
Experimental Study of Concave Rectangular Winglet Vortex Generators Effect on Thermal-Hydrodynamic Performances of Airflow inside a Channel

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Abstract

The present study focuses on the effect of CDW VG on the rate of heat transfer and flow pressure drop. The present experimental study was conducted by observing the effect of attack angles of VGs varied from 15 to 45°. In addition, the effect of number of pairs of VGs on convection heat transfer coefficients and flow pressure drop was also investigated. In order to observe the longitudinal vortex (LV) formed, flow visualization was performed in this work. The velocity of the airflow varied from 0.4 to 2.0 m/s with an interval of 0.2 m/s. In this work, the authors compared the thermal and hydrodynamic performance between cases using CRW and RW VGs. The results showed that the use of CRW VGs at an attack angle 45° increased convection heat transfer coefficient of up to 188% against the baseline (without using VG), whereas the use of RW VGs at the same attack angle increased the convection heat transfer coefficient by up to 100% against the baseline. The value of convection heat transfer coefficient increased with increasing angle of attack of VGs. However, the increase of attack angle has an impact on increasing pressure drop.

Keywords: concave rectangular winglet VG, convection heat transfer coefficient, pressure drop

1. Introduction

The fin and tube heat exchanger is mostly found in power plants, HVACR (heating, ventilating, air conditioning and refrigeration), chemical industry, and automotive. Improved performance of the fin and tube heat exchanger is a necessary thing to do to achieve high efficiency.

The thermal performance of heat exchanger can be indicated by increasing the value of its heat transfer coefficient. The improvement of heat transfer can be done in various ways; one effective way is to use a vortex generator (VG). Fiebig et al. used wing-type VG to obtain heat transfer enhancement [1]. They observed the effect of using delta winglet VG with in-line and staggered arrangements on the heat transfer enhancement. They concluded that the use of VG can reduce the size and mass of heat exchangers at the same heat load. Zhu et al. investigated the incorporation of rib-roughness with rectangular winglet VG in enhanced heat transfer [2]. They found that the use of rib-roughness with a rectangular winglet VG increases Nusselt number (Nu) by 405%.

The improvement of convection heat transfer on the surface using longitudinal vortex generator (LVG) has been expressed by Jacobi and Shah [3]. They said that the use of LVG to enhance heat transfer is promising. In order to achieve this goal, however, a deep understanding of the interaction between the flow structure and heat transfer is required. Biswas et al. studied numerically and experimentally the interaction between the flow structure and heat transfer in the presence of LVG [4]. Their work was able to identify the existence of main vortex, corner vortex and induced vortex in complex flow structures. The combined effect of these vortices was capable of distorting the temperature field within the channel resulting in an increase in heat transfer between the main fluid and the fluid near the surface. Gentry and Jacobi investigated in more detail the interaction between LV and the boundary layer experimentally [5]. They installed a delta wing VG to enhance the thermal performance of the fluid flow over the flat plate. Their experiments indicated that there was an increase in heat and mass transfer from the baseline (not using VG). Guo et al. proposed the concept of heat transfer improvement by estimating the angle between the flow velocity and the temperature gradient [6]. They found that the improvement of heat transfer may be indicated by increasing angle between fluid velocity and temperature gradient. They claimed that this novel method can estimate the heat transfer enhancement more effectively.

Lee et al. studied numerically the effect of LV on the characteristics of heat transfer within the turbulent boundary layer [7]. They found that Reynolds Stress Model (RSM) was able to predict anisotropy more accurately than the standard $k-\epsilon$ model. Their work also showed that disturbance in the boundary layer caused the rise of Stanton number with the flow direction to the wall, but the mixing of fluid inside the vortex core was observed to be weak. One of various ways of VG installation was the punched surface to the wall as has been performed by Chen et al. [8]. Their result showed that the staggered arrangement of punched delta winglet VG was greater in heat transfer improvement compared to in-line arrangement. In order to observe the complexity of the flow structure within the channel in the presence of VG, the flow visualization needs to be performed as done by Wang et al. [9]. They presented the flow visualization on a fin-and-tube heat exchanger with/without VGs (vortex generators). The results of this study showed that LVs (longitudinal vortices) formed behind the tube in the presence of annular VG. Tiwari et al. studied numerically heat transfer improvement in cross-flow heat exchanger with oval tubes and multiple delta winglets [10]. They revealed that the combination of oval tubes with delta winglet pairs VGs enhanced heat transfer significantly.

Leu et al. analyzed numerically and experimentally heat transfer and fluid flow in plate fin and tube heat exchanger by mounting VG pair of block shape [11]. Their study results indicated that the pair of block shapes can generate LVs and improve heat transfer performance in the wake region. The use of delta wing VG to enhance heat transfer in refrigerator evaporator applications has been proposed by Sommers and Jacobi [12]. Their results found that the use of delta wing VG decreased thermal resistance by up to 42%. Ferrouillat et al. studied experimentally and numerically thermal performance improvement and fluid mixing capabilities in the presence of delta winglet VG [13]. Their goal was to investigate a multifunctional heat exchanger as a flow mixer. The main objective of their research was the determination of turbulent flow in various geometries by using computational fluid dynamic. Hiravennavar et al. showed heat transfer enhancement within a channel by using a pair of winglet delta VGs that generate counter rotating LV [14]. They observed that heat transfer was doubled up by using a pair of VGs compared with using a VG. They also found that delta winglet VG with a certain thickness was superior compared with that without thickness.

