficient heat transfer and flow properties.

#### 3.1. Plain fins

Plain fins are still popular as they are simple, durable and versatile in applications. Wang et al. [12] studied on sensible heat and friction characteristics of plate fin-and-tube heat exchangers having plain fins. They found that fin spacing has inconsistent effects on heat transfer coefficient; number of tube rows has negligible effect on friction factor; fin thickness does not affect heat transfer and friction factor. Wang et al. [13] showed that the heat transfer is independent of fin pitch for number of tube rows greater than or equal to 4 and Reynolds number ( $Re$ ) higher than 2000. Kim et al. [2] studied heat transfer characteristics of flat plate finned-tube heat exchanger with large fin pitch. Their results show that heat transfer decreases as fin pitch decreases. Bhuiyan et al. [14] performed a 3D numerical analysis of plain fin and compared to Wang et al. [12] and the results were similar. Their result shows that heat transfer increases as fin pitch increases. Besides, heat transfer decreases with increasing longitudinal and transverse pitch of tube spacing for both inline and staggered arrangements.

#### 3.2. Wavy fins

As researchers strive for better geometry and enhanced performance, fin patterns were modified by interrupting it periodically along the streamwise direction like wavy fins. Wavy fins are vastly used in industries as they were developed to improve heat transfer where the path of the airflow is lengthened so heat transfer increases [15]. Besides, wavy fins give compactness aspect for the heat exchanger which leads to reduced space usage. Wang et al. [15] experimented on wavy fins and showed that heat

transfer coefficient decreases as the number of rows increases within  $Re$  of 900. As the  $Re$  increases from 900, the heat transfer coefficient increases, and similar results were obtained by Rich et al. [16] as well.

Moreover, heat transfer coefficient is independent of wavy fin pitch and effect of tube row on friction factor is negligible. Wang et al. [17] presented empirical correlations for herringbone wavy fin on heat transfer and friction factor which implies a significant improvement on thermal-hydraulic performance compared to plain fins. Wongwises et al. [18] studied on fin pitch and number of tube rows and the results shows that wavy fin pitch has negligible effect on heat transfer meanwhile friction factor increases as fin pitch increases at  $Re$  greater than 2500. Pirompugd et al. [19] stated that heat transfer increases as fin pitch decreases under dehumidifying conditions. Junqi et al. [20] presented that heat transfer and flow properties decreases with increasing  $Re$  between 800 to 6500. Wang et al. [21] found that heat transfer decreases as number of tube rows increases and higher heat transfer is obtained for larger wavy fin pitch for number of tube rows more than two.

### 3.3. Rectangular offset-strip fins

Rectangular offset-strip fins provide higher degree of surface compactness, and substantial heat transfer is obtained due to the periodic starting and development of the laminar boundary layer over uninterrupted channels formed by fins and their dissipation in the fin wakes [22]. They provide better heat transfer performance due to a large amount of heat transfer area in a small volume [23] however, they are associated with increase in pressure drop due to increased friction and drag contribution. The fin offset is usually equal to the half fin spacing and uniformly arrayed in the flow direction. Suzuki et al. [24] found that thicker fins lead to increased pressure drop. Local  $Nu$  increases as  $t/S$  is increased where  $t/S$  is the fin thickness to hydraulic diameter ratio. They also stated that the  $Nu$  increases as offset length is decreased. Dong et al. [25] conducted experimental study and his results shows that heat transfer coefficient and pressure drop decreases as fin space, fin height and length increases. De Losier et al. [23] stated that thicker fins increases pressure drop so thinner fin are preferred. Lastly, it was learnt that as fin length increases, pressure drop decreases.

