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A REVIEW STUDY ON VORTEX GENERATORS

B.Sc. Engineering (Mechanical) THESIS

BY

NAFISA TASNIM, M. RASEED ANJUM

Department of Mechanical and Production Engineering

Islamic University of Technology (IUT), OIC

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BY

NAFISA TASNIM (160011053),
M RASEED ANJUM (160011040)

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Signature of the Supervisor

Rahman 15/03/21

Prof. Dr. Md. Hamidur Rahman
Professor
Department of Mechanical & Production Engineering (MPE)
Islamic University of Technology (IUT), OIC

Candidate's Declaration

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Signature of the Candidates'

Nafisa Tasnim

NAFISA TASNIM

Student No: 160011053

M. Rasheed Anjum

M. RASHEED ANJUM

Student No: 160011040

Department of Mechanical & Production Engineering (MPE)
Islamic University of Technology (IUT), OIC
Board Bazar, Gazipur
Dhaka, Bangladesh.

Signature of the Supervisor

Rahman 18/03/21

Prof. Dr. Md. Hamidur Rahman
Professor
Department of Mechanical & Production Engineering (MPE)
Islamic University of Technology (IUT), OIC

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C_f	Skin friction coefficient
Nu	Nusselt number
Re	Reynolds number
f	Friction Factor
β	Angle of attack
H	Fin Thickness
Dh	Hydraulic Diameter

Abstract

This paper presents a review on the heat transfer increase and reduction in pressure drop for compact heat exchangers (CHXs) by using protrusion of surfaces in the form of surfaces in the form of vortex generators (VGs). The effect of the shape, angle of attack and various other types of VGs are discussed. The purpose of this study is to collect various information on the features of CHXs that are presented by experimental and numerical studies for improving the design of heat exchangers. The effects of different shapes of VGs, their configuration, location and angles of attack on the heat transfer augmentation and drop of pressure decrease of heat exchangers have been examined. Longitudinal vortex generators that are induced by VGs have proved to cause a reduction in the weaker heat transfer region behind tubes and promote better mixing and turbulence intensity. Nevertheless, the strength and intensity of vortices still depend on Reynolds number.

Keywords

Heat transfer augmentation, Vortex Generators (VGs), Compact heat exchangers (CHXs)

Chapter 1 **Introduction**

The heat exchanger is a instrument that allows heat to be switched between fluids. The separator that splits the two fluids is called a heat transfer surface and can vary with various types of heat exchangers. The general organization of heat exchangers is absorbed on their types of structure, flow preparations, surface compactness, heat transfer method, pass arrangement, fluid stage and heat transfer mechanism. HXs have a higher rank and are found everywhere, e.g. in thermal power plants, air conditioning systems, motorized radiators, space vehicles and refrigerators.

Thermodynamic efficiency of HXs is a major concern of designers and researchers. Several methods have been developed over the last decades to increase the thermal effectiveness of heat exchangers by reducing the rate of entropy and the amount of exercise (destruction of determined available work). These methods are referred to as active techniques, passive techniques, and compound techniques.

Active procedures include the use of electrical control to surge the rate of heat transfer in heat exchangers. For instance, cumulative the mixing flow rate by revolving the surface or by grinding, vibrating the heat transfer surface to restart the boundary layer and creating secondary flow, spread on electrical and magnetic fields to provide persuaded convection, thereby enhancing the bulk fraternization of hot and cold material, and injecting.

Swirl flow systems hold advanced importance in the heat transfer field [1]. Devices such as vortex generators (VGs) play an significant role in improving heat transfer efficiency and reducing pressure drop [2], [3]. Vortex generators are described as the protrusion from the heat transfer surface responsible for generating a swirling flow around the axis which leads to the generation of vortices.

They are commonly categorized based on their form, shape and geometry. VGs are often referred to as disturbed surfaces accountable for the induction of main convective heat transfer mechanisms in portable heat exchangers [4], [5]as follows.

- Induce secondary flow or eddy flow with the aid of disturbed surfaces.
- Mixing the flow sideways the wall by creation the surfaces rough by mixing the planes.
- Mixing the flow around the wall by making surfaces rough or mixing the dominant flow with passive techniques.
- Developing boundary_coating reducing the width of the boundary layer by adding fins and VGs.
- Augmenting turbulence strength by assimilating rough surfaces.

Interrupted surfaces such as vortex generators (VGs) can play a fundamental and significant role in obtaining thermal transfer mechanisms above, with the aid of heat transfer enhancement of the passive swirl flow technique [6]. VG-induced vortices are divided into two groups, such as transverse vortices and longitudinal vortices [4].

The transverse vortices have their axes normal to the direction of flow and are aligned with the 2D flow, while the longitudinal vortices axis is in the direction of flow and is implicit in the 3D flow. Vortex generators (VGs) contribute to better heat transfer efficiency by reducing the thickness of the boundary layer by upsetting and weakening it and thereby intensifying the turbulent flow.

Variation of various parameters, such as longitudinal tube pitch, transverse tube pitch, fin pitch, etc., plays a major role in the efficiency of finned tube heat exchangers [7]–[10]. Detailed parametric experiments for various flow ranges were critically investigated by the authors for flat and wavy finned tube heat exchangers [11], [12], [13].

The orientation, form, type, pattern and geometry of vortex generators also plays a key role in improving the heat transfer rate of heat exchangers. In [14], a numerical investigation was conducted to test the effect of five separate winglet type vortex generators (CFU, CFD, CFU-CFU, CFD-CFD, CFU-CFD) on the Reynold scale from 250 to 1580.

Fiebig et al.[15] carried out a computational analysis to identify the impact of longitudinal vortex generators on heat transfer and lack of flow in parallel plate heat exchangers. He discovered that longitudinal vortices caused by fins in the form of longitudinal vortex generators have a substantial effect on the enhancement of heat transfer.

Wu et al. [16]examined the effect of the longitudinal vortex generator parameters on the laminar convection heat transfer in the channel by means of a numerical investigation. They concluded that once the LVG's are mounted away from the inlet and also reduce the gap between the LVG's pair, there will be a decrease in the Nusselt number at the price of no drop in pressure.

Fiebig et al. [17] examined the effect of built-in wing and winglet type vortex generators in internal movement on heat transfer and pressure drop. Its central outcome was that the

Reynold number of LVGs yields restored heat transfer competence than the TVGs at the cost of the similar pressure loss.

As LVGs and their peers are vulnerable to found boundary layers without delay, causing swirl flow and, eventually, destabilizing and offensive the flow, turbulence upsurges, making them more influential than TVGs. He also observed that vortices would top to a reduction of the critical number of Reynolds increased by a factor of 10 or more and that wings and winglets provide the identical increase in heat transfer at a minor rate.

In recent centuries, several investigators [18]–[24] have operated with the aid of vortex generators (VGs) to upsurge heat transfer competence by using special kind of inserts [25], [26], using numerous types of nano-fluids [27], modifying the form of heat exchangers, etc.[28]–[30]

The key determination of the present investigation is therefore to clarify novel methods of swelling heat transfer and plummeting pressure losses. The effect of vortices produced by disrupted surfaces, such as vortex generators, on the enhancement of heat transfer rates in heat exchangers is widely studied after careful and in-depth analysis by numerous researchers and professors in experimental and numerical discipline.

The effect of the form, shape, geometry, direction, and position etc of the VGs is also evaluated and the outcomes are represented in graphs depicting the relationship between the j-factor and the Reynold number, the heat transfer coefficient (h) vs Reynold number (Re) and the Nusselt number (Nu) vs Reynold number (Re) and the relationship between about other crucial factors in terms of the heat transfer and friction factor (f).

The main purpose of the analysis is to consider the new development of ingenious ways to enhance temperature transmission efficiency in heat exchangers. This thorough analysis would be extremely useful for designers to develop compact heat exchangers with an smooth reduced volume density area, small thermal resistance on both airborne and fluid sides, efficient with advanced heat transfer, less pressed.

Generally, this study will recapitulate the recent growths in enhancing heat transfer and pressure drop efficiency by the use of vortex producer (VGs) seeing three forms of readings. Such as the simulation of the flow arena done dye inoculation, the numerical showing of the heat exchanger and the experimental work performed by the investigators to cover the effect of the heat exchanger. Effect of winglet patterns with dissimilar transverse rows, effect of heat transfer and pressure drop for dissimilar tube shapes, Influence of angle of attack and elevation belongings of block type VGs on heat transfer, influence of winglet type VGs on heat transfer growth, effect of VGs height on heat transfer growth and pressure drop etc.[31]

Chapter 2 **Literature Review**

2.1 Experimental studies

Zhang et al.[20] obtained from naphthalene sublimation heat/mass correspondence experiments in selecting the best geometrical parameters of tube bank fin heat exchanger with fins mounted with vortex generators are compared with the results obtained from the condensing experiments of the real heat exchangers with vortex generators punched out on the fins. The results declare that VGs pouched or mounted on fin surfaces have only limited effects on heat transfer performance in the studied configurations; the naphthalene sublimation method can be used to select fin patterns with reasonable reliability. The findings of naphthalene sublimation heat/mass analog experiments in the selection of ideal geometric parameters of tube bank fin heat exchanger with vortex-mounted fins are contrasted with the findings of the condensation experiments of the real vortex generator heat exchangers. The findings note that the VGs fixed or mounted on fin surfaces have negligible effects on heat transfer efficiency in the configurations studied; the naphthalene sublimation method can be used to select fin patterns with satisfactory precision. As a result, the analog heat/mass transfer test by naphthalene sublimation is easy to perform on a large scale and on a substantial number of screen tests in the establishment of a new fin model of tube bank fin heat exchanger. The VG punched is not easy to model when comparing the heat/mass sublimation of naphthalene. In these cases, VG is a practical solution. In this situation, sir. Unless the surface-to-surface VG ratio is very high, the stunted and mounted VGs are almost equal in therapeutic transfer and pressurization. The analog heat/mass transfer test with naphthalene sublimation is easy to perform on a large scale and on many screen tests in the development of a new fin model of tube bank fin heat exchanger.

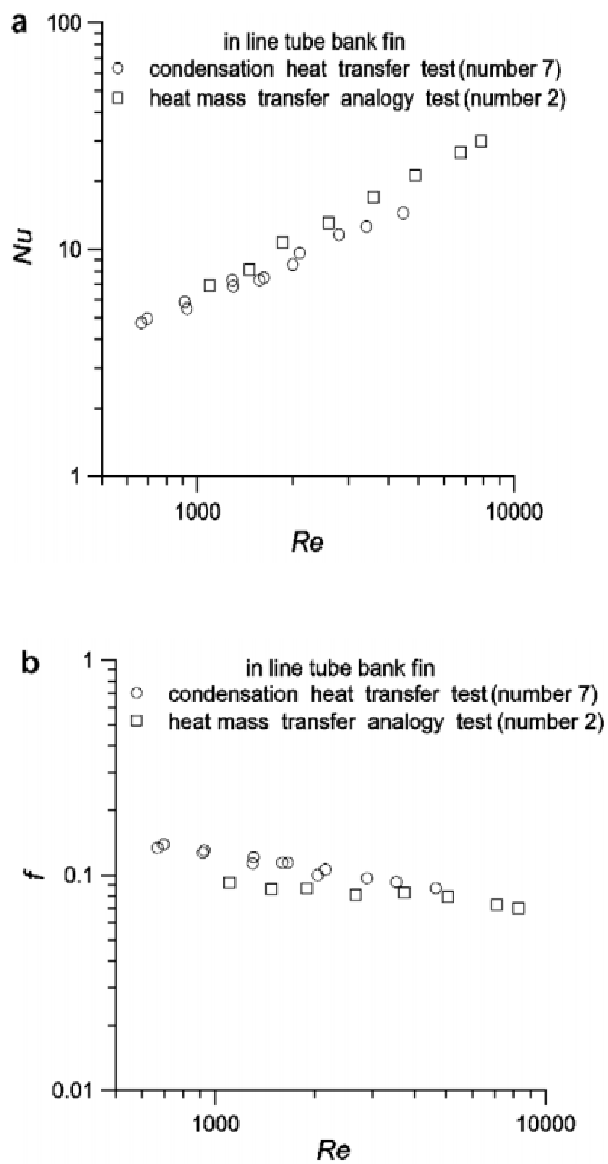


Figure 1 Comparison of heat/mass analogy test results (Number 3) with condensation test results (Number 4), (a) Nu, and (b) f. [20]