Wu and Tao verified heat transfer improvement by using the field synergy principle [15]. Their numerical analysis revealed that the improvement of heat transfer by using rectangular winglet VG can be explained well by using the field synergy principle. The concept of a field synergy principle is to observe the intersection angle between the flow velocity and the temperature gradient. It can be revealed that the smaller the intersection angle the greater the heat transfer. Wu and Tao also studied some parameters that affect heat transfer improvement [16]. These parameters included the location of VG in the channel, the geometry size and the shape of the VG. A three-dimensional numerical analysis of the fin and oval tube heat exchanger by installing a punched delta winglet has been carried out by Chu et al. [17]. They analyzed based on the field synergy principle to provide a fundamental understanding of the correlation of flow structures and enhancement of heat transfer. They found that the placement of VG in the downstream, 30° attack angle and the minimum number of rows gave the highest increase of heat transfer. Min et al. presented fluid flow and heat transfer characteristics within the rectangular channel in the presence of modified rectangular wing VG [18]. Their experimental results showed that modified rectangular wings have better fluid flow and heat transfer characteristics than that of rectangular wing VG.

Wu and Tao presented the impact of delta winglet VG on the performance of heat transfer and pressure drop with different tube diameter [19]. Their numerical simulation showed that the fin and tube heat exchanger with the diameter of the first row tube smaller than that of the second row tube indicated better heat transfer with a smaller pressure drop than the traditional fin and tube. Wu and Tao have analyzed experimentally and numerically to know the effect of VGs on the heat transfer in a rectangular channel [20]. They varied the angle of attack to determine its effect on heat transfer characteristics. They found that the Nusselt number at an attack angle of 60° was slightly higher than at 45°, but the pressure drop also increased with increasing angle of attack. He et al. numerically analyzed heat transfer and pressure drop in a fin and tube heat exchanger with the use of rectangular winglet VGs [21]. They tried to determine the effect of the attack angle, the number of pairs of VGs, and the placement of VGs. Their results showed that longitudinal vortices (LVs) generated by rectangular winglet VGs were

the main reason for heat transfer improvement. The staggered arrangement of VGs produced a smaller pressure drop than the in-line arrangement. Zhou and Feng investigated experimentally the effect of curved winglet VG with punched hole on heat transfer enhancement [22]. Their experiment proved that the curved winglet VGs produced better thermal-hydraulic performance than the plane winglet VGs. Punched holes on VG improved heat transfer and decreased pressure drop. Syaiful et al. evaluated numerically and experimentally the effect of concave delta winglet VG on heat transfer augmentation in a rectangular channel [23]. From the results of their study, it might be concluded that the concave delta winglet (CDW) VG provided greater heat transfer augmentation than delta winglet (DW) VG at the same fluid velocity. Syaiful et al. studied numerically the attack angle effect of CDW VG on the improvement of heat transfer in the fin and tube heat exchanger for the EGR cooler application [24].

Oneissi et al. investigated the novel design of the delta winglet VG for heat transfer enhancement [25]. They examined the use of inclined projected winglet (IPW) VG against the increase of heat transfer and its effect on pressure drop. IPW VG exhibited the same heat transfer augmentation with that of DW VG but with a lower pressure drop. Song et al. studied experimentally the effect of geometric size of curved DW VGs and tube pitch on heat transfer augmentation in a fin-and-tube heat exchanger [26]. They found that small-size VGs resulted in improved heat transfer at lower Reynolds numbers, while large VGs resulted in heat transfer augmentation at high Reynolds numbers. Syaiful et al. analyzed the effect of the concave delta winglet VGs on the thermo-hydrodynamic performance of the fluid flow in a rectangular channel [27]. They observed that CDW VG resulted in a higher heat transfer enhancement compared to DW VG. However, this increase in heat transfer was followed by an increase in pressure drop.

This chapter discusses the experimental results of concave rectangular winglet vortex generator (CRW VG) application to enhance heat transfer in the flow. The negative impact of using CRW VG on pressure drop is also informed in this chapter. The angle of attack and the number of rows VG become parameters that are considered at present. The flow visualization was performed to observe the longitudinal vortex (LV) structure formed behind the VGs.

2. Materials and experimental set up

This work aims to obtain better performance on heat exchanger with the installation of a rectangular and concave rectangular vortex generator in it. VG producing LV increases fluid mixing resulting in a rise in the rate of heat transfer.

