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Comparison of Thermal-Hidraulic Performances of Vortex Generators Mounted on Heated Plate: Experimental Study and Flow Visualization

Syaiful[1], Nazaruddin Sinaga[1], Bambang Yunianto[1], MSK. Tony Suryo Utomo[1]

[1]Department of Mechanical Engineering, Diponegoro University, Jl. Prof. Soedarto, Semarang 50275, Indonesia

*Corresponding author: syaiful.undip2011@gmail.com

Abstract. Improvement of heat transfer in fin and tube heat exchangers for improving energy efficiency is required to be performed. In the present study, an enhancement in the rate of heat transfer is done by manipulating fin geometry on the fin and tube using longitudinal vortex generators. Perforated concave delta winglet is introduced as the latest longitudinal vortex generator that can improve heat transfer better than previous vortex generators. Experimental study is conducted to investigate the thermal and hydraulic performance of perforated concave delta winglet vortex generators in a rectangular channel. From the results of the study, it is found that the heat transfer rate increases up to 78.9% of the baseline by using three pairs of concave delta winglet vortex generators with three holes. This value is 27.3% higher than using delta winglet vortex generator with three holes. However, this increase in heat transfer rate is also accompanied by an increase in pressure losses in the flow. Pressure drop increases up to five times from the baseline by installing three pairs of three-hole concave delta winglet vortex generators.

Keywords*: antioxidant additives, induction period, Acid value, oxidation stability*

1. Introduction

Fin and tube is one of the compact heat exchangers that are widely used in the chemical industry, power generation, refrigeration and air conditioning, automotive, etc. Energy efficiency by improving the rate of heat transfer in the fin and tube heat exchanger is a crucial matter that is needed. Therefore, heat transfer improvement on the fin side of the fin and tube needs to be performed because of the high thermal resistance in this area. One of the ways to reduce thermal resistance is to install a vortex generator (VG) on the fin side.

Wu and Tao studied numerically the laminar convection heat transfer within a rectangular channel by applying longitudinal vortex generators based on the field synergy principle [1]. They investigated the effect of presence and without punched holes on the installation of longitudinal vortex generators (LVGs) to heat transfer improvement. From the results of their study, there was better heat transfer enhancement with a smaller pressure drop in the case of punched holes. At their next stage, they analyzed in more detail some of the parameters that affect the improvement of heat transfer and flow resistance [2]. They observed that the increase in heat transfer improvement was always marked by a decrease in

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the field synergy principle. Their results also show that the increase in the LVG surface area has an impact on the increase in flow resistance or pressure drop.

Full-scale experimental investigation of the use of delta winglet vortex generators for heat transfer improvement to plain-fin and tube heat exchangers has been carried out by Joardar and Jacobi [3]. Their work showed that three VG pairs yielded in better heat transfer performance compared to one pair of VG but also resulted in greater pressure losses. He et al. performed numerical analysis of heat transfer and pressure losses on fin and tube heat exchanger by applying rectangular winglet vortex generators [4]. Some of the results of their numerical investigations were compared to the experiments that have been conducted by Joardar and Jacobi [3]. He et al. revealed that the rectangular winglet pairs (RWPs) VG provide promising heat transfer improvement. They also investigated the effects of angle of attack, the number of VG pairs and the arrangement of VGs.

Saha et al. compared the effect of delta and rectangular winglet VGs with different flow arrangement on the heat transfer enhancement [5]. Synergy analysis was used by them to determine the relationship between local flow behavior and heat transfer improvement. Based on their analysis, the rectangular winglet pair (RWP) VG was more effective in increasing heat transfer than the delta winglet pair (DWP) VG. Zhou and Feng studied the enhancement of heat transfer using curved winglet vortex generators [6]. They compared the effect of using curved winglet with plain winglet VGs on heat transfer performance. They observed that VG curved winglet was able to improve heat transfer better than plain winglet VG. Their results revealed that curved winglets provide better improvement heat transfer than plain winglets.