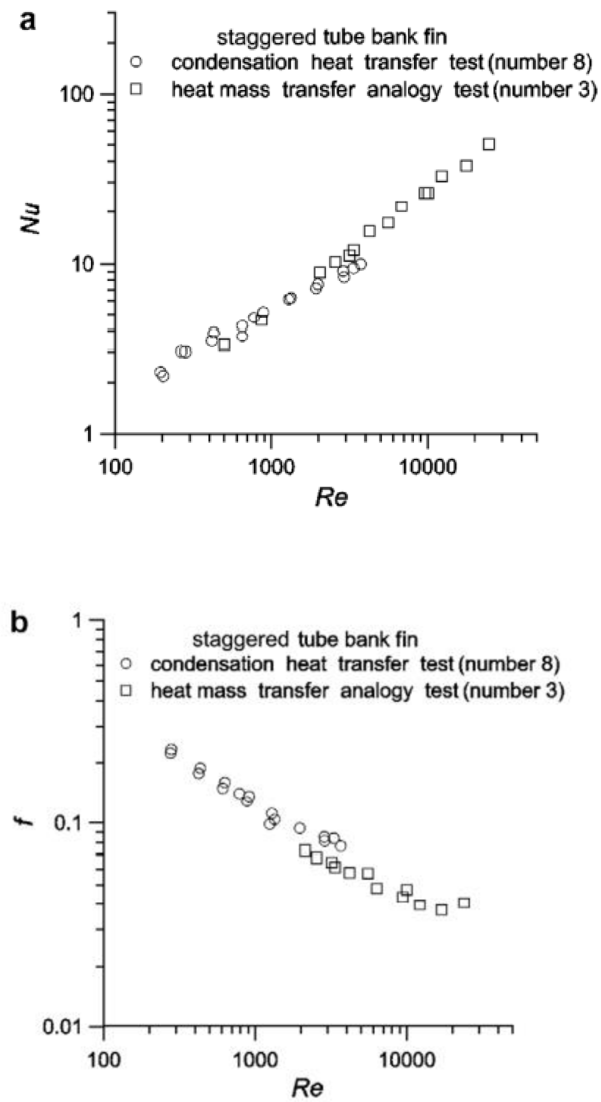


Figure 2 Comparison of heat/mass analogy test results (Number 5) with condensation test results (Number 6), (a) Nu, and (b) f. [20]

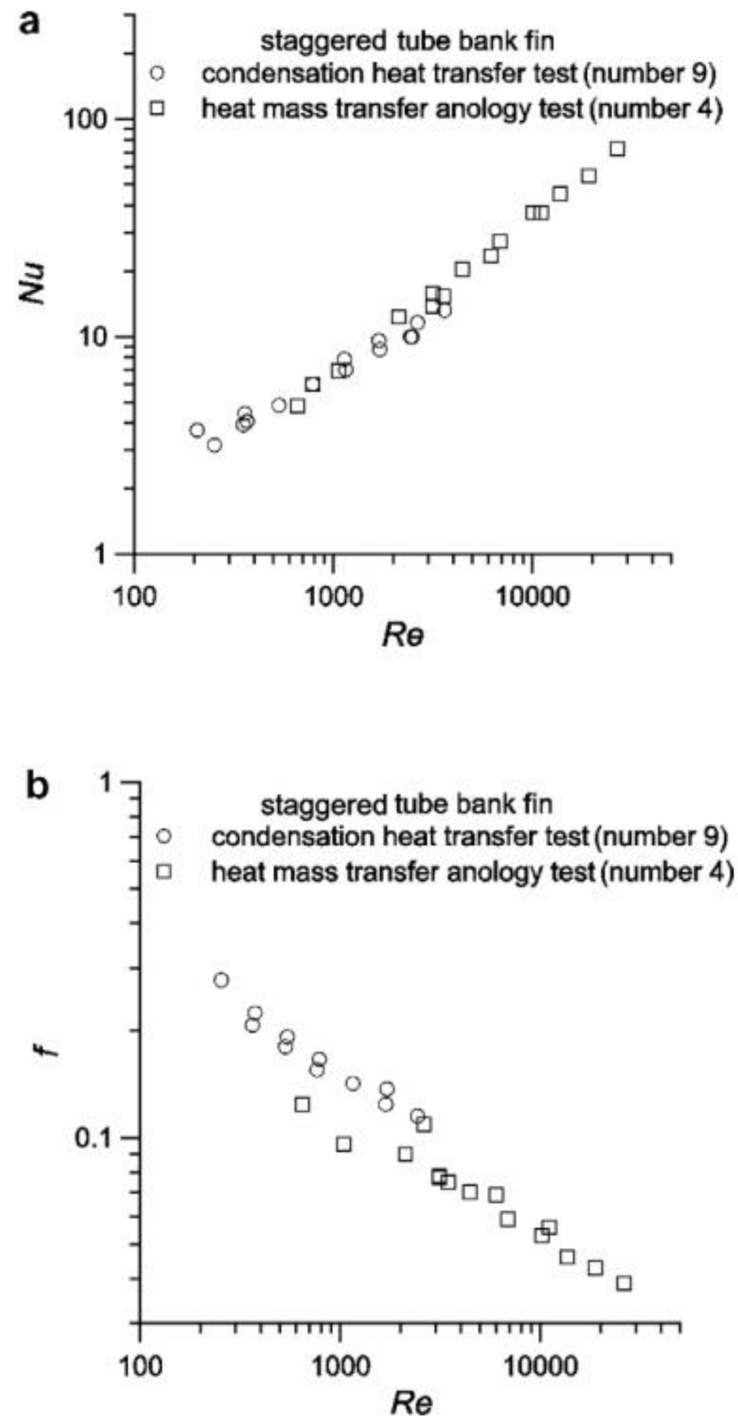


Figure 3 Comparison of heat/mass analogy test results (Number 7) with condensation test results (Number 8), (a) Nu, and (b) f [20]

Zhou et al. [32] have experimentally investigated and compared with conventional vortex generators and rectangular winglets, trapezoidal winglets, and delta winglets using dimensionless variables. The efficiency of curved trapezoidal vortex generators was tested experimentally and compared to rectangular winglets, trapezoidal winglets, and delta winglets. RWP has the best performance in terms of heat transfer rise, but it also has the highest pressure drop among the four-winglet pairs. CTWP delivers the best thermos-hydraulic efficiency as well as a low-pressure decrease in the turbulent regime due to its streamlined configuration. On the other hand, it performs the best in the laminar and transitional flow regimes. For the CTWP, smaller attack angles (β=0° and 15°) lead to a better thermohydraulic performance factor, 'R'. The best thermohydraulic performance of 'R' is achieved at Re>18000 and β=0°. The higher the curvature (b/a) of the CTWP, the greater the thermohydraulic performance. Higher angles of inclination lead to better thermodynamic performance, considering the present conditions of the experiment.

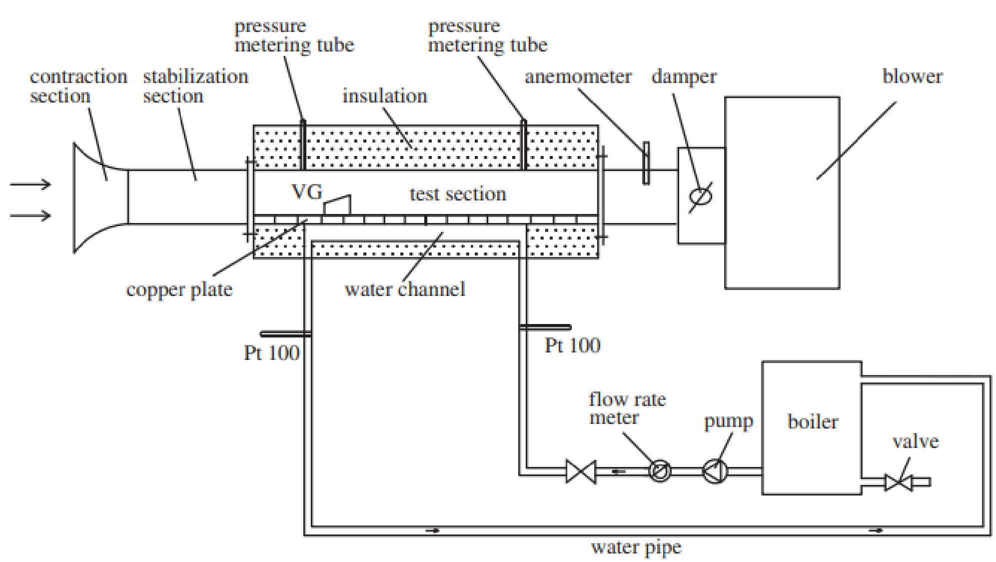


Figure 4. Schematic sketch of the experimental setup [32]

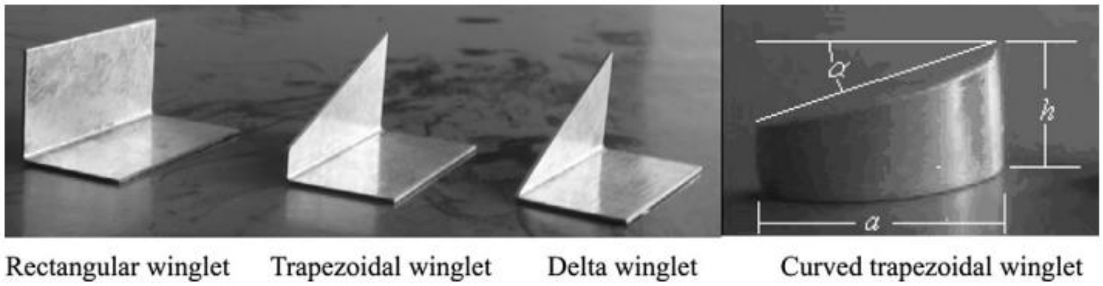
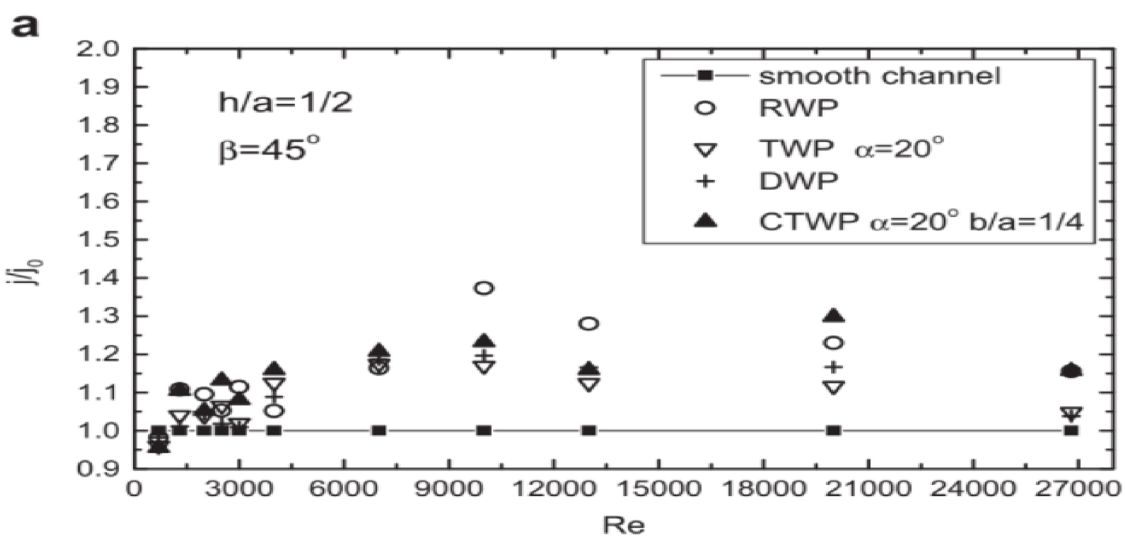


Figure 5. Pictorial diagram of vortex generators. [32]