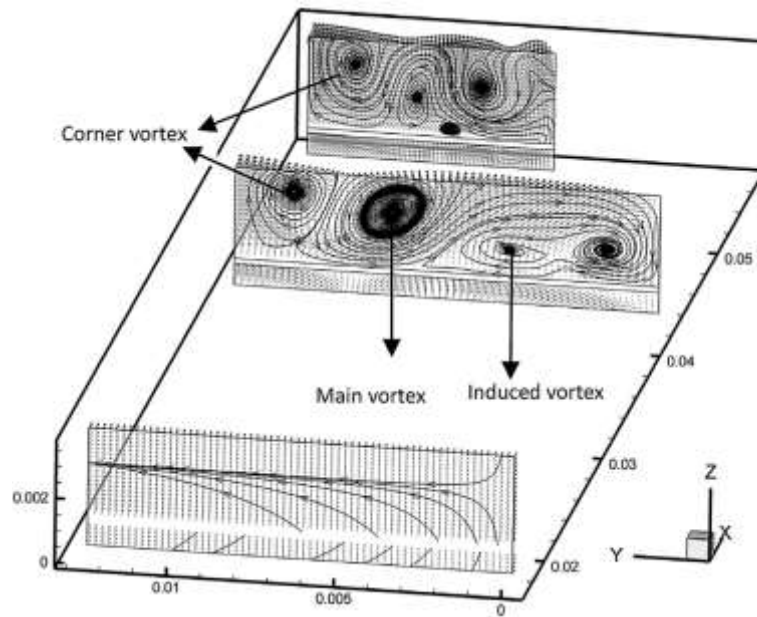
To summarise in terms of thermal-hydraulic performance, wavy fins are understood to have higher heat transfer coefficients compared to plain fins however, the penalty of the friction factor is even higher for wavy fins. Guo et al. [26] and Sanaye et al. [27] stated that since their staggered surfaces interrupt the flow and temperature boundary layers along the flow orientation, offset strip fins have higher heat transfer performance than plain fins. Ranganayakulu et al.'s [28] numerical investigation showed that thermal-hydraulic performance of offset fins were higher than wavy fins.

## 4. Effects of vortex generators (VGs) on thermal-hydraulic performance

VGs are said to be very effective in improving thermal-hydraulic performance. It mainly involves in bulk flow mixing, boundary layer development, swirl formation and flow destabilisation.

### 4.1. Working principle of VGs

The effects of using VGs have been documented for many years whereby majority of the research works shows that thermal-hydraulic performances were improved. In early research works such as Fiebig et al. [29], the effects of VGs on flow structure, flow losses and heat transfer were studied experimentally. They concluded that VGs can generate stable vortices whereby additional drag due to VGs are independent of  $Re$ . According to Ya-Ling et al. [30] when fluid flows, vortices are generated due to friction and separation on the edge of the vortex generator. This was verified numerically by He et al. [30] where Figure 5 illustrates the vector plots and streamlines generated by VGs. It can be seen that there are 3 types of vortices generated namely corner vortex, main vortex and induced vortex. They concluded that the main vortex is formed due to the flow separation and friction on the leading edge of the VGs; corner vortex is formed by the deformation of the near-wall streamlines; and the induced vortex is formed by the interaction between the main vortex and the fin surface. The combined effect of these vortices will enhance heat transfer.

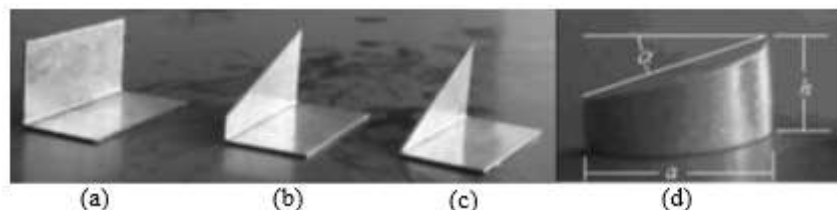


**Figure 5.** Vector plots and streamlines generated by VGs [30].

Besides, Fiebig et al. [31] conducted similar studies with wing type VGs for both inline and staggered tube arrays whereby there was 55-65% increase in heat transfer with 20-45% increase in friction factor for inline arrays and much lower heat transfer for staggered arrays but even lower friction factor which implies VGs with staggered tubes is more economical. Biswas et al. [32] numerically studied the flow structure with and without VGs and concluded that vortices generated by VGs in the wake region has increased the heat transfer by 240%. To further understand interactions of VGs with the boundary layer, Gentry et al. [33] conducted an experiment which resulted in an effective way of thinning the boundary layer which is by introducing vortices towards the edge of the boundary layer. This has increased the heat transfer performance to 50-60%. Wang et al. [34] conducted an experiment with the same purpose using annular and delta VGs and they concluded that fins with VGs produces more vortices compared to fins without VGs. Furthermore, Torii et al. [35] experimentally concluded that heat transfer enhancement for fin-and-tube heat exchanger with VGs are 10-30% for staggered tube arrays and 10-20% for inline tube arrays while reduction in pressure loss was 34-55% and 8-15% for staggered and inline tube arrays respectively. This is because VGs reduces form drag and wake region.