2.1. Test equipment

This test was performed inside a glass air duct with a thickness of 10 mm as can be shown in **Figure 1**. This air channel has a rectangular cross section with a length of 370 cm, a width of 8 cm, and a height of 18 cm. The air was sucked by a blower coming into the channel through the straightener which consists of a number of tubes with the diameter of 5 mm arranged stacked. The air from the straightener then passed through a wire mesh to obtain uniform flow within the channel entry region. A hot wire anemometer (Lutron AM4204, resolution of 0.1 m/s) was placed 26 cm from the wire mesh to measure the velocity of the airflow inside the channel. A number

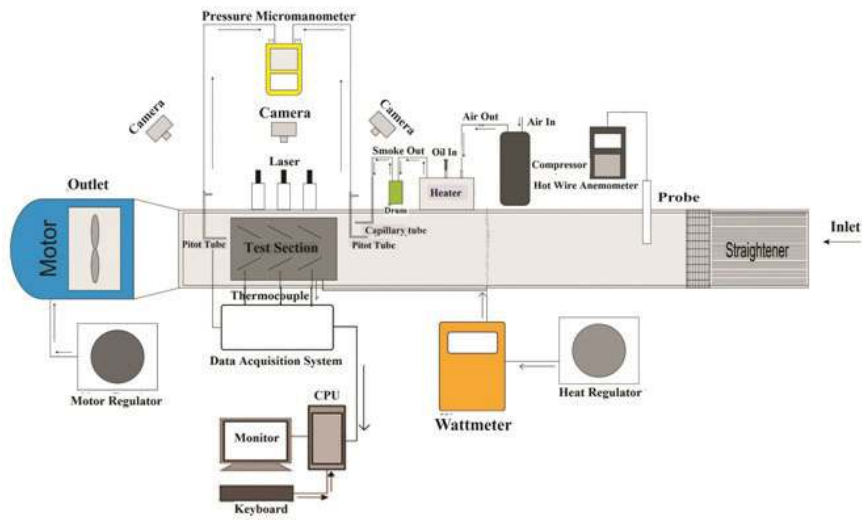


Figure 1. Schematic diagram of experimental set up.

of thermocouples (K-type with an accuracy of 0.75%) were placed on the test plate to measure the wall temperature of the plate. Several thermocouples were also set on the upstream and downstream of the test plate to measure inlet and outlet air temperatures, respectively. These thermocouples were connected to the acquisition data connected to the CPU. Data acquisition converts analog signals into digital signals and then stored in the CPU. A micro-manometer (Fluke 922 pitot tube with an accuracy of 1%) with two pitot tubes was set on the upstream and downstream of the test section to measure pressure drop. The airflow velocity inside the channel was varied from 0.4 to 2 m/s with an interval of 0.2 m/s using a motor regulator. A heater was placed in the test section to induce a constant heat rate of 35 W which was controlled by using a heating regulator. The volatile liquid was used to produce smoke for flow visualization purposes. A compressor was used to pump smoke into the smoke injector. Smoke was captured by a cross section of the green laser field that was fired from three laser pens. A camera was placed in three locations alternately to obtain the best flow visualization image.

2.2. Test specimen (VG)

The test specimen used in this experiment was a hot plate attached by RW VGs expressed by **Figure 2** and CRW VGs shown in **Figure 3**. Both VGs shown in **Figures 2** and **3** had the same aspect ratio. The height of the RW and CRW VGs was 27 mm with an attack angle of 30°. VGs were mounted on a 500 mm × 155 mm heating plate. VGs were arranged in-line with spacing between pairs of 20 mm and the distance of one pair of VGs with the other pair was 125 mm. Several parameters investigated in this experiment are shown in **Table 1**. Baseline means that the specimen test is a heating plate without VGs. The attack angle for CRW VG is the angle between the flow direction and the tangent at the front end of VG. **Figure 4** shows the test plate mounted with RW and CRW VGs.

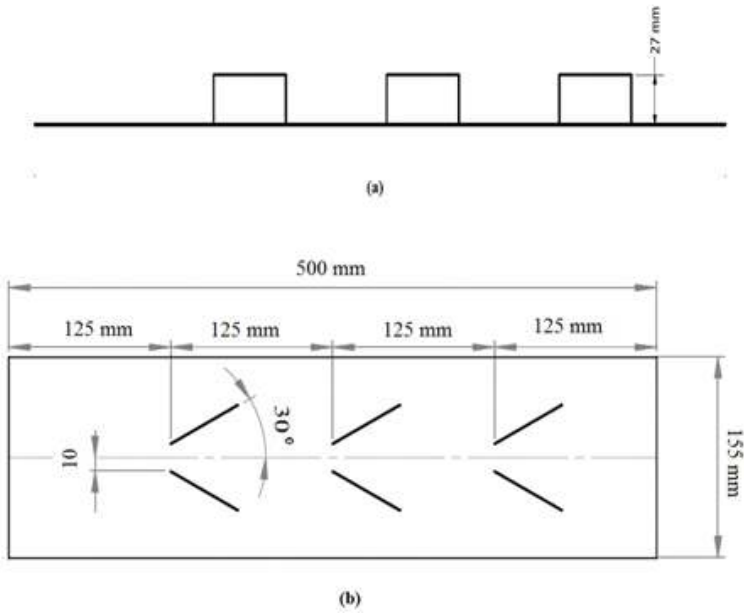


Figure 2. Three rows of rectangular winglet pairs (RWPs) of VGs: (a) side view and (b) top view.