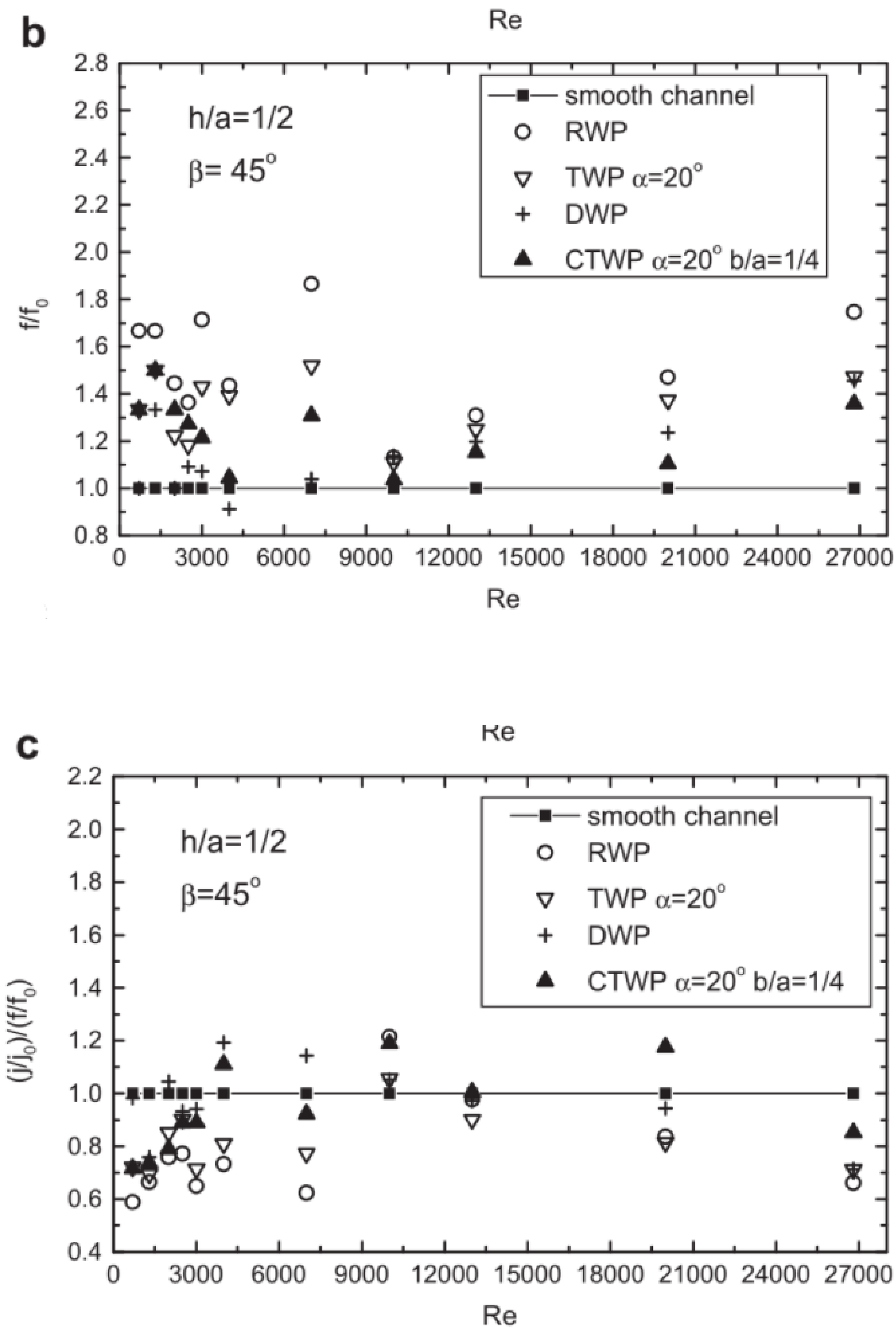


Figure 6 . Comparison of performances of the four kinds of VG pairs. (a) j/j0 vs. Re; (b) f/f0 vs. Re; (c) (j/j0)/(f/f0) vs. Re. [32]

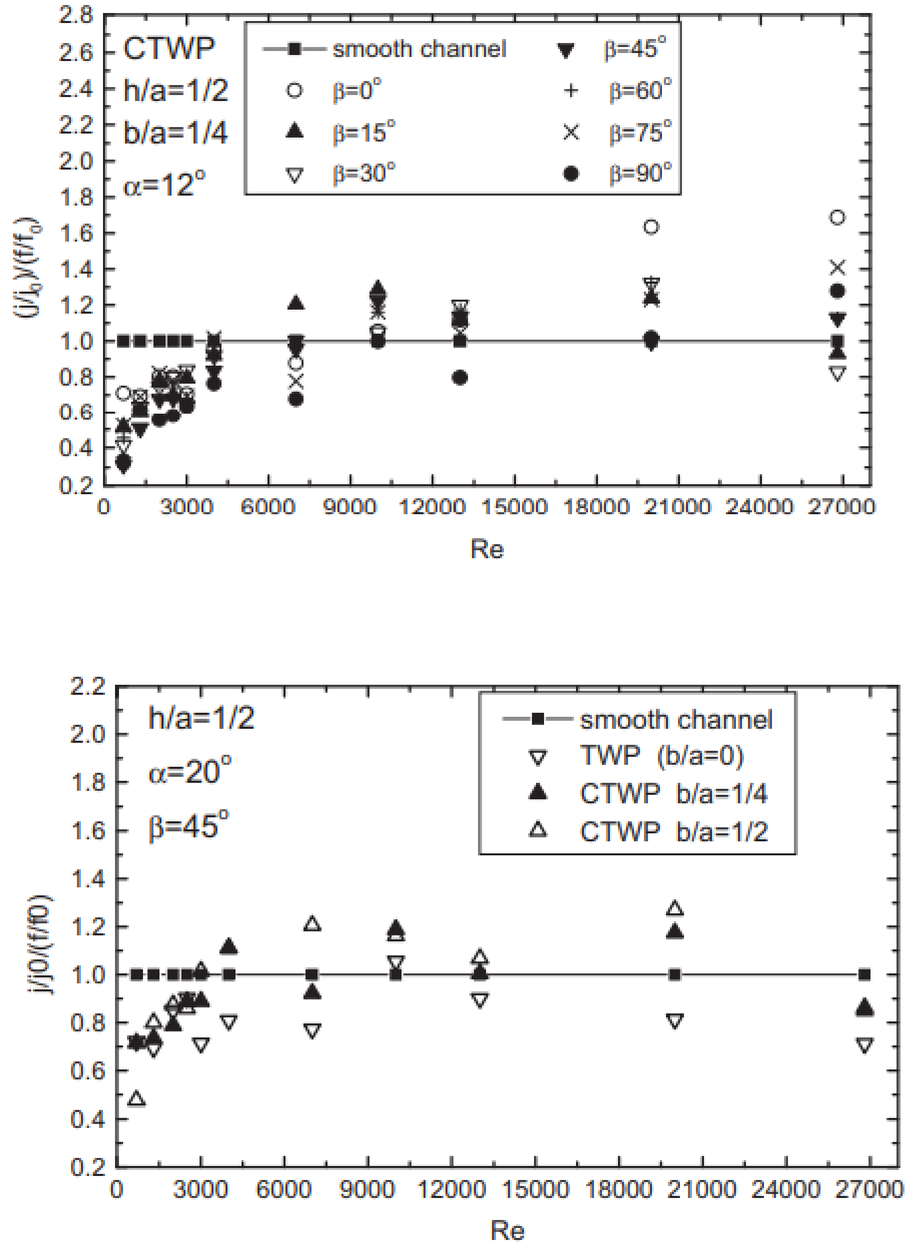


Figure 7 Effect of angle of inclination on the CTWP performance [32]

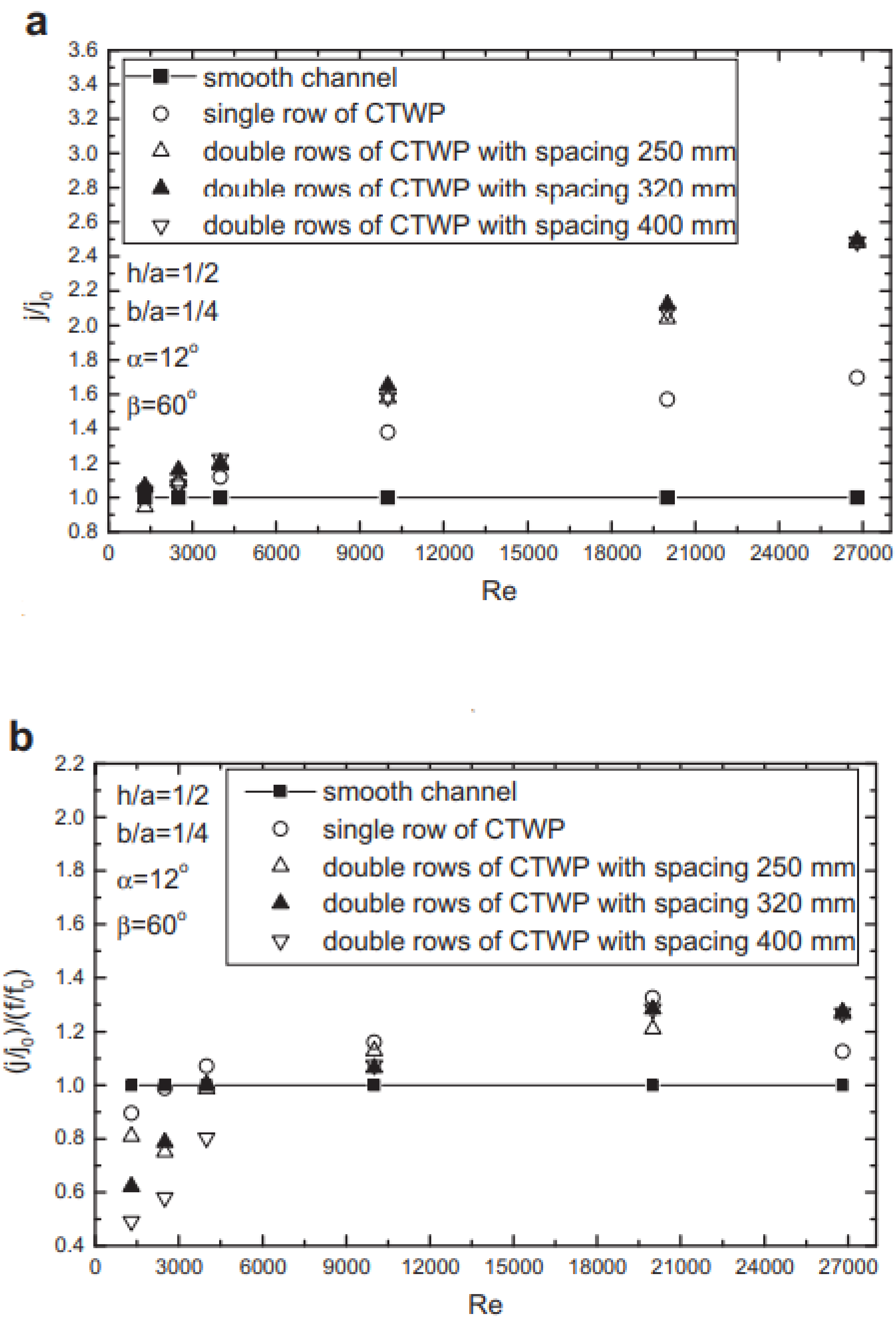


Figure 8 . Effect of spacing between two rows of CTW pairs. (a) j/j0 vs. Re; (b) (j/j0)/(f/f0) vs. Re. [32]

The efficiency of a pair of modern vortex generators and CTW has been experimentally investigated and compared to conventional vortex generators and rectangular winglets, trapezoidal winglets, and delta winglets. Some conclusions can be drawn as follows. DWP is the best in the laminar and transitional flow region, while CTWP has the best thermohydraulic performance in a fully turbulent region due to the streamlined configuration and then the low-pressure drop, which indicates the advantages of using this kind of vortex generators for heat transfer enhancement. Small attack angle of CTWP, such as b ¼ and 15, have better thermohydraulic performance of R than larger attack angles. Particularly, when Re is larger than 18,000, b ¼ presents the best thermohydraulic performance with R as high as 1.6. The larger curvature of CTWP and b/a has improved thermohydraulic efficiency under the present conditions. A larger angle of inclination provides improved thermohydraulic efficiency under present conditions due to the narrower projective region facing the airflow and the lower flow resistance. However, further studies are required for optimization. Sufficient distance between the leading edges of the CTW VG pair should be considered for different flow areas. In the present analysis, while double rows of CTWP display improved heat transfer efficiency for most Re numbers, thermohydraulic performance is even lower than the single row of CTWP due to higher pressure drops.

This research [33] aimed to develop an understanding of flow visualization and the frictional changes that occur due to expanding fin-and-tube heat exchangers with or without the influence of vortex generators.

The vortex generators used in this study were the annular winglet and the delta winglet. A plain fin geometry was also analyzed in this study.

For the plain fin geometry, at Re=500, the horseshoe vortex produced by the tube is not very noticeable and separates into two streams as it flows across the second row. At Re=1500, separation of the horseshoe vortex did not occur but there was an unsteady swing as the flow approached the third row. A detectable periodic shedding was seen from the vortex formed behind the second row and the unsteady swing of the horseshoe vortex was related to the vortex shedding.

In the presence of the annular vortex generator, a pair of longitudinal vortices was present behind the tube. The increase in the annular height raises the strength of the counter-rotating vortices. The longitudinal vortices may even swirl with the horseshoe vortices and other flow streams due to the high strength it possesses.

The delta winglet provides stronger vortical motion and flows unsteadiness, for the same winglet height, compared to the annular winglet. This results in a better flow mixing and lower pressure penalty using the delta winglet, for the same Reynolds number.

The vortex generators put forward in this experiment provide a pressure drop of 10-65% greater than that of the plain fin geometry and the pressure drops from the vortex generators to the plain fin were comparatively unaffected by the change in Reynolds number.