#### 4.2. Different shapes of VGs

VGs increase heat transfer by forming vortices however this is normally accompanied with flow resistance. Hence, many research works were done to improve heat transfer with lower pressure drop and one way to accomplish this is to improve the designs of VGs. For example, in 2012, Zhou et al. [36] experimented on curved type VGs as shown in Figure 6.

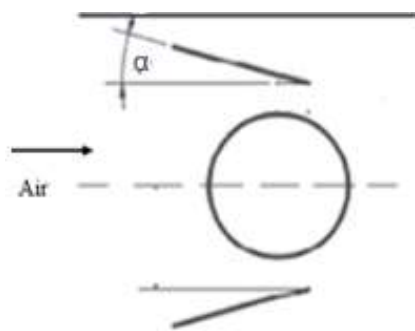


**Figure 6.** (a) Rectangular VG (b) Trapezoidal VG (c) Delta VG (d) Curved Trapezoidal VG [36].

They concluded that delta winglet VGs has the highest heat transfer for laminar flow while the curved trapezoidal VGs has the best thermal-hydraulic performance. They also claim that this is most likely because curved trapezoidal VGs produces a streamlined flow with low pressure drop. To further improve the thermal-hydraulic property, Zhou et al. [37] in the year 2014 experimented on different shapes of VGs such as plane and curved VGs with punched holes. They found out that for VGs with punched holes, the flow resistance was reduced. By increasing the diameter of the punched hole and positioning it at the centreline of the VG, it further improves hydraulic performances. In addition, they concluded that curved delta VG improves heat transfer better than any other VGs. This results is also similar to Song et al.'s [38] and Lin et al.'s [39] results whereby their curved delta VGs experienced heat transfer enhancement by 20.04% and 16.1% respectively. Du et al. [40] numerically investigated the influence of single and double; delta, and rectangular VGs on the thermal-hydraulic performances. They concluded that the delta winglet pairs produced the highest heat transfer enhancement at 13.5-61.2% and also at a reasonable increment in pressure drop at 5.62-46.2%.

#### 4.3. Attack angles of VGs

One of the ways to improve thermal-hydraulic performances is to have VGs inclined at an angle to the flow as shown in Figure 7. Theoretically, as the attack angle is increased, vortices generated should be more stable and strong. Fiebig et al. [29] concluded that as the attack angle is increased from 20° to 60°, heat transfer is enhanced.



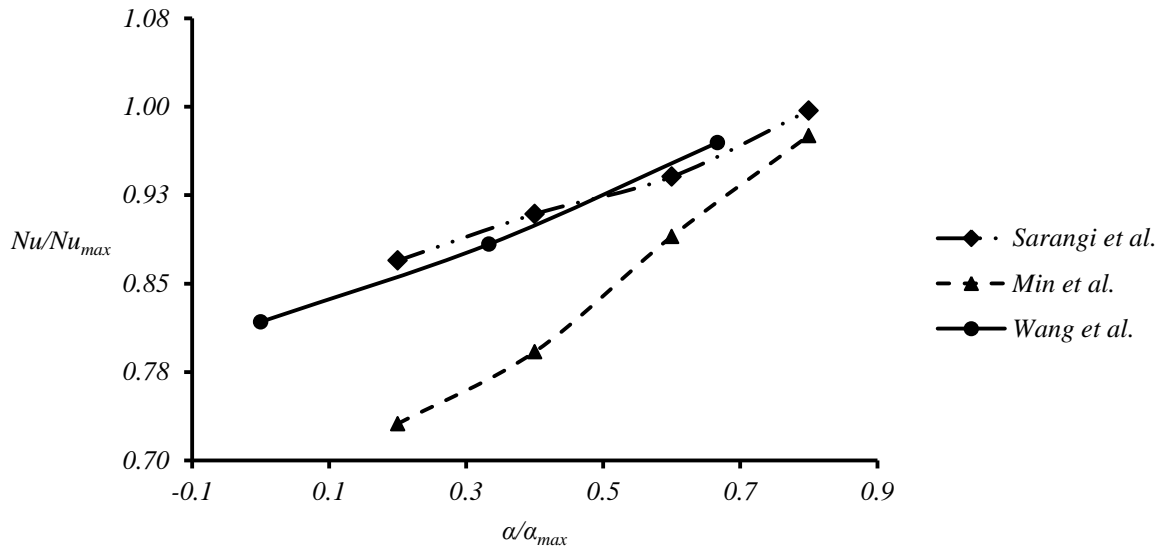
**Figure 7.** Placement of VGs at an angle to fluid flow [41].