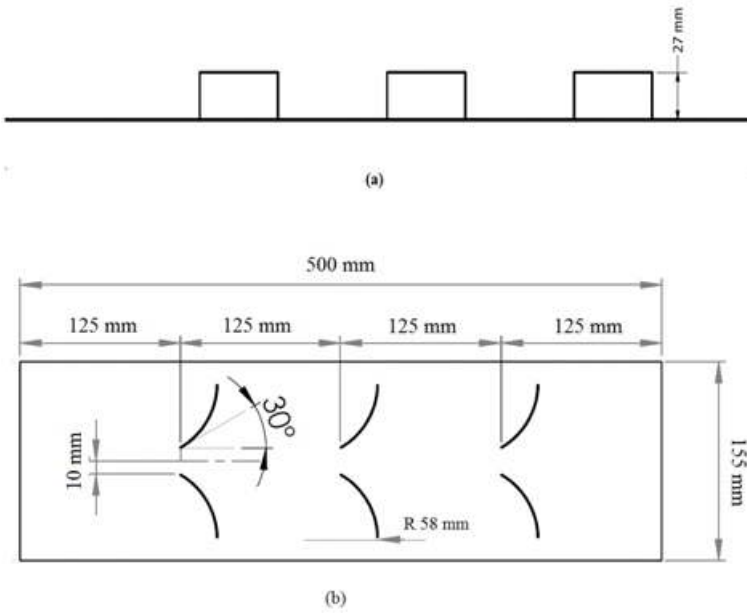


Figure 3. Three rows of concave rectangular winglet pairs (RWPs) of VGs: (a) side view and (b) top view.

No.	Test parameters
1.	Baseline, RW VG and CRW VG
2.	Attack angle: 15, 30 and 45°
3.	A number of row: one, two and three

Table 1. Some parameters in the experiment.

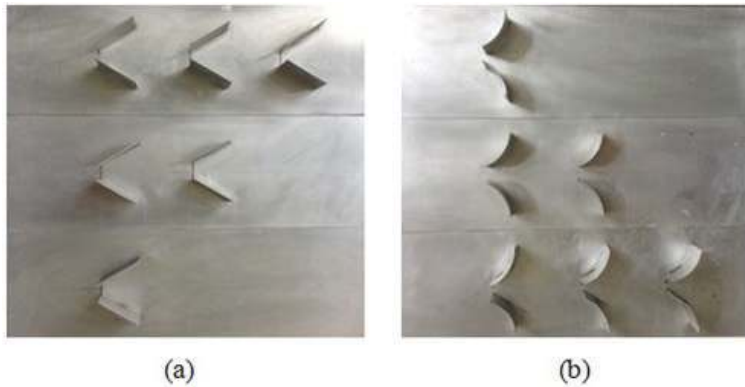


Figure 4. Test specimens. (a) RWPs one, two and three rows, (b) CRWPs one, two and three rows.

2.3. Testing procedures

Checking the temperature values of the thermocouple before the heat rate on the test plate was induced. All temperature values should be equal to ambient temperatures. The heat of 35 W was induced into the test plate by monitoring it through a watt meter. The heating of this plate was carried out in the absence of airflow until the surface temperature of the plate reaches a steady state of 54–55°C. Then the airflow speed was set from 0.4 to 2 m/s with 0.2 m/s interval using motor regulator by changing the frequency. The volatile liquid was flowed into the heater, and then the formed smoke was compressed into the capillary tube using a compressor and then injected into the airflow at a velocity of 0.4 m/s.

3. Results and discussion

3.1. Effect of attack angle on heat transfer

Figure 5 shows the effect of the attack angle on the convection heat transfer coefficient at various air velocities. In general, the convection heat transfer coefficient increases with increasing airflow velocity for all cases. This can be explained easily because the convection heat transfer coefficient is directly proportional to the flow velocity [28]. Higher velocity values decrease the thickness of the boundary layer resulting in higher heat transfer [21]. By installing a RW of three pairs of VG