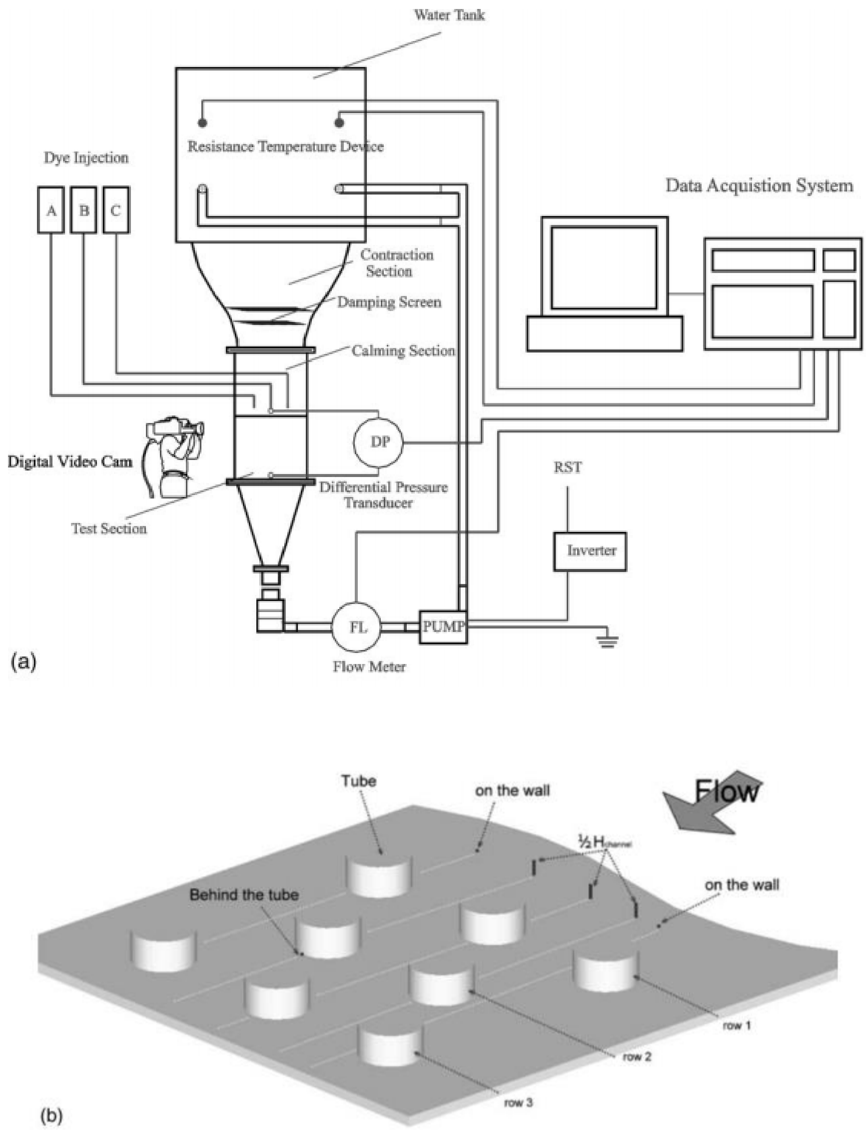


Figure 9 Schematic of (a) the test facility and (b) the arrangements of the injection port [33]

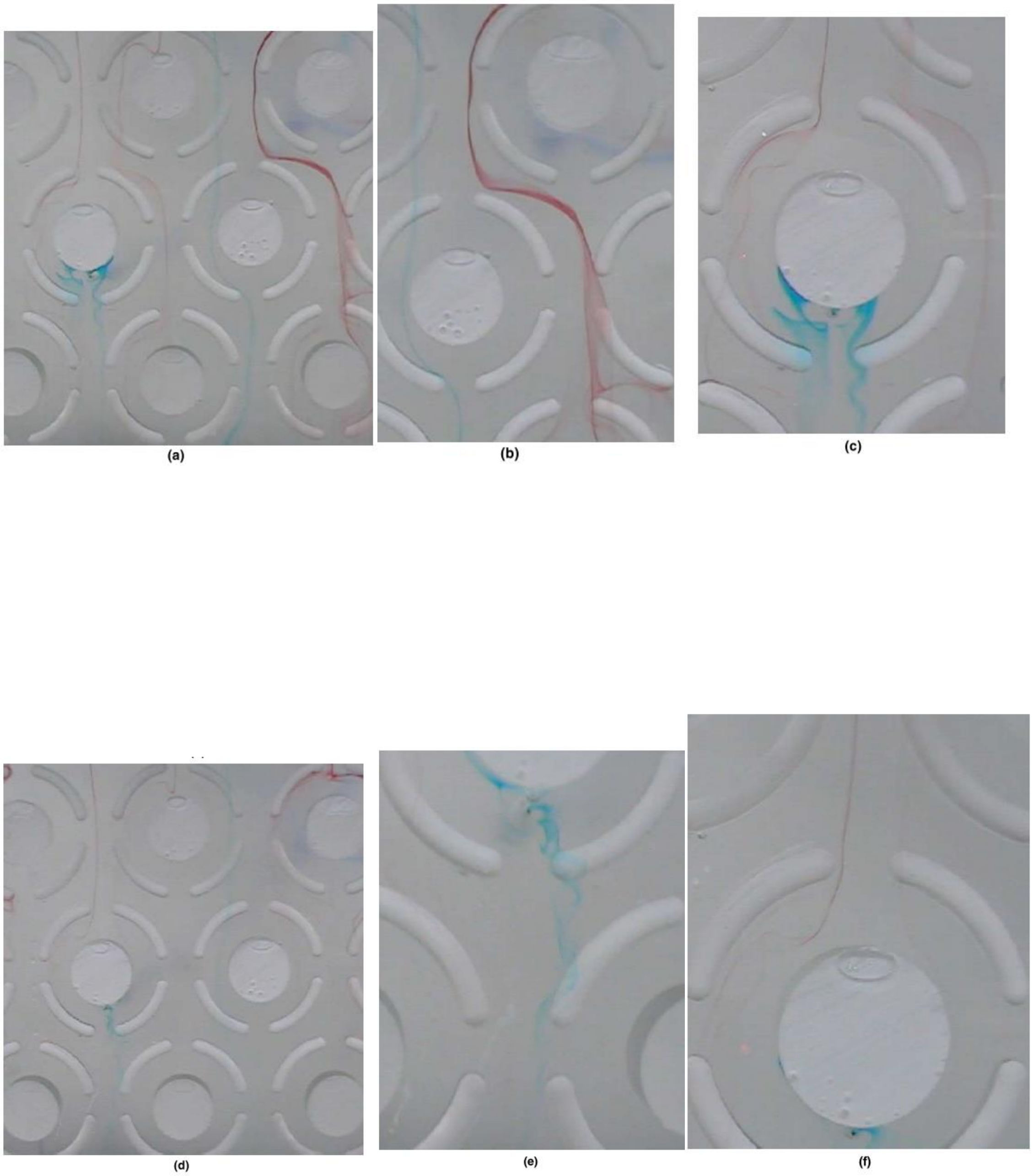


Figure 10 . Flow visualization of the STVG4 vortex generator at (a)–(c) Re = 500 and (d)–(f) Re = 1500. [33]

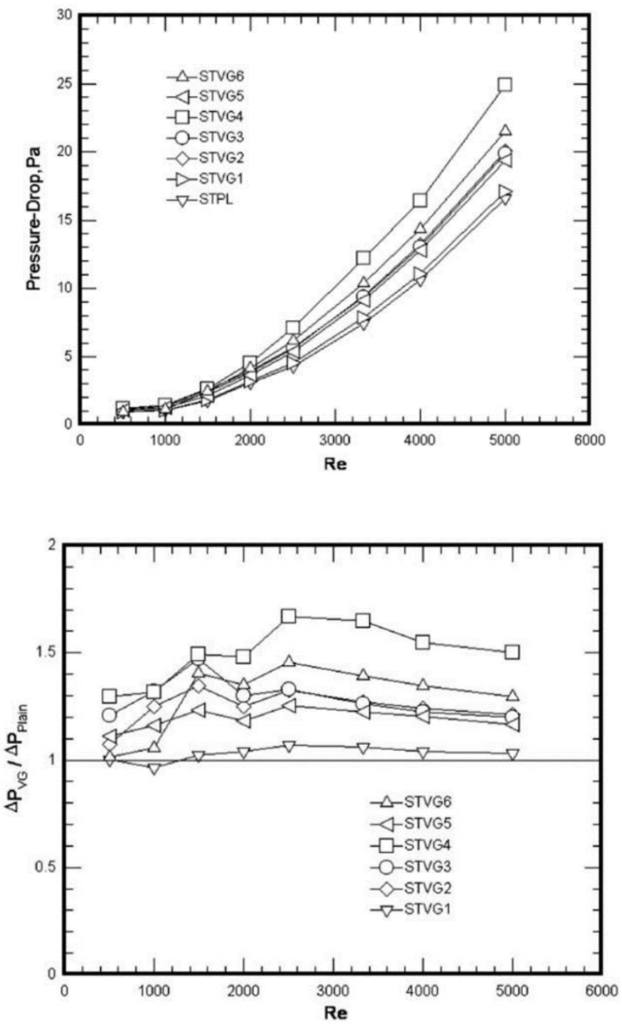
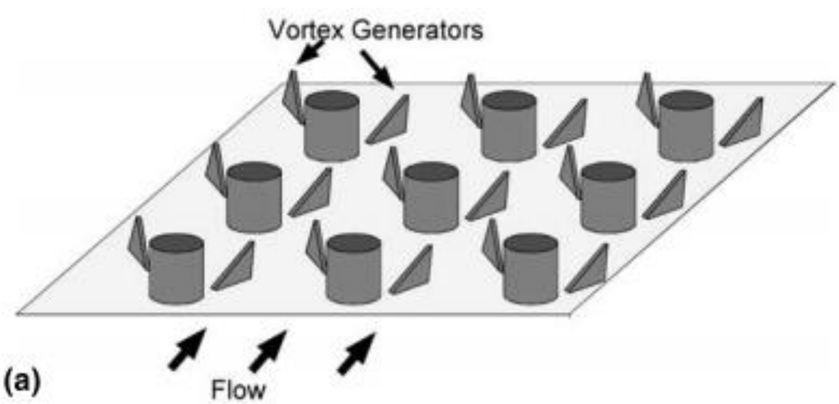


Figure 11. Frictional performance for the plain fin geometry and vortex generators. [33]

An experimental analysis was carried out by Tori et al. [34] to achieve heat transfer and pressure loss in the test section, simulated with a fin-and-tube heat exchanger, in-line or staggered tube banks of delta winglet vortex generators of different configurations. The present experiment verifies that the latest innovative technique of integrating a circular tube with a delta winglet pair of the "normal flow up" configuration enables one to amazingly close the heat transfer together with a large amount of pressure loss reduction. It's far different from the traditional heat transfer enhancement kit. The nozzle-like flow pathways provided by the delta winglet pair and the aft area of the circular tube encourage acceleration in order to cause a delay in separation and reduce the drag of the tube, and to eliminate the weak heat transfer zone from the wake.

The heat transfer and pressure drop attributes for a fin-and-tube heat exchanger was experimentally investigated. Delta winglets were used as vortex generators in a 'common-flow-up' configuration for staggered and in-line tube arrangements. For Reynolds number ranging from 350 to 2100, in the presence of delta winglet pairs for the used configuration, the staggered tube arrangement augmented the heat transfer from 30% to 10%. The pressure drop was also reduced from 55% to 34%. For the same range of Reynolds number, the in-line tube arrangement augmented the heat transfer from 20% to 10% and the pressure drop was reduced from 15% to 8%. Delta winglet pairs were able to delay the flow separation and decrease the form drag from the tube and also remove poor heat transfer zones from the wake region.



(a)

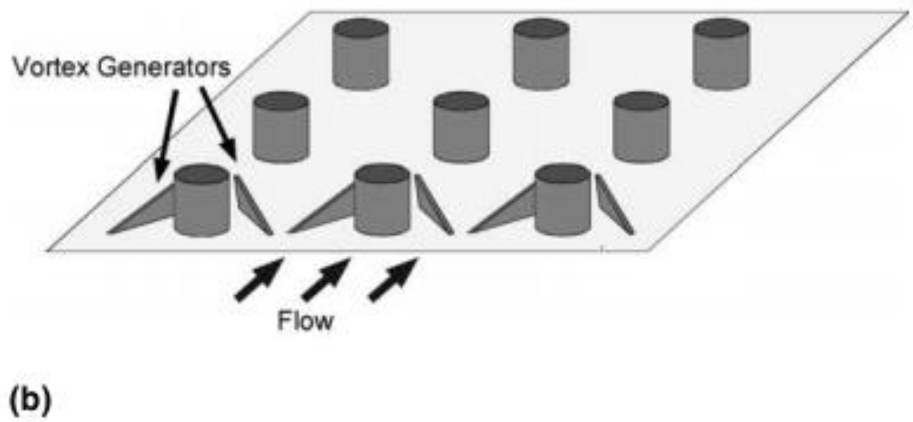


Figure 12 Configuration of winglet type vortex generator on the fin surface-tube bank: (a) ‘‘common flow down’’ configuration; (b) ‘‘common flow up’’ configuration. [34]