Experimental study of heat transfer enhancement within a tube by inserting delta winglet VGs with different arrangements has been carried out by Aliabadi et al. [7]. They compared the heat transfer and pressure drop inside the tube inserted VGs with a plain tube. They observed that insertion of VGs into the tube enhances the heat transfer coefficient and pressure drop rather than plain tube. Zdanski et al. investigated the effect of delta winglet VG on heat transfer from the flow across the tube bank [8]. They tried to evaluate the effect of several parameters related to heat transfer improvement. Their results indicated an increase in Nusselt numbers by using turbulent promoters. They found that heat transfer can be enhanced up to 30% but pressure drop is increased by 40%. Syaiful et al. numerically analyzed the concave delta winglet VG effect on the heat transfer augmentation within the channel [9]. They introduced the concave delta winglet as the newest vortex generator to improve heat transfer. Their investigation results revealed that the use of the concave delta winglet VG is capable of enhancing heat transfer almost twice that of the plain delta winglet.

Syaiful et al. investigated numerically the effect of the attack angle of the concave delta winglet VG on the improvement of heat transfer in the EGR cooler application [10]. From the results of their study, it was observed that the increase in angle of attack results in increased heat transfer and pressure drop. Tang et al. tried to examine the winglet VG configuration to enhance the heat transfer within a rectangular channel [11]. Field synergy principle was used by them to analyze the characteristics of heat transfer improvement in the presence of VG. Their results showed a smaller synergy angle for the case with VG than those without VG. Lotfi et al. studied the thermal and hydraulic characteristics of a wavy fin heat exchanger by introducing a new type of vortex generator [12]. The results of their numerical investigations demonstrated that CARW VG with a small attack angle yields the best thermal-hydraulic performance.

Syaiful et al. also investigated experimentally the effect of concave rectangular winglet VG on heat transfer [13]. Their experimental results showed that three rows of concave rectangular winglet VGs provide the best heat transfer improvement. Li et al. studied the use of delta winglet VGs for the improvement of heat transfer in the pin-fin heat sink [14]. In their numerical and experimental studies, some parameters of heat transfer improvement were evaluated. Their results showed that VG with 30□ attack angle provides the best thermal-hydraulic performance. Syaiful et al. evaluated numerically and experimentally the thermal and hydrodynamic characteristics of the fluid flow through the concave delta winglet VGs inside a rectangular channel [15]. They found that longitudinal vortex produced by CDWP VG was stronger and wider than that produced by DWP VG resulting better heat transfer augmentation.

Li et al. attempted to study numerically and experimentally the performance of a fin and tube heat exchanger by comparing the wavy fin and plain fin with the delta winglet VGs around the tube [16]. They installed some delta winglet VGs around tubes with wavy fin and plain fin. They used the entransy analysis to evaluate the heat transfer augmentation between enhanced fin and wavy fin. Entransy analysis proved that enhanced fin with longitudinal vortex generator provides better heat transfer improvement than that of wavy fin. Syaiful et al. studied the effect of the number of pairs of concave rectangular winglet VGs on heat transfer enhancement in the fin and tube heat exchanger [17]. From the results of their work, it can be observed that the highest number of VG pairs yields in the highest heat transfer enhancement followed by high pressure losses as well. Syaiful et al. realized that the use of concave winglet has a significant impact on the increase in pressure drop even though it results in high heat transfer improvement compared to plain winglet. Therefore, Syaiful et al. tried to reduce the high pressure loss due to VG installation by investigating the use of perforated VG [18, 19]. They found that the use of perforated VGs only reduces the convection heat transfer coefficient of 1.07% of VG without holes. However, the use of perforated VG can reduce pressure drop to 25.65%.

From an evaluation of previous studies there has not been a thorough investigation of the improvement of heat transfer and pressure drop due to the use of perforated concave winglet VG and without a hole. Therefore, the present study is focused on evaluating the thermal and hydraulic performance of airflow through a heated plate in a rectangular channel in the presence of a concave delta winglet VG and comparing it with a plain winglet VG.