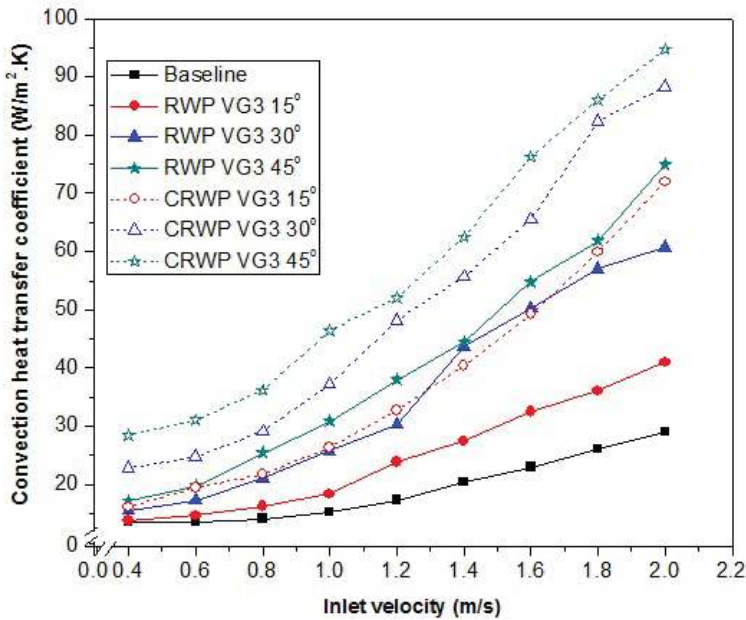


Figure 5. Convection heat transfer values with variations of inlet velocity at different angle attack for RW and CRW VGs.

(RWP VG3 15), the convection heat transfer coefficient increased 41.6% against the baseline at a flow rate of 2 m/s. This increase in heat transfer is due to the appearance of longitudinal vortex (LV) in the wake area of VG resulting in a good mixing of hot fluids near the wall with cold fluids in the main flow [27]. **Figure 5** also shows that the greater the attack angle of the flow to VG, the value of the convection heat transfer coefficient tends to increase at the same flow velocity. This is because the rectangular winglet with a larger angle of attack produces higher vortex circulation [4, 20]. LV promotes better fluid mixing resulting in a decrease in angle between the velocity field and the temperature gradient field. This results in an increase in the rate of heat transfer [6]. LV attenuates the boundary layer in the down wash region resulting in an increase in heat transfer [8].

For the case of RW VGs, an increase in the angle of attack from 15 to 45° at a velocity of 2 m/s results in 83% increase in heat transfer rate. In the case of CRW VG, the installation of VGs with 15, 30 and 45° attack angles resulted in a 158.1% increase in heat transfer, respectively, to the baseline at the flow velocity of 2 m/s. Increases in attack angles from 15 to 45° for CRW VGs cases resulted in 31.5% increase in heat transfer at a flow rate of 2 m/s. Just as the preceding reason, VGs with a larger angle of attack produce LV with higher strength which results in better heat transfer [10]. By installing CRW VGs, heat transfer increased 75.6, 45.4 and 26.3% against RW VGs at the same attack angles of 15, 30 and 45°, respectively, at the flow velocity of 2 m/s. This is due to the instability of the centrifugal force on the concave surface resulting in a larger radius of LV with higher strength of vortex circulation than that of RW VGs [29]. The formed LV when the flow passing through a concave surface is called the Görtler vortex in which the growth rate is 10 times of vortex generated by flat plate [30]. Disturbances caused by the presence of Görtler vortex increase local heat transfer [31].

3.2. Effect of a number of VG rows on heat transfer

Figure 6 shows the effect of the number of rows of VGs on convective heat transfer coefficient values at various flow velocities with 30° attack angle for RW and CRW VGs cases. Two and three rows of VG pairs were arranged in-line in this case. By mounting VGs, in general, improvement of heat transfer was found against the baseline. In the case of RW VGs, the use of two and three pairs of VGs increased the heat transfer by 5.5 and 26.4% of a pair of VGs, respectively. This increase was triggered by the acceleration of formed LV by LV produced by a previous pair of VGs [11]. In the case of CRW VGs, the increase in heat transfer rates at two and three pairs of VGs increased from 19.4 to 37.9% of a single pair of VGs. The use of CRW VGs in heat transfer improvement was better than RW VGs on the same number of rows of VGs pairs. As mentioned earlier, CRW VGs generate LV with a larger vortex radius and stronger vortex circulation than that of LV produced by RW VGs due to the instability of centrifugal force. In the baseline case, an increase in the flow rate from 0.4 to 2 m/s resulted in an increase of 114.7% heat transfer rate. **Table 2** presents the percentage increase in the rate of heat transfer to the increase of flow velocity inside the channel.

3.3. Effect of attack angle and number of pairs of VG on pressure loss penalty

Figure 7 expresses the effect of the number of pairs of VGs lines on the pressure loss penalty (pressure drop) for various flow velocities at the attack angle 15°. RWP VG1, RWP VG2 and RWP VG3 reveal one, two and three rows of pair of RW VG, respectively. The same is true for