Similarly, Chu et al. [42] discovered that increasing the attack angle from 15° to 30° would increase the strength of vortex generated hence increasing the heat transfer. However, they claimed that as the attack angle is increased further, the vortices may break down and reduce heat transfer. For the case of friction factor, it increases as attack angle is increased because the form drag increases with attack angle. This results is also in very much good agreement with He et al. [43] whereby their results showed that VGs at an angle of attack of 30° has better heat transfer enhancement compared to 10° and 20°. Du et al. [40] obtained a similar trend of increasing heat transfer and as well as increasing pressure drop from 10° to 25°.

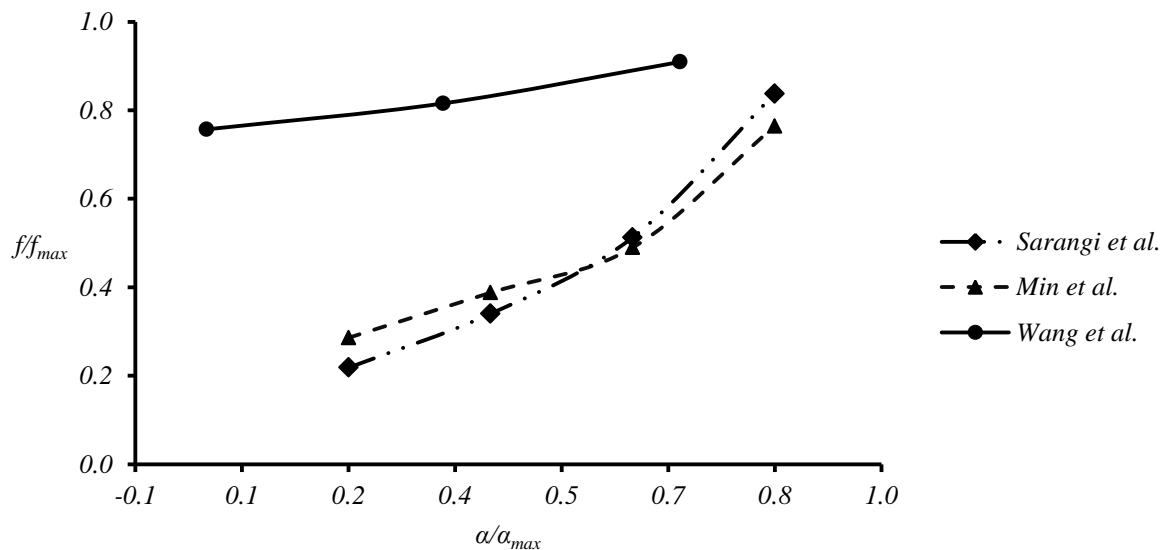
Besides, Appa et al. [44] investigated the effects of attack angle numerically whereby they concluded that VGs at 45° and 30° enhances heat transfer by 38-55.68% and 18.68-46.38% respectively. They claimed that this was most likely due to reduction in wake region and as well as acceleration of fluid due to the nozzle-like region near the rear part of the tube as in Figure 7 created with the presence of VGs. On the other hand, pressure drop for VGs at 30° and 45° increased by 9.26-56.35% and 81.57-190.30% respectively. Due to very high pressure drop increment for 45°, it was concluded that VGs at an attack angle of 30° is more suitable. In a recent numerical investigation conducted by Sarangi et al. [41], their flow visualization shows that as the attack angle is increased from 5° to 20°, the wake region reduces and the flow velocity increases which is similar to Appa et al.'s findings. Besides, they observed that due to increase in flow velocity near the wall and impingement of fluid on adjacent wall, the heat transfer enhances significantly. Due to this phenomena, at VG attack angle of 20°, the heat transfer is enhanced by 60% however friction factor



was increased by 100%. Figure 8 and Figure 9 shows the variation of normalized  $Nu$  and  $f$  respectively with normalized attack angles of VGs. Both figures indicate that similar results were obtained by many other authors whereby increasing attack angles of VGs will increase both  $Nu$  and  $f$  [41, 45, 46].