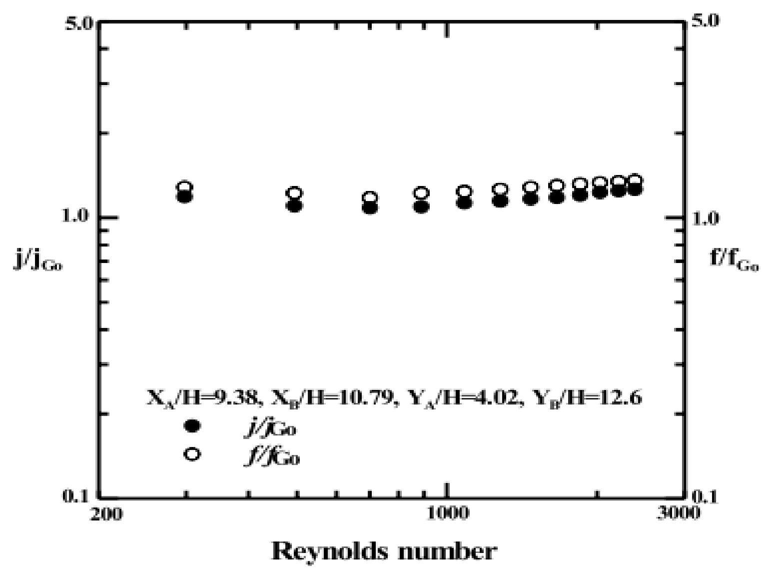


Figure 13 The comparison of j=jGo and f =fGo with respect to Reynolds number. [34]

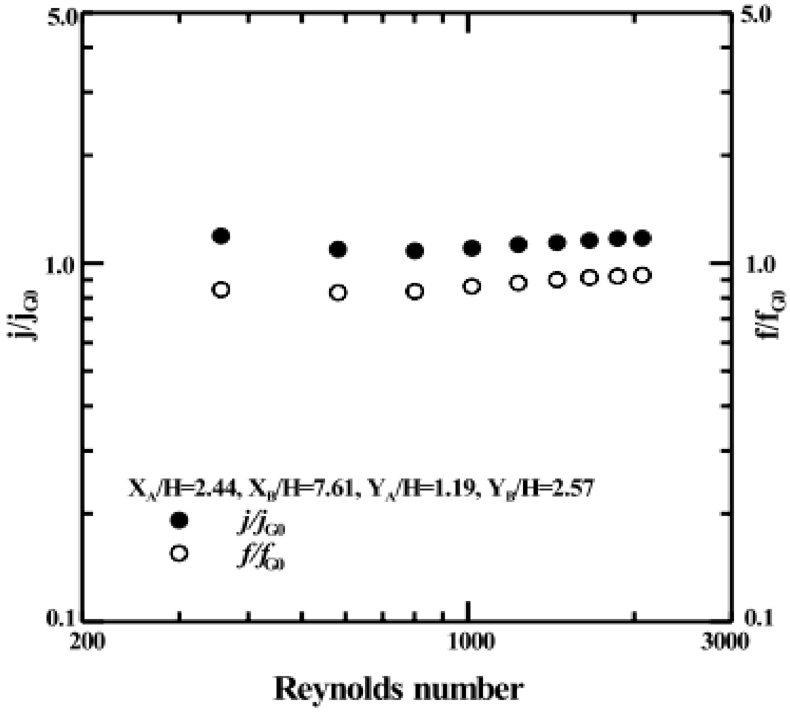


Figure 14 The comparison of j/j_{Go} and f $/f_{Go}$ with respect to Reynolds number. [34]

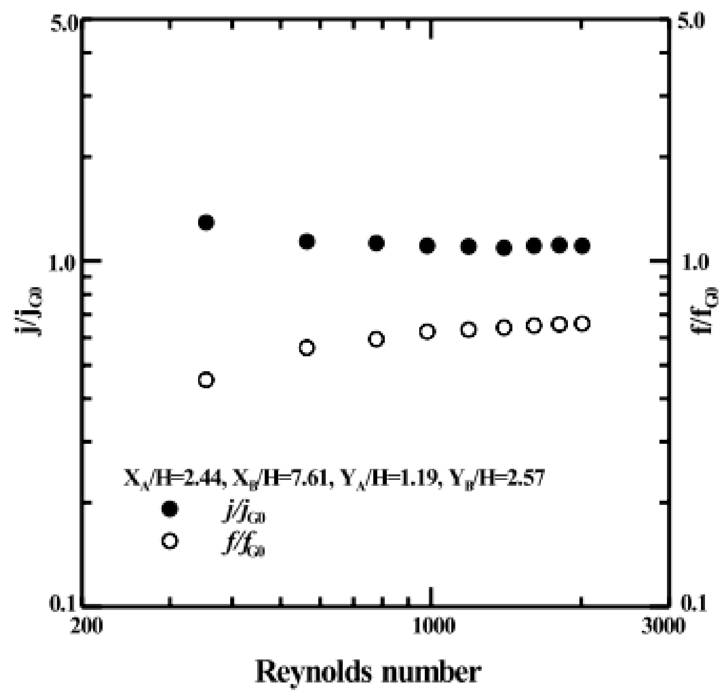


Figure 15. The comparison of j/j_{Go} and f $/f_{Go}$ with respect to Reynolds number. [34]

Tiggelback et al. [35] investigated the performance of four basic types of vortex generators in rectangular channels. Each channel contains a particular built-in vortex generator. Local heat transfer and drag for each of the four configurations of vortex generators was measured. The results were compared in the Reynolds number range of 2000 to 8000 and the angle of attack was also varied from 30 to 90 degrees. The Nusselt number is said to increase at a higher rate in a channel containing vortex generator rather than a channel without a vortex generator, with increasing Reynolds number. At a higher Reynolds number, the drag coefficient remains just about constant compared to the channel without a vortex generator where the drag coefficient decreases. Results indicate that winglets have better performance compared to wings. At angle of attack greater than 30 and Re>3000, delta winglet pairs provide more increment in the heat transfer performance than rectangular winglet pairs. Delta winglet pairs are able to augment heat transfer by 46% at Re=2000 and by 120% at Re =8000.

This experimental investigation [36] was used to evaluate the effect of wavy delta winglets on the heat transfer performance and friction factor characteristics for an absorber plate of a solar air duct.

The number of waves and the relative pitch length was among the varied parameters. The turbulent flow regime was applied in this experiment with Reynolds ranging from 4000 to 17,300.

The Nusselt number was inversely proportional to the relative longitudinal pitch. For all types of wavy winglets, the increase in the relative longitudinal pitch led to a decrease in the Nusselt number. The highest augmentation of Nusselt number is achieved for a relative longitudinal pitch of 3 and the least value is achieved for 6. The number of waves which resulted in the maximum value for Nusselt number was 5 and this behavior was seen for all the relative longitudinal pitches.

Increasing Reynolds number resulted in lower friction factor values for all the types of winglets and at all the relative longitudinal pitches. The maximum friction factor was found to be at a relative longitudinal pitch of 3 and the least value was found to be at 6.

For a relative longitudinal pitch of 3, the winglet pairs with a wave number of 5 have shown the highest augmentation in the Nusselt number enhancement factor of 3.2, over a smooth plate. The 7-wave winglet pairs gave the maximum value of friction factor of 10.9, at a relative longitudinal pitch of 3.

For Reynolds number of 4000, the 5-wave winglet pair gave the enhancement factor of 2.09 at a relative longitudinal pitch of 3.

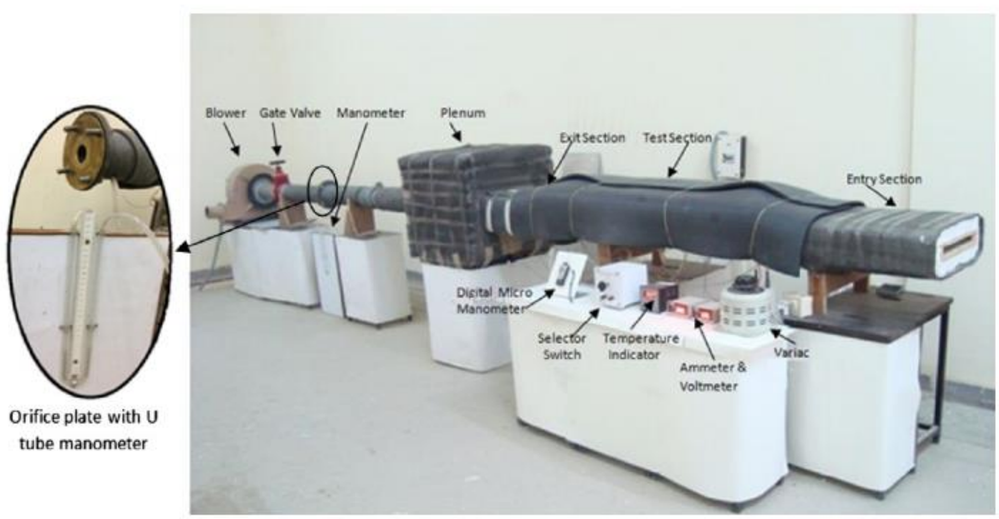


Figure 16. Photograph of experimental setup. [36]

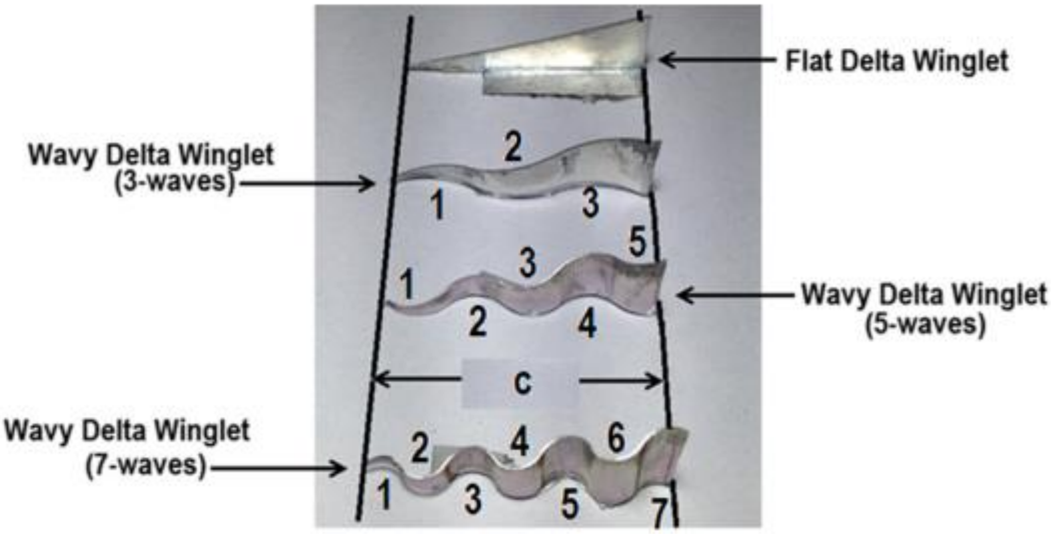


Figure 17. Photographic view of waves on wavy winglets. [36]

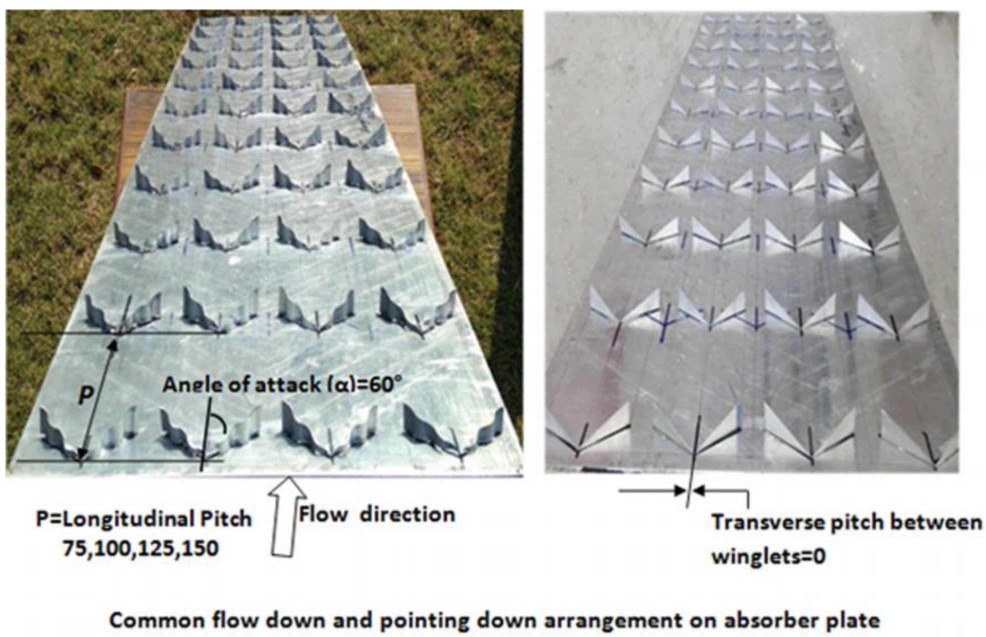


Figure 18. Photographic view of geometrical arrangement on absorber plate. [36]