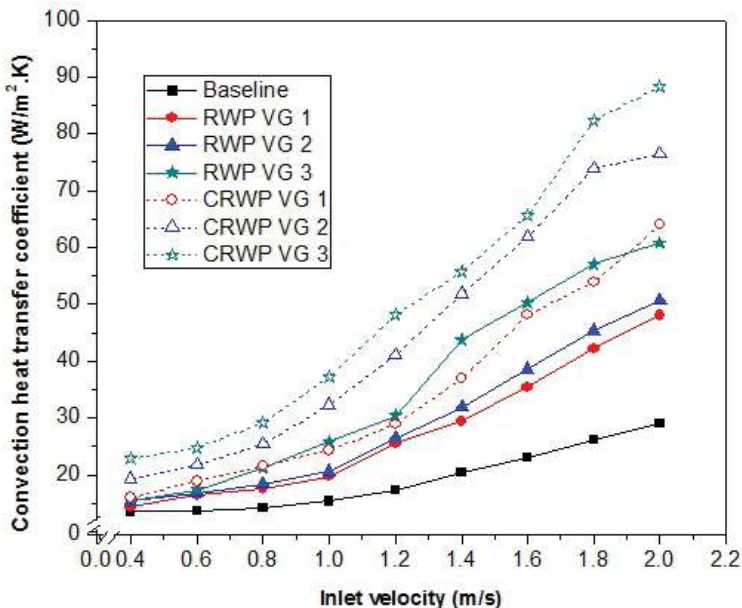


Figure 6. Convection heat transfer values with variations of inlet velocity in different a number of VG rows at 30° attack angle for RW and CRW VGs.

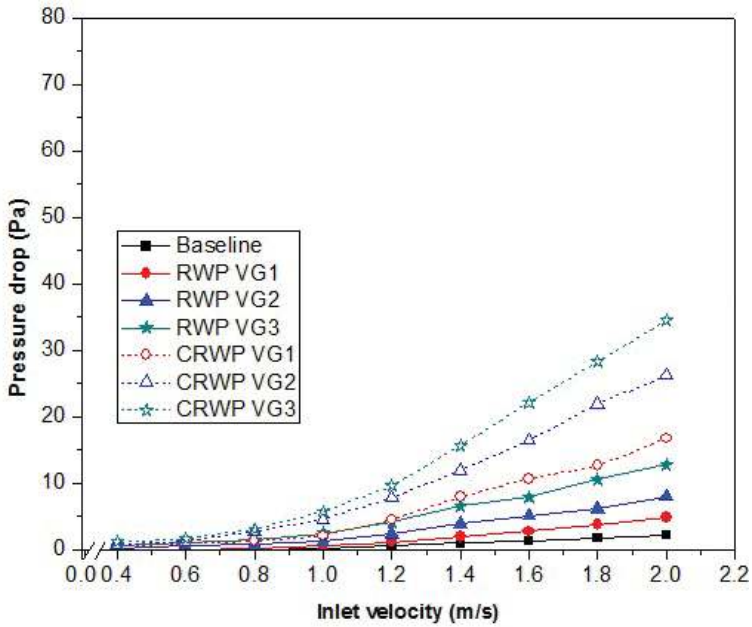


Figure 7. Pressure drop values with variations of inlet velocity in different a number of VG rows at 15° attack angle for RW and CRW VGs.

Baseline	RWP VG1	RWP VG2	RWP VG3	CRWP VG1	CRWP VG2	CRWP VG3
114.7	236.2	231.4	290.9	299.4	296.9	286.8

Table 2. Heat transfer augmentation for increasing in flow velocity (%).

CRW VGs. In general, the pressure drop increases with increasing flow velocity for all cases. This is because the pressure drop is directly proportional to the flow velocity [32]. The value of the pressure drop increases with the increase of the number of rows of VGs. The increase in pressure drop is mainly caused by the addition of formed drag from VGs [21]. **Table 3** shows the increase in pressure drop to flow velocity for each case. These values describe what times the pressure drop increases when the flow velocity inside the channel was increased from 0.4 to 2.0 m/s for each case. For baseline and RWP VG1 cases, the pressure drop values might not be compared because of the limited accuracy of micro-manometers especially for velocities below 1 m/s. From **Figure 6**, it is found that the use of CRW VGs increases higher pressure drop than the use of RW VGs due to the greater area of the obstruction on CRW VGs [33].

Figure 8 illustrates the pressure drop generated from the variation in the number of pairs of RW and CRW VGs as well as the baseline at the attack angle of 30°. The experimental results

Baseline	RWP VG1	RWP VG2	RWP VG3	CRWP VG1	CRWP VG2	CRWP VG3
-	-	31.2	24.4	30.4	34.4	29.8

Table 3. Pressure loss penalty at attack angle of 15° for increasing in flow velocity (times).

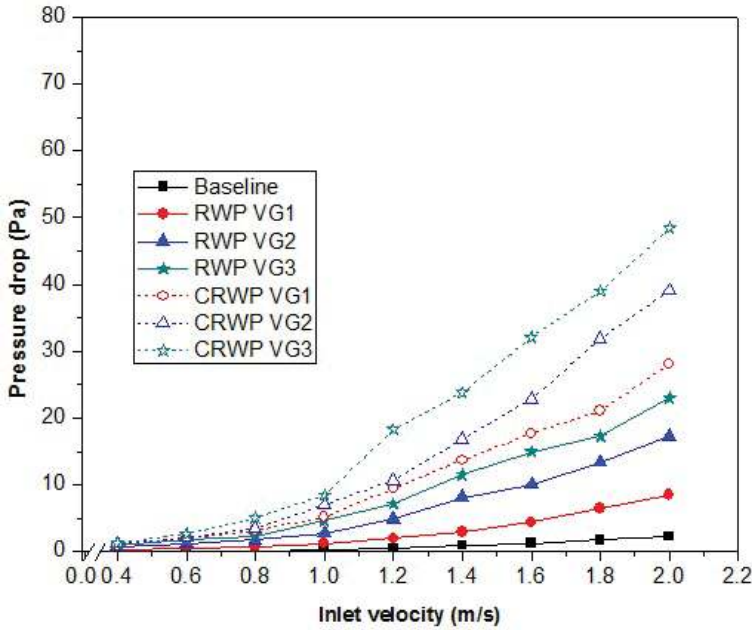


Figure 8. Pressure drop values with variations of inlet velocity in different a number of VG rows at 30° attack angle for RW and CRW VGs.