**Figure 8.** Variation of normalized  $Nu$  with normalized attack angle of VGs.



**Figure 9.** Variation of normalized  $Nu$  with normalized attack angle of VGs.

#### 4.4. Location of VGs

The location of VGs is crucial as it plays an important role to enhance thermal-hydraulic performances by generating vortex and increasing fluid flow and both of these are influenced by the placement of VGs. According to Gentry et al. [33], by thinning the boundary layer, fluid flow will be channelled into the wake region. This can be done by bringing in free-stream fluid into the boundary layer. An efficient way of doing this is by placing the VGs upstream whereby the vortex generated will force the free-stream fluid into the boundary layer. Similarly He et al. [43] claimed that vortices generated at upstream can affect a larger downstream domain. This was in good agreement with Allison et al.'s [47] results whereby they placed VGs upstream which lead to a heat transfer and pressure drop increment of 87% and 53% respectively.

Besides, Pesteei et al. [48] experimented on different locations of VGs with respect to tube dimensions. They concluded that placing VGs slightly to the rear of the tube would enhance heat transfer by forming a nozzle-like structure so that fluid is accelerated to the wake region. Specifically, placing VGs at  $x = 0.5D$  and  $y = 0.5D$  ( $D =$  diameter of tube) will increase heat transfer and pressure drop by 46% and 18% respectively. In addition, Sinha et al. [49], suggested that placing the VGs downstream forms a narrower nozzle-like structure which might further increase the fluid velocity flowing into the wake region. Similarly, Jang et al. [50] numerically tested different locations and concluded that placing VGs further away from the tube for inline tube arrays increased heat transfer and pressure drop by 14.71-30.74% and 12.54-22.19% respectively whereas for staggered tube arrays heat transfer and pressure drop increased by 9.28-13.96% and 7.4-12.53% respectively.

In general, vortex generators functions mainly by producing vortices that enhances heat transfer. The produced vortices normally swirls into the wake region as well. Hence, improved thermal-hydraulic performance. It was understood that curved shaped VGs improved thermal-hydraulic performance very well but considering manufacturability, straight delta shaped VGs were better. Besides, increasing the attack angle to a certain value improved the performance as the vortex intensity increased and wake region reduced. In addition, some researchers concluded that placing VGs slightly to the rear end of the tube creates a nozzle-like structure that accelerates fluid into the wake region. An upstream placement should be considered as well because it helps in reducing the boundary layer thickness thus bringing the free stream fluid into the wake regions.

## 5. Challenges and future advancements

Further developments for fin-and-tube heat exchanger is necessary as it is a common device used in today's industry. Most of the experimental and numerical investigations has some deviations between them thus it is important to focus on reducing this gap. In addition, certain experiments were considered to be tedious so a very small range of parameters were covered. This shows that proper experimentation methods and apparatus should be devised by considering user friendliness and accuracy. The combined usage of suitable tube parameters, best fin designs and optimum configuration of VGs is an innovative idea to improve the thermal-hydraulic performance of the heat exchanger. Main challenge is to increase heat transfer capabilities with low pressure drop but there were a few combinations and configurations with good heat transfer and low pressure so there is still possibility for more improvements.

## 6. Conclusions

Parameters mentioned in this paper influences the performance of fin-and-tube heat exchangers by distorting the fluid flow normally by producing swirls or vortices. Besides, it was understood that for most adjustments made to the parameters to increase heat transfer, there were substantial amount of pressure drop increment as well but certain designs provided high heat transfer with low pressure drop.

In terms of tube parameters, the best tube arrangement is the staggered tube arrays. Basically, multiple tubes either inline or staggered forms a close gap between the adjacent fins creating a nozzle-like structure that accelerates fluid thus increasing both heat transfer and pressure drop. This nozzle-like effect was found to be more significant for staggered tube arrays. Besides, wider tubes like elliptical and flat tubes are said to produce small wake region thus pressure drop was low. In addition, increasing the tube inclination angle intensified the formation of vortex swirls that increased heat transfer.

Research works on variety of fins showed that it improves heat transfer by increasing the exposed area to allow more heat transfer and as well as distorting the flow to produce swirls and causing bulk fluid mixing. It was clear that standard wavy and rectangular fins provided better heat transfer but increased pressure drop as well. Offset strip fins were found to distort the temperature boundary layer effectively thus producing much better heat transfer and a much lower pressure drop.

Finally, vortex generators produces vortex that enhances heat transfer because of better fluid mixing. Considering ease of production, delta winglet VGs are said to be the best shape and increasing its attack angle improved the performance because vortex intensity increased and wake region is reduced. Besides, placing VGs carefully to produce the nozzle-like effect accelerates fluid into the

wake region and helps in reducing the boundary layer thickness to bring in the free stream fluid into the wake area which increased heat transfer and reduced pressure drop.

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