2. MATERIALS AND EXPERIMENTAL SET UP

2.1 Test Equipment

This experiment was carried out inside a rectangular air channel made of glass with a thickness of 10 mm as shown in Figure 1. The air was inhaled by a centrifugal blower and entered through the inlet side at velocity variations of 0.4 to 2 m/s with a 0.2 m/s interval regulated by an inverter. Then, air was passed through a straightener consisting of pipes arrangement with a diameter of 5 mm and a screen for producing uniform flow. The air velocity in the channel was measured using a hot wire anemometer (Lutron type AM-4204 with an accuracy of ± 0.1) placed 30 cm in front of the straightener in the flow direction. Air was passed through a plate with/without VGs given a constant heat flux of 35 W by a heater controlled by a heater regulator. A wattmeter (Lutron DW-6060 with an accuracy of ± 1.0) was used to monitor the heat rate to the plate. Inlet, outer and plate surface temperatures were measured using K type thermocouples associated with acquisition data (Advantech USB-4718 type with an accuracy of ± 0.001) and computer CPU. Pressure drop of airflow passing the specimen was measured using pitot tubes mounted on the inlet and outlet sides of the test section. Both pitot tubes were connected

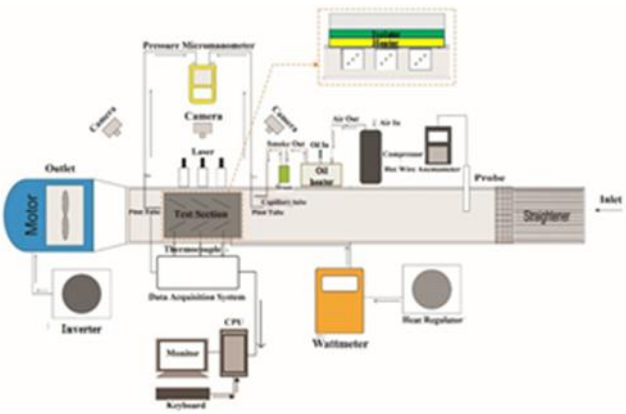


Figure 1. Experimental set-up

with a micromanometer (Fluke type 922 with an accuracy of ± 0.001) to monitor the pressure drop. In order to observe the longitudinal vortex structures generated by VGs in the flow, flow visualization was performed by injecting smoke generated from oil heated by oil heater. A compressor compressed the

DWP VG

smoke generated by the oil heater into the smoke injector mounted on the inlet side of the test specimen. Three green laser pens arranged in sequence in the direction of flow were fired on three cylinders that light up the beam into the channel to form cross-sectional areas of the stream. The two-dimensional longitudinal vortices formed by the installation of VGs were captured by this cross-sectional area.

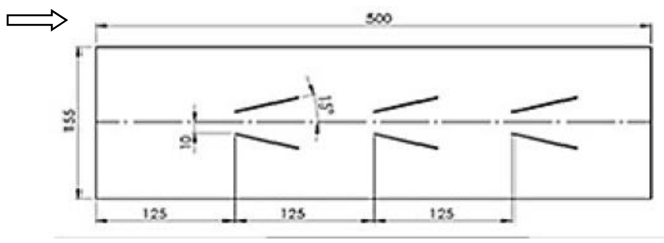
2.2 Test Sepecimen

The test specimens used in this study were delta winglet pair vortex generator (DWP VG) and concave delta winglet pair vortex generator (CDWP VG). The test specimens were mounted on an aluminum plate with a length of 500 mm, a width of 155 mm, and a thickness of 1 mm. The flow configuration used was common flow down (CFD) with the distance between the leading edge was 20 mm. The angle of attack was the angle between the main flow and the leading edge of VG was determined 15° as expressed in Figure 2. Figure 3 shows the test specimens of perforated DWP and CDWP VGs mounted on aluminum plate with variations of one, two, and three pairs of VGs.

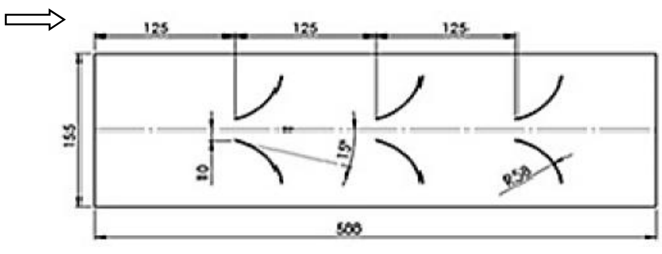
2.3 Test Procedure

In order to evaluate the thermal performance, the inlet (a thermocouple installed on a hot wire system), outlet, and surface temperature of the plate (test section) were measured using a K type thermocouple associated with data acquisition. The plate was heated at a constant heat rate of 35 W using a heater located behind the test plate and the rear surface was isolated as shown in Figure 1. A heater regulator was used to control the rate of heat transfer issued by the heater. The test specimens were heated to a steady temperature of 54°C-55°C. After steady condition was reached, testing begun by turning on the blower and adjusting the frequency of the inverter until the readings of the airflow velocity on the hot wire anemometer reach the desired velocity. The flow velocity range in this test is 0.4 m/s up to 2.0 m/s with an interval of 0.2 m/s.