found that the pressure drop increased with increasing flow velocity. The increase in pressure drop to the increase in flow velocity in the channel for each case can be expressed in **Table 4**. For the baseline case, the increase in pressure drop might not be determined because the pressure drop value was not detected in the measurement at the flow velocity of 0.4 m/s.

This was triggered by the increase in formed drag by increasing flow velocity. At a flow rate of 2 m/s, the pressure drop increased almost three times from the baseline when a pair of RW VGs was mounted on the plate. This value increased to nine times when three pairs of RW VGs were installed. By installing three pairs of CRW VGs, the pressure drop value increased 20 times compared to the baseline at a flow rate of 2 m/s. This indicates that the use of CRW VGs increases the pressure drop greater than the use of RW VGs. This is the disadvantage of using CRW VGs. For the case of three pairs of CRW VGs, the pressure drop increased significantly at a flow velocity above 1.0 m/s (**Table 5**).

Baseline	RWP VG1	RWP VG2	RWP VG3	CRWP VG1	CRWP VG2	CRWP VG3
-	32.8	22.3	22.2	27.3	32.1	37.4

Table 4. Pressure loss penalty at attack angle of 30° for increasing in flow velocity (times).

Baseline	RWP VG1	RWP VG2	RWP VG3	CRWP VG1	CRWP VG2	CRWP VG3
-	67.3	34.1	38.8	33	37	30.8

Table 5. Pressure loss penalty at attack angle of 30° for increasing in flow velocity (times).

Figure 9 shows the pressure drop for various flow velocities and VG types at an angle of attack 45°. By comparing Figure 9 with Figures 7 and 8, the pressure drop increases very high against the baseline. The formed drag is large at large angle of attack which is the main reason for the significant increase in pressure drop. The area of the flow obstruction increases with the larger angle of attack [33]. A strong LV also contributed to the increase in pressure drop

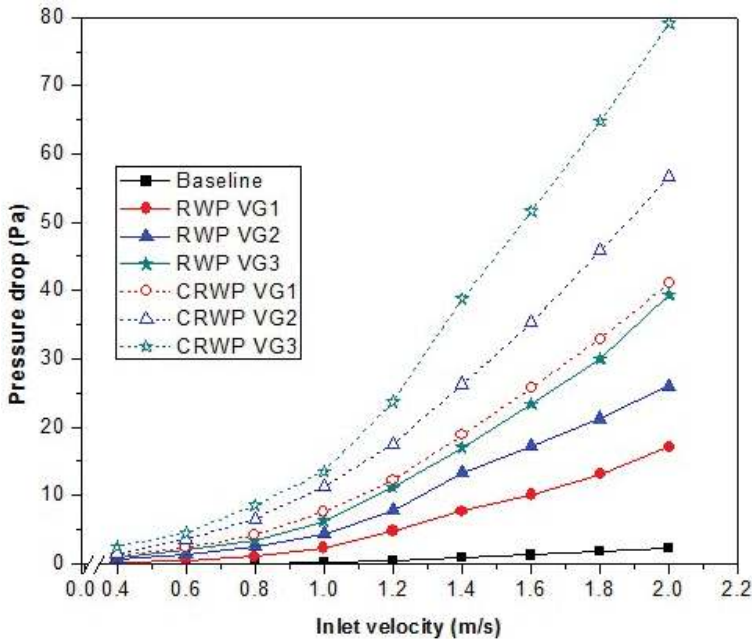


Figure 9. Pressure drop values with variations of inlet velocity in different a number of VG rows at 45° attack angle for RW and CRW VGs.