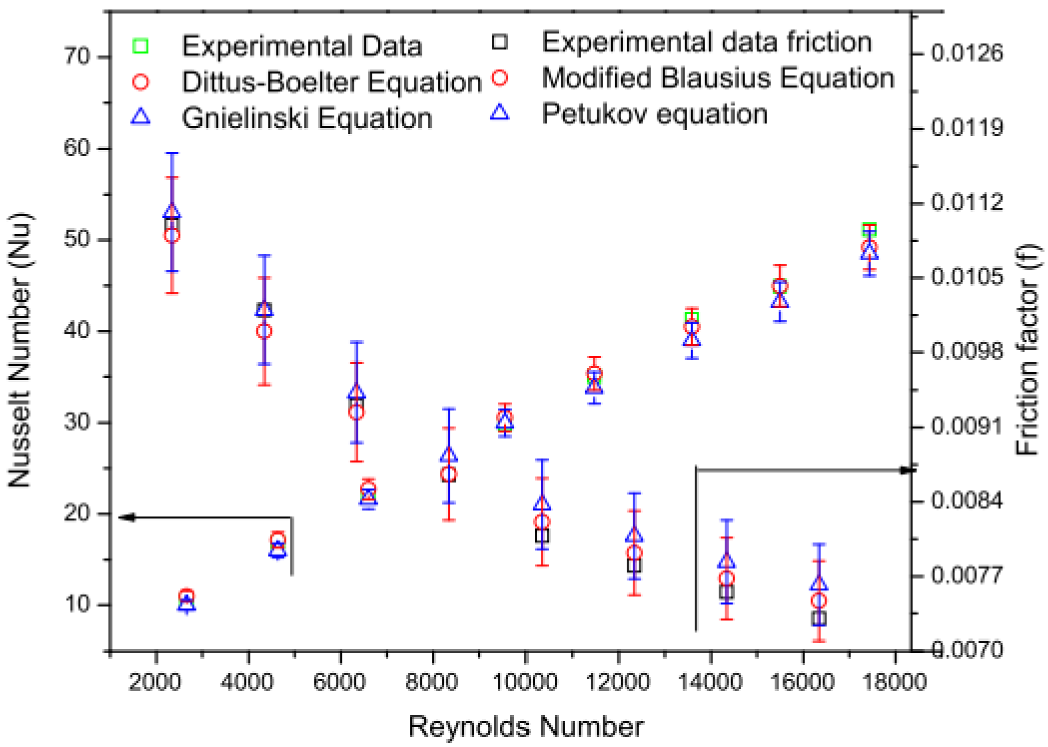


Figure 19. Comparison of experimental and predicted values of Nusselt number and Friction Factor for smooth plate. [36]

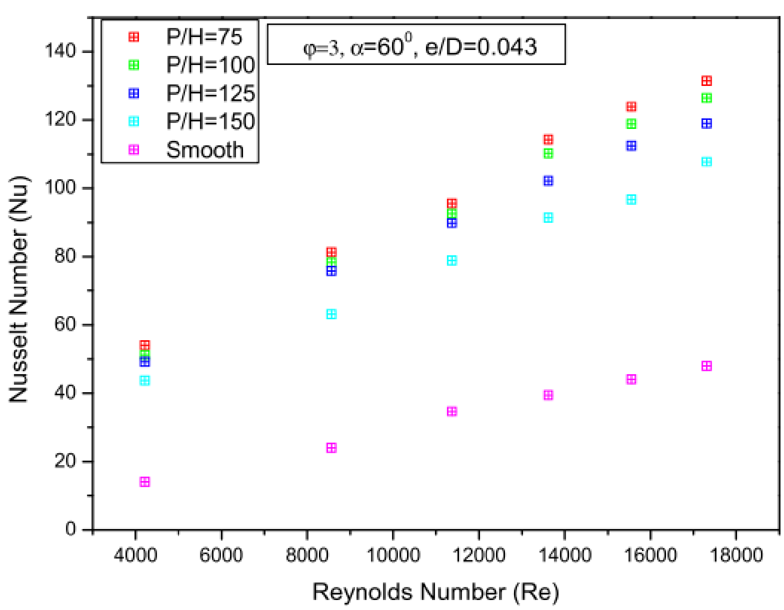


Figure 20. Nusselt Number variation for different values of P/H[36]

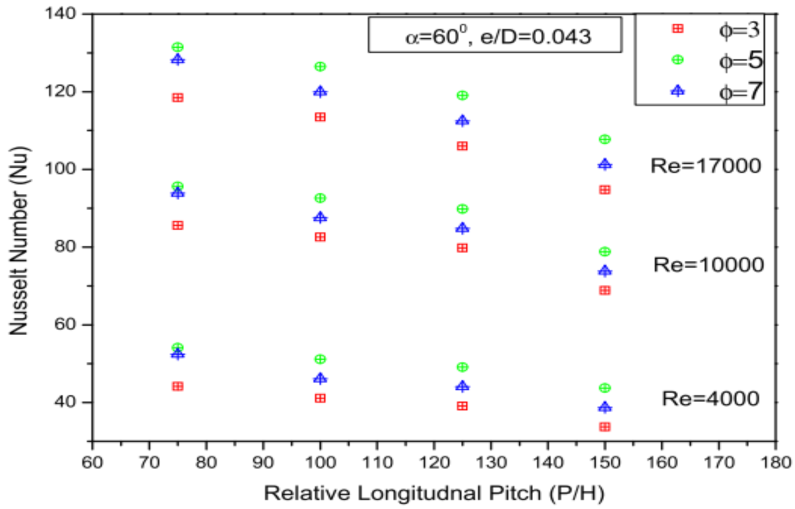


Figure 21. Influence of P/H and ϕ on Nusselt Number at different Reynolds number. [36]

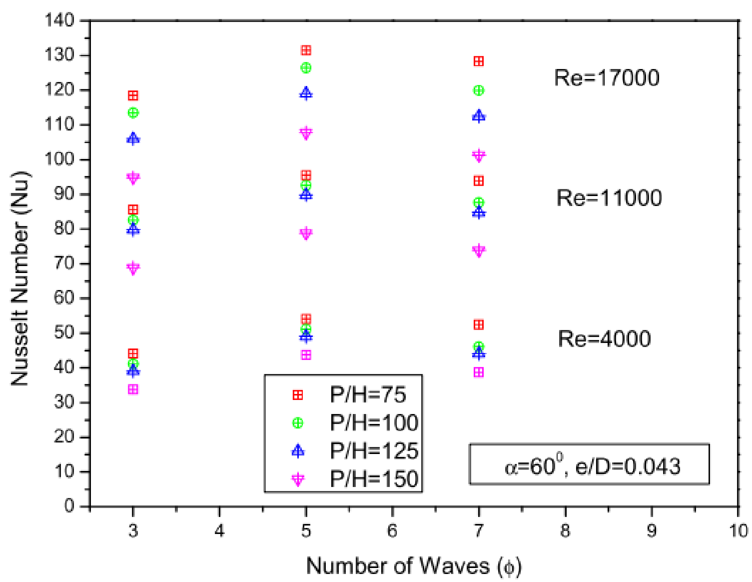


Figure 22. Nusselt Number variation for different values of P/H and ϕ. [36]

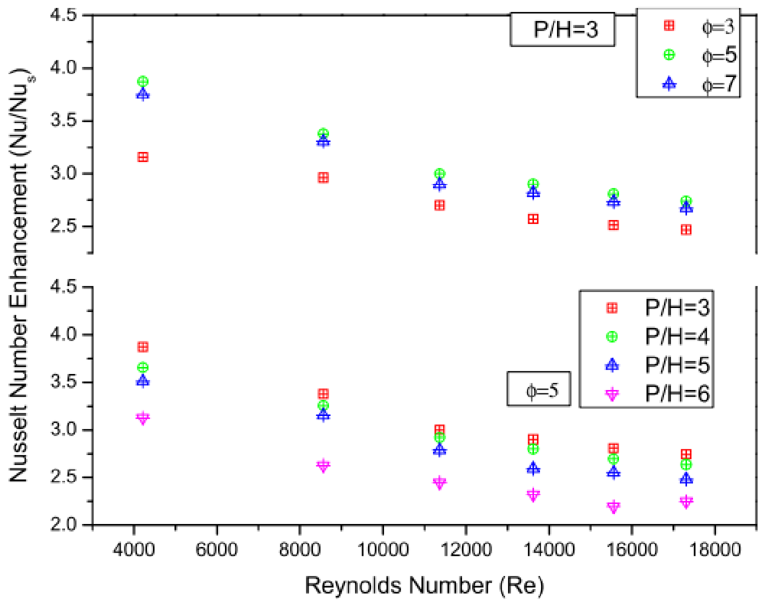


Figure 23 . Nusselt Number enhancement for different values of P/H and ϕ. [36]

Caliskan et al. [37] investigated the heat transfer and pressure drop attributes of a rectangular duct containing vortex generators were experimentally investigated.

The two types of vortex generators used in the experiment were punched triangular vortex generators (PTVGs) and punched rectangular vortex generators (PRVGs).

The heat transfer rate was augmented by a significant amount for both the PTVGs and PRVGs. But PTVGs had a higher averaged heat transfer rate than PRVGs. Punched holes led to the formation of disturbance in the boundary layer, generating higher turbulence due to separated and reattached flows.

For both the PTVGs and PRVGs, the b/e (ratio of the distance from channel to the height of the winglet) value of 0.017 provided greater heat transfer augmentation. The next values of (b/e) providing higher transfer augmentation were 0.067, 0.2 and 0.3, in that order.

The effects of the attack angles and the distance from the bottom of the channel to the punched winglet were negligible on the heat transfer augmentation and pressure drop, at low Reynolds number.

Both the PTVGs and PRVGs provided higher heat transfer coefficients compared to the smooth channel.

PTVGs provide the optimum heat transfer performance compared to PRVGs due to its highest heat transfer enhancement factor(η) of about 2.92. For lowest Reynolds number the enhancement factor(η) for PTVGs ranges from 2.92-2.67 and for the PRVGs, ranges from 2.90-2.46.

2.2 Numerical Studies

Zheng et al. numerically investigated the effect of hybrid nanofluid, water-DWCNT-TiO_2 in a tow-dimensional rectangular channel containing triangular and semi-circular vortex generators. It was seen that semi-circular vortex generators had the highest Nusselt number. The VGs with 1 mm and 3 mm heights had higher differences in Nusselt number for various Reynolds number, compared to the VGs of 2 mm height.

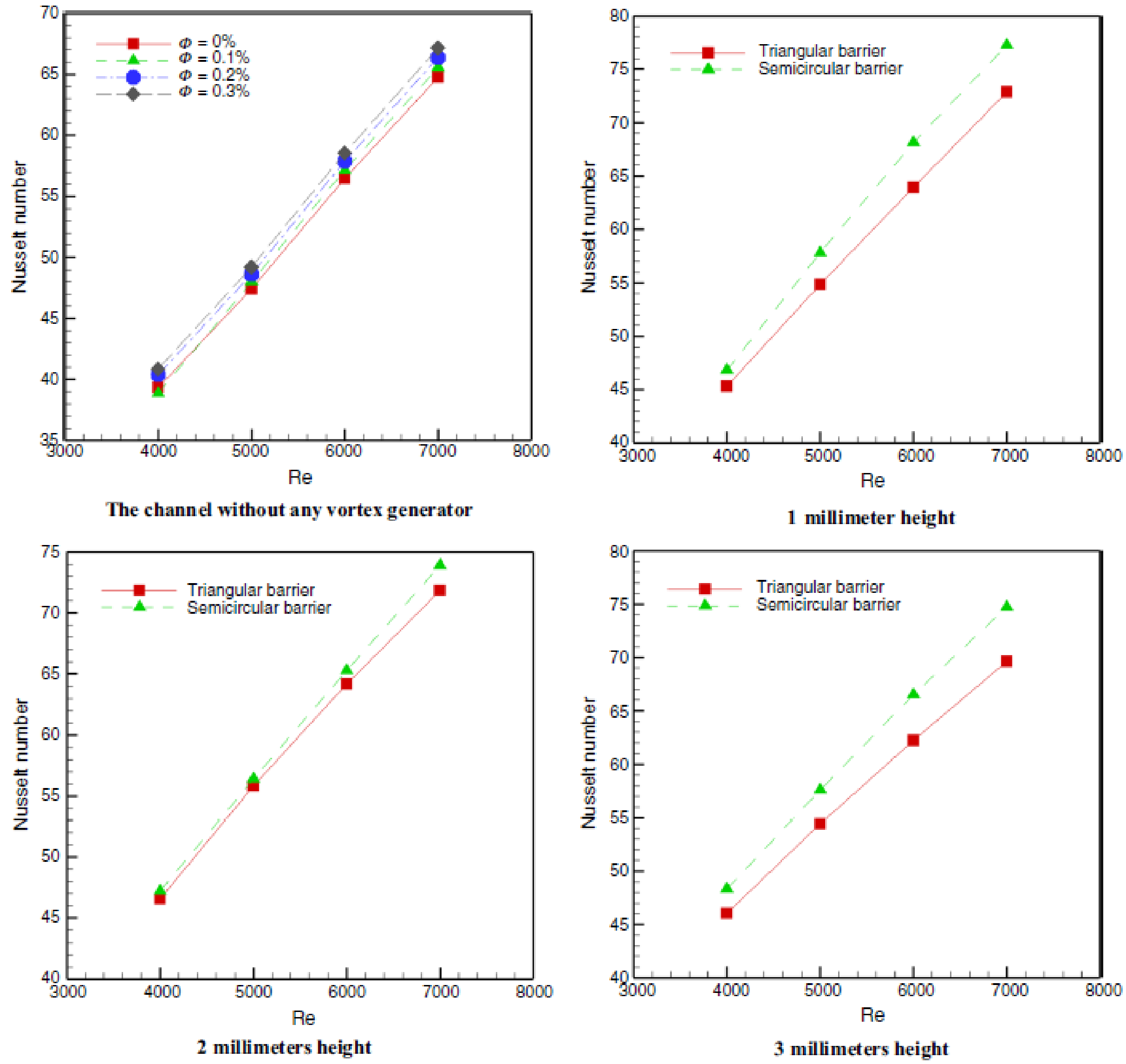


Figure 24 Variations of the Nu_{avg} with regard to Reynolds number for vortex generators with various heights in 0.3% volume fraction of nanoparticles