For hydraulic performance testing, pressure drop measurements were performed by monitoring pressure on the inlet and outlet sides of the test specimen in the test section. Two pitot tubes were placed on the inlet and outlet sides of the test section. Both pitot tubes were connected with a micromanometer to read pressure drop. The pressure drop data was recorded 30 times with 5-second intervals at any velocity variation.



DWP VG



CDWP VG

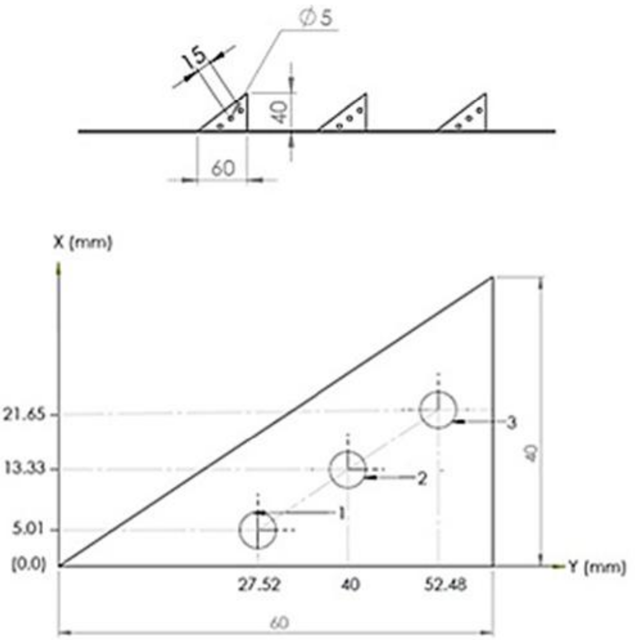


Figure 2. Detail geometry of perforated concave and plain delta winglet vortex generators

The flow visualization test was performed by monitoring the flow that was injected by the smoke from the oil. This smoke was obtained by heating the oil using a heater and the smoke was pumped by a compressor into the channel through the smoke injector located in the inlet of the test section. In order to observe the longitudinal vortex (LV) structure in the flow, three green laser pens were arranged in a flow direction. The laser beam was refracted by using a transparent cylinder to form the cross-sectional area of the flow to which the LV was captured.

3. Results and Discussion

Experimental results and several previous studies can be concluded that the use of a vortex generator increases the rate of heat transfer but is followed by an increase in pressure drop as well. Some parameters that influence heat transfer and flow pressure drop inside the channel in this study are geometry, location, angle of attack, arrangement (inline or staggered), number of pairs, and number of holes from vortex generator. However, the results of the present study are focused on discussing the effect of variation on the number of pairs and the number of vortex generators at an attack angle of 15°. The convection heat transfer coefficient and pressure drop were determined using correlation as revealed in Ref. [13].

3.1 Effect of the Concave and Plain Delta Winglet Vortex Generators on Heat Transfer

Figures 3 (a) to (c) show the comparison of heat transfer coefficients due to the installation of one row of concave and plain delta winglet VGs. From Figure 3 (a) it is observed that the heat transfer coefficient increases with the increase of the Reynolds number. This is because the fluid is more turbulent as the Reynolds number increases [20]. In general, the use of CDWP VGs results in higher improvement of heat transfer than that of DWP VGs.

This is because the LV radius of the CDWP is greater than the DWP as a result of the instability of the centrifugal force [15]. The heat transfer coefficient was found to be slightly different at a flow rate lower than 1.4 m/s. With a larger velocity of 1.4 m/s, CDWP with/without holes shows a higher heat transfer coefficient than that of DWP VGs as denoted in Figure 3(a). The use of CDWP VGs causes an increase in heat transfer coefficient of about 12.6% higher than DWP VGs or an increase of 32.9% from baseline (without VG) for the case without hole at the flow velocity of 2 m/s. The value of heat transfer coefficient for perforated CDWP VGs cases was increased by 32.5% from the baseline case at 2 m/s. This heat transfer improvement is slightly decreased compared to the use of CDWP VGs.