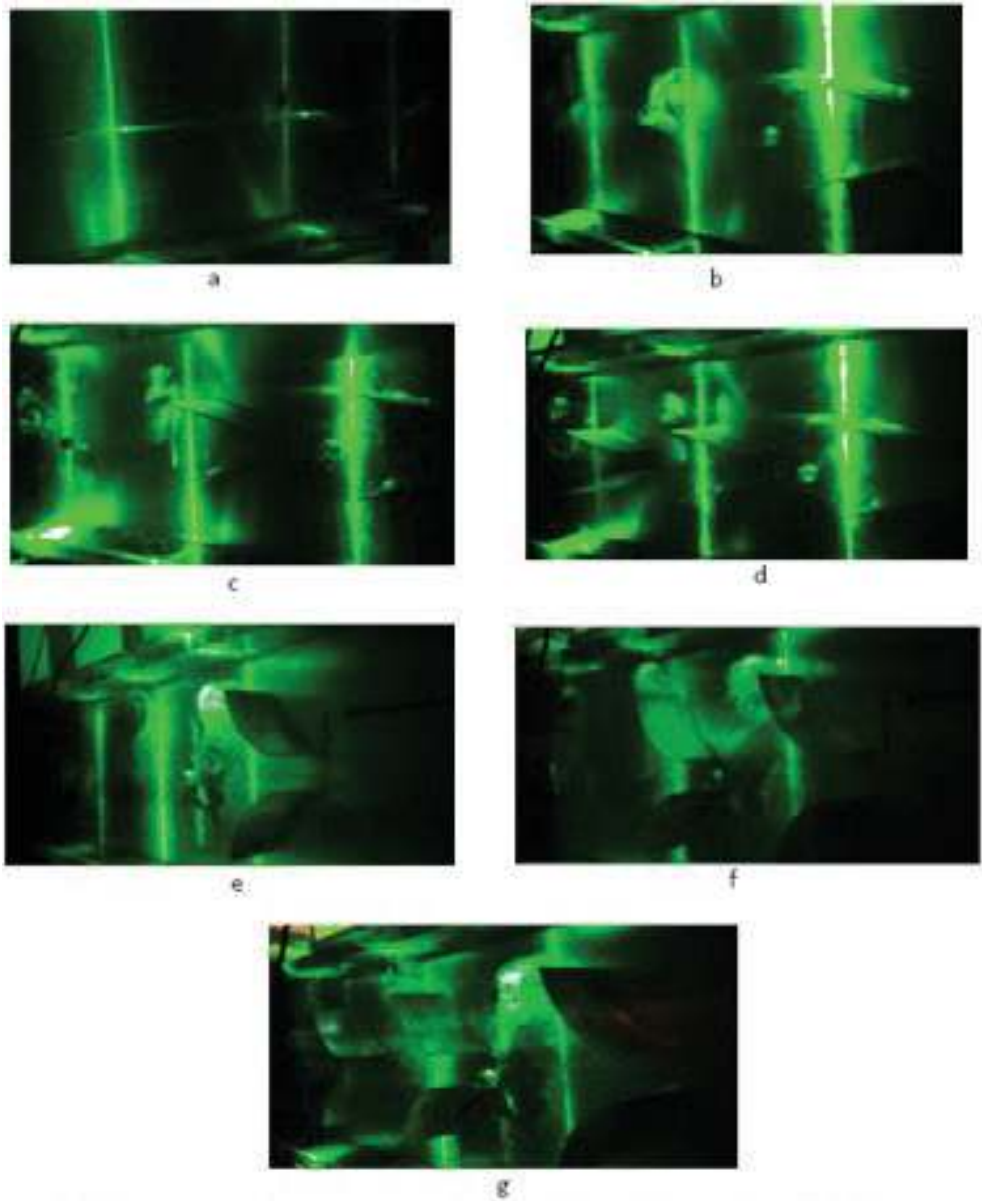


Figure 10. Flow structure of fluid flow passes through flat plate with and without VGs. (a) Baseline; (b) RWP VG1; (c) RWP VG2; (d) RWP VG3; (e) CRWP VG1; (f) CRWP VG2; and (g) CRWP VG3.

of fluid flow in the channel [34]. In general, the generation of vortex causes extra drag which leads to an increase in pressure drop [35].

3.4. Flow visualization

This flow visualization aims to know the flow structure as it passes through VGs. **Figure 10** shows the airflow structure through the plate for each case. In the baseline case, LV is not visible when the fluid passes through the plate because there are no VGs as can be seen in **Figure 10a**. LVs appear at two locations in the downstream of the VGs for the case of RWP VG1 as shown in **Figure 10b**. LV located on the third green laser cross section appears weaker than LV in front of it. This is due to viscous dissipation in the flow direction [36]. LVs are observed at three sites behind VGs with LV at the third location decreases in strength due to viscous dissipation as denoted in **Figure 10c**. Two vortices are observed in the second and third locations after the fluid passes through the VGs as shown in **Figure 10d**. When the fluid passes through the CRWP VG1, two vortices are formed in the wake region of the VGs and weaken their strength due to viscous dissipation as shown in **Figure 10e**. Vortices generated by CRW VG have a larger radius than those produced by RW VG. Vortices are also found when the fluid passes through CRWP VG2 and CRWP VG3 with a larger radius as shown in **Figure 10f** and **g**.

4. Conclusion

Experimental to know the effect of concave rectangular winglet vortex generator (CRW VG) has been completed. The heat transfer rate increased with increasing angle of attack. However, this increase in attack angle had a negative impact on the pressure loss penalty in which the pressure drop also increased with increasing angle of attack. Similar tendencies were also found when the number of VG pairs was increased, heat transfer increased with increasing pressure drop. The flow visualization was able to show the flow structure when the fluid passed through VGs. Longitudinal vortex (LV) was observed in the wake region of VGs.

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