Lotfi et al. [38] numerically investigated the heat and pressure drop characteristics of a SWEFT(Smooth Wavy Fin-and-Elliptical Tube) heat exchanger with four new VGs (vortex generators), RTW (rectangular trapezoidal winglet), ARW (angle rectangular winglet), CARW (curved angle rectangular winglet) and WW (Wheeler wishbone). Their numerical model was validated with experimental results. Their study evaluates the performance of a

SWEFT heat exchanger with and without the presence of the new winglet VGs. Based on the hydraulic diameter, the Reynolds number ranges from 500 to 3000. As the Reynolds number increases, the Nusselt number Nu for both the baseline case(without the presence of VG) and enhanced cases, increases. However, the Nusselt number Nu of the SWEFT heat exchangers with winglet VGs is larger than that of the baseline case under different Reynolds numbers. The vortex generators were mounted in the SWEFT heat exchanger using two common configurations: common-flow up(CFU) and common-flow down(CFD). Lotfi et al. [38] used combinations of smooth wavy fin, elliptical tube and the two winglet VG pairs to enhance the heat transfer significantly, especially in the dead water zone. Fig shows the effect of the position of the RT winglet pairs on the heat transfer augmentation of the SWEFT heat exchanger. Since these winglet pairs are situated near-up and down-stream side of the elliptical tube, the horseshoe vortices and longitudinal vortices both cause heat transfer augmentation. Two winglet pairs cause higher increase in Nusselt number Nu than one winglet pair at the same Reynolds number. But in the case of circular tube

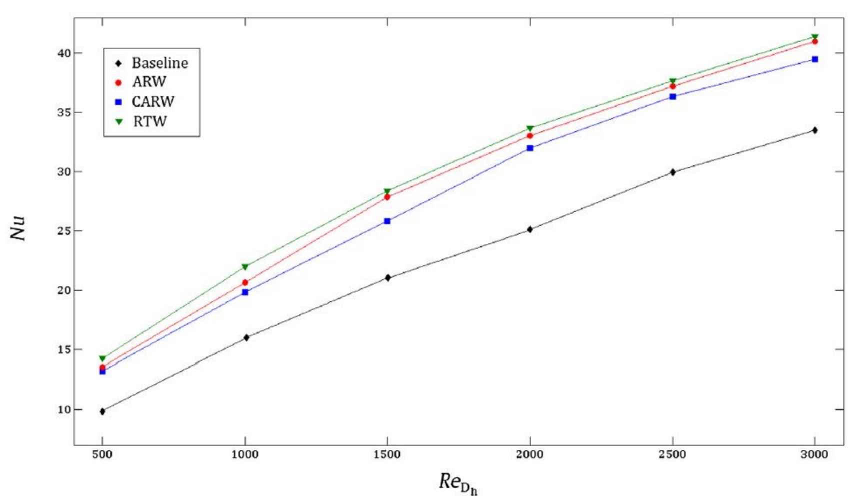


Figure 25Influence of winglet VGs on Nusselt number Nu in comparison with baseline case. [38]

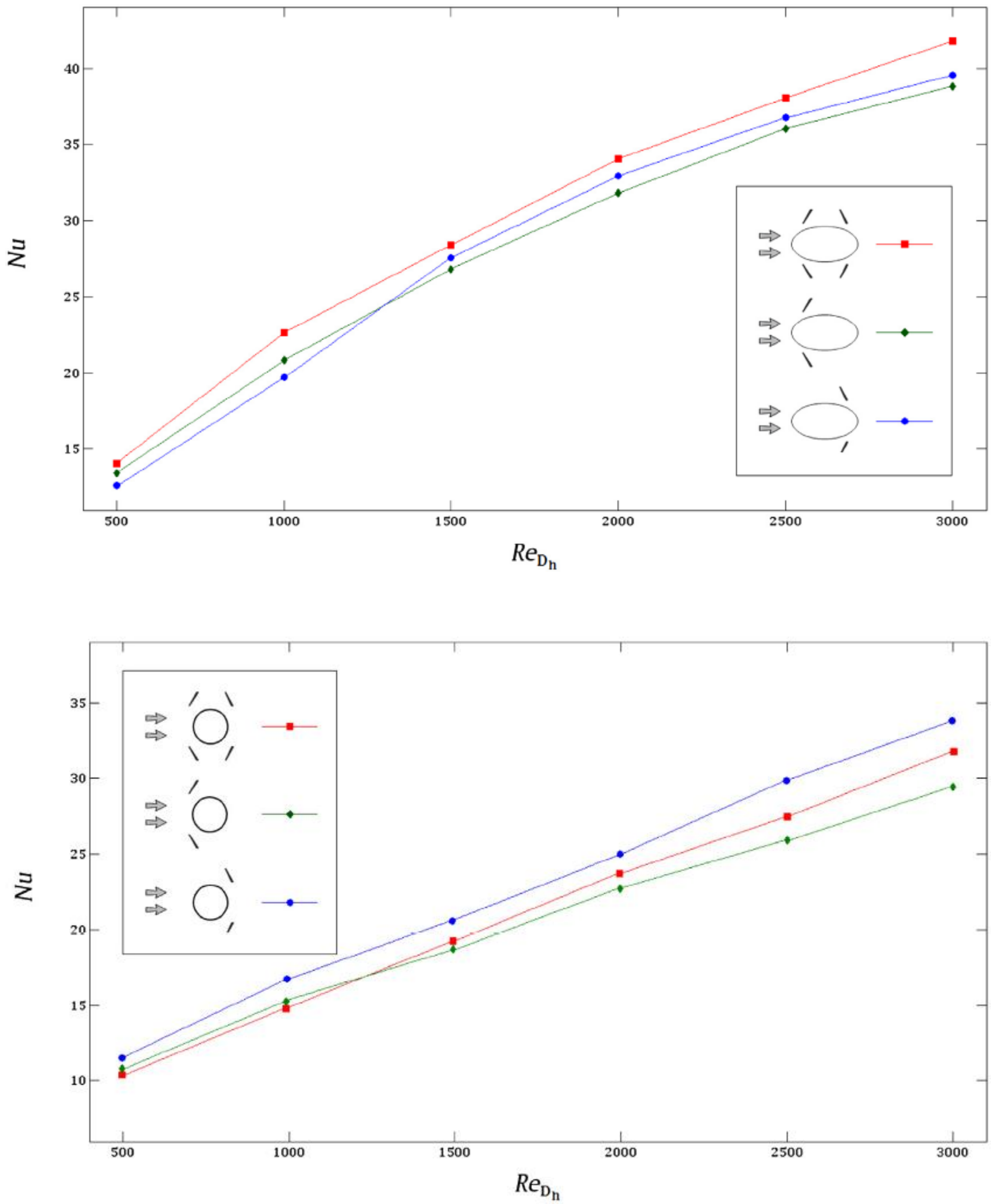


Figure 26 comparison of Nusselt number Nu between the single and two winglet VG pairs. [38]

Awais et al. [39] performed numerical simulations to investigate the effects of interrupted surfaces on compact heat exchangers. The effect of delta winglet vortex generators (DWVG) on the thermo-hydraulic performance of the heat exchanger was illustrated. The effect of varying the attack angle, tube shape and arrangements, and the configuration of the DWVGs was analyzed. There was a higher heat transfer enhancement by circular and oval tubes compared to square tubes. Staggered arrangement provides higher heat transfer enhancement compared to inline arrangement. The optimal angle of attack in their study was found to be 165°. For the arrangement of VGs, CFU configuration was found to have better performance than CFD configuration.

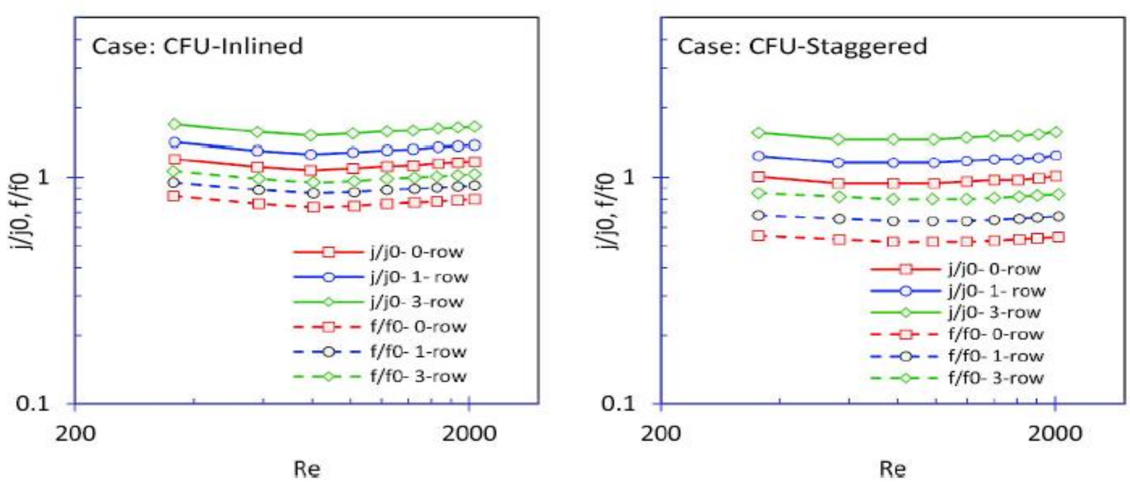


Figure 27 Comparison of different rows of winglets in in-lined and staggered tube arrangement of circular tubes having 165° attack angle with CFU condition. [39]

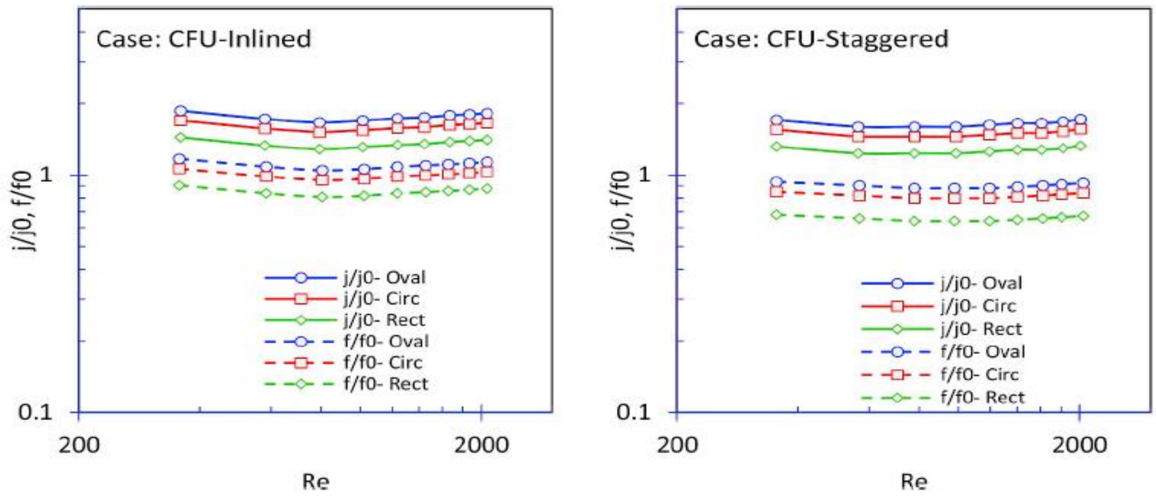


Figure 28 Comparison of tube shape in in-lined and staggered tube arrangement having three rows of winglets with 165° angle of attack for CFU condition. [39]

The effect of cylindrical vortex generators was analyzed [40] numerically in a microchannel. These vortex generators are based on cylinders with half-circle and quarter-circle cross-sections and are attached to the base of the microchannel. The influence of the VGs was evaluated in terms of the thermal resistance, pressure drop and a combination of these forming a performance evaluation criteria(PEC) index. Cylinders with quarter-circle cross-sections were only effective for lower Reynolds number and larger radius with increased pressure drop under these conditions. For the VGs containing half-circle cross-sections, the thermal resistance decreased monotonically with the VG radius. Due to a constriction in the flow, the pressure drop increased with increasing Reynolds number. According to the PEC index, small-radius centered VGs offer better performance in terms of improving the efficiency of the microchannels especially at lower Reynolds number. At a radius of 30µm, the PEC was found to be maximum.

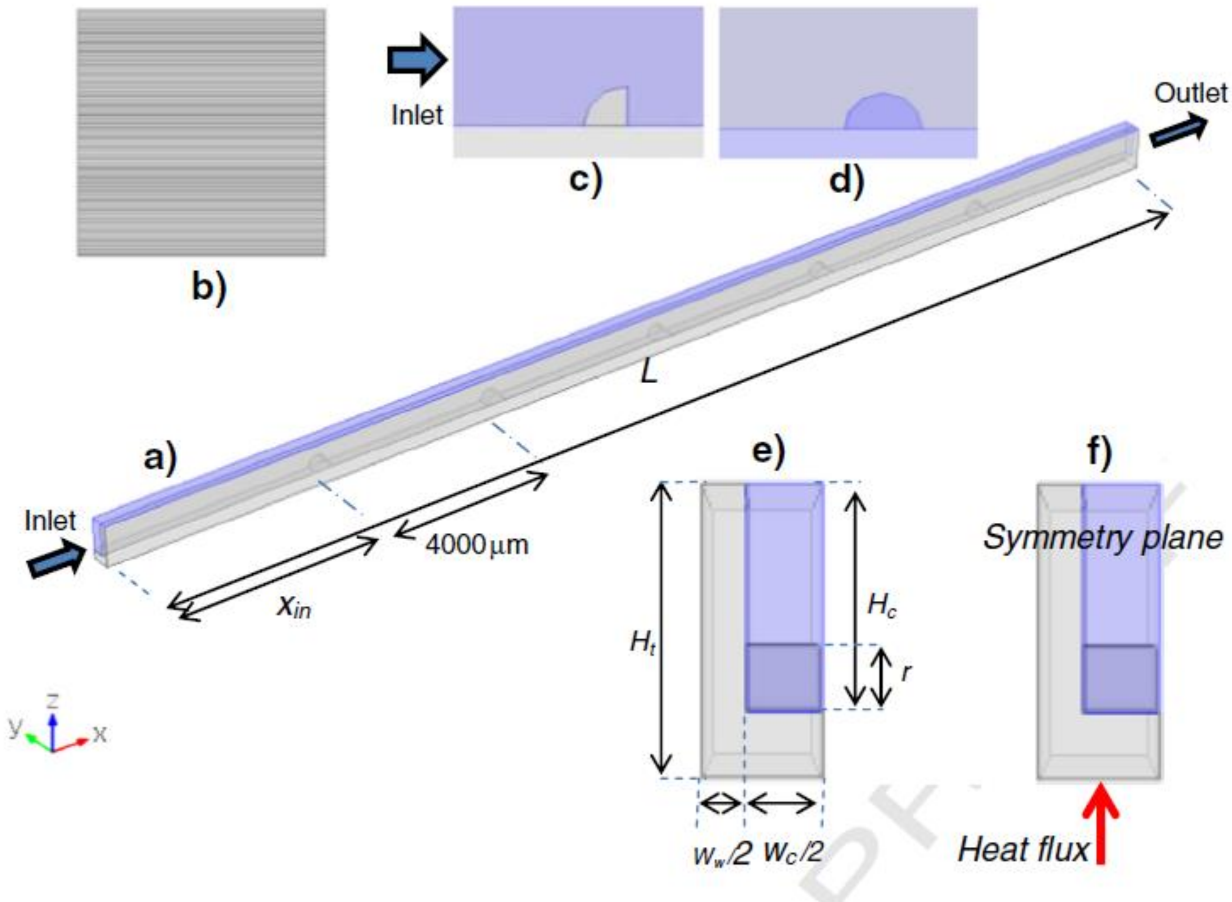


Figure 29 Geometry description: (a) rectangular micro-channel containing vortex generators; (b) top view of a heat sink comprised of a series of micro-channels; (c) side-view cross-section of a quarter-circle vortex generator; (d) side-view cross-section of a half-circle vortex generator; (e) view along the channel showing the definition of parameters governing the dimensions of the geometry; (f) boundary conditions applied. [40]

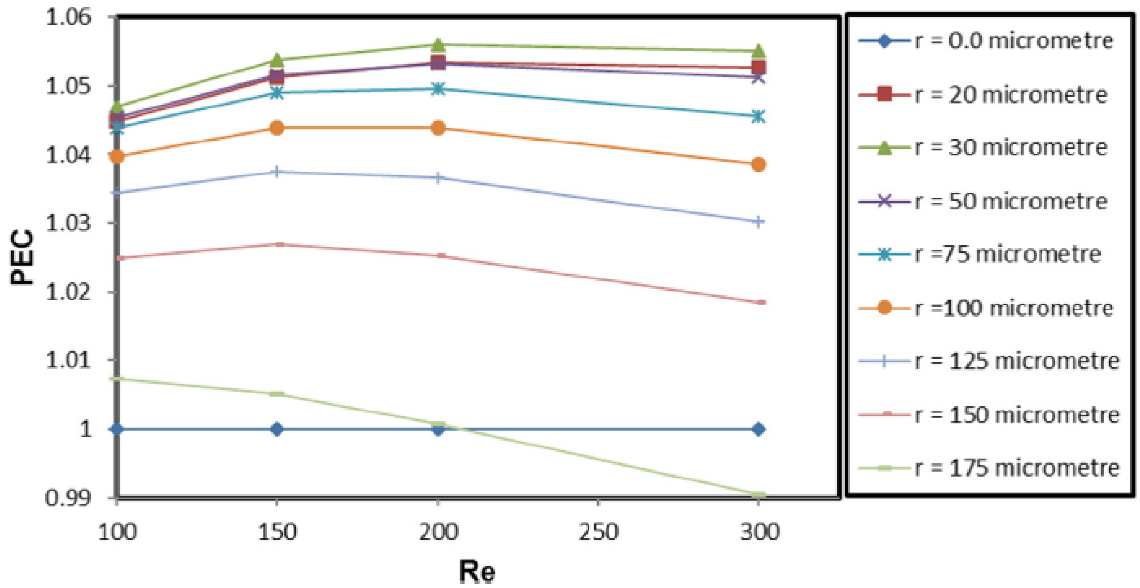


Figure 30 Variation of PEC index with Reynolds number for centred half-circle VGs of various radii. [40]

Naik et al. [41] investigated the effect of mounting rectangular winglet pairs (RWPs) on heat transfer augmentation for flow over a flat plate. Different geometric parameters have been varied such as the distance between the leading winglets, length, and angle of attack of the RWPs with Reynolds number ranging from 400 to 2000. Convective heat transfer is improved due to fluid mixing caused by longitudinal vortices. As the length of the winglets increases, the heat transfer augmentation also increases. The effect of larger Reynolds number is prominent for larger length of winglets.

Sabaghan et al. [42] used the newest version of the two phase Eulerian-Eulerian approach to simulate a rectangular microchannel consisting of six longitudinal vortex generators (LVGs). TiO2-based nanofluids with different water-based fluids, ethylene glycol and water mixtures (EG: W (60:40 by mass)), and transforming oils are considered for simulation. Certain parameters like the diameter along with the volume concentrations of the nanoparticles were varied. It was found that without the use of nanofluid, LVGs caused a 14% enhancement in heat transfer and with the addition of nanofluid, the heat transfer enhancement increased to about 27%. As the Reynolds number and nanoparticle diameter increase, the efficiency of the nanoparticles decreases at a high rate. On the other hand, an increase in the volumetric concentration leads to heat transfer augmentation due to the increase in effective thermal conductivity.

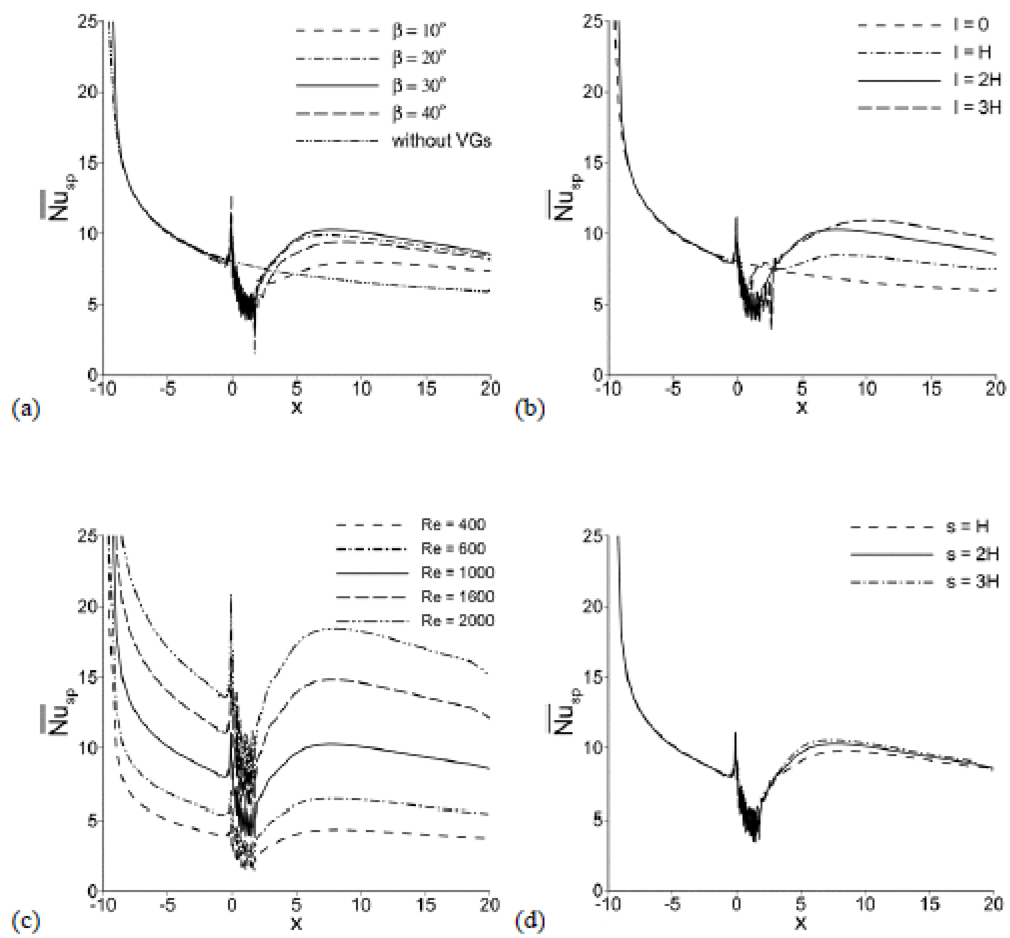


Figure 31 Variation of span-averaged Nu along length of the plate for different values of (a) angle of attack at l = 2H, s = 2H, Re = 1000 (b) length at s = 2H, β = 30°, Re = 1000 (c) Re at l = 2H, s = 2H, β = 30° (d) spacing at l = 2H, β = 30°, Re = 1000 [41]

Table 1 Types and performance features of vortex *generators*

No.	Type of VG	VG characteristics	Augmentation characteristics	Related Refs.
1	Delta Winglet Vortex Generators (DWVGs)	• There are two categories of vortices, transverse and longitudinal vortices.	• Heat transfer rate is augmented at the cost of moderate pressure drop.	[4]
2	Inclined Longitudinal Vortices (ILVs)	• Compared to the traditional wavy finned flat tubes, LVGs cause higher enhancement.	• Nusselt number was increased by 21-60% with moderate increase in pressure drop.	[17]
3	Triangular Prism (TP)	• They are interrupted surfaces that create longitudinal vortices that travel in the downstream region.	• The channel containing TP has higher Nu compared to the plane channel.	[43]
4	Curve rectangular vortex generators (CRVGs)	• VGs applied on the fin surfaces of circular tube bank fin HXs.	• The fin surface contacting with the wake region has higher Nu.	[44]

Chapter 3 **Conclusion**

A review study was performed in order to analyse the different methods for augmenting heat transfer frictional loss reduction for CHXs through various number of experimental and numerical investigations. Vortex generators are known to promote better heat transfer enhancement with reducing air side thermal resistance. The following are some important concluding remarks for this review study:

- VGs are protrusions from the surfaces that play an important role in augmenting the heat transfer enhancement for a heat exchanger and also help to design a heat exchanger with lower area and volume and also smaller thermal resistance.
- There are three characteristics of longitudinal vortex generators such as, generation of secondary flow, boundary layer development and increasing the intensity of turbulence for the fluid flow. LVGs induce the main and corner vortices which cause a reduction in the boundary layer thickness.
- VGs can be used to reduce the wake region or weak heat transfer region behind tubes by a significant amount. Heat transfer in downstream regions can be enhanced by a significant amount as well.
- Various geometric parameters like location, angle of attack and size for a VG are important for the enhancement of heat transfer. Pressure drop is independent of the location of VGs.
- Staggered arrangement of winglets causes higher heat transfer augmentation compared to the inline arrangement. Winglets are more superior to wings in terms

of heat transfer enhancement and pressure loss. DWPs have superior performance over RWPs.

- From numerous numbers of investigations, various angle of attacks was found but the optimum angle of attack lies in the range of 30°-45°.
- Transverse vortices produced by transverse vortex generators are inferior to longitudinal vortices that are generated by delta winglets.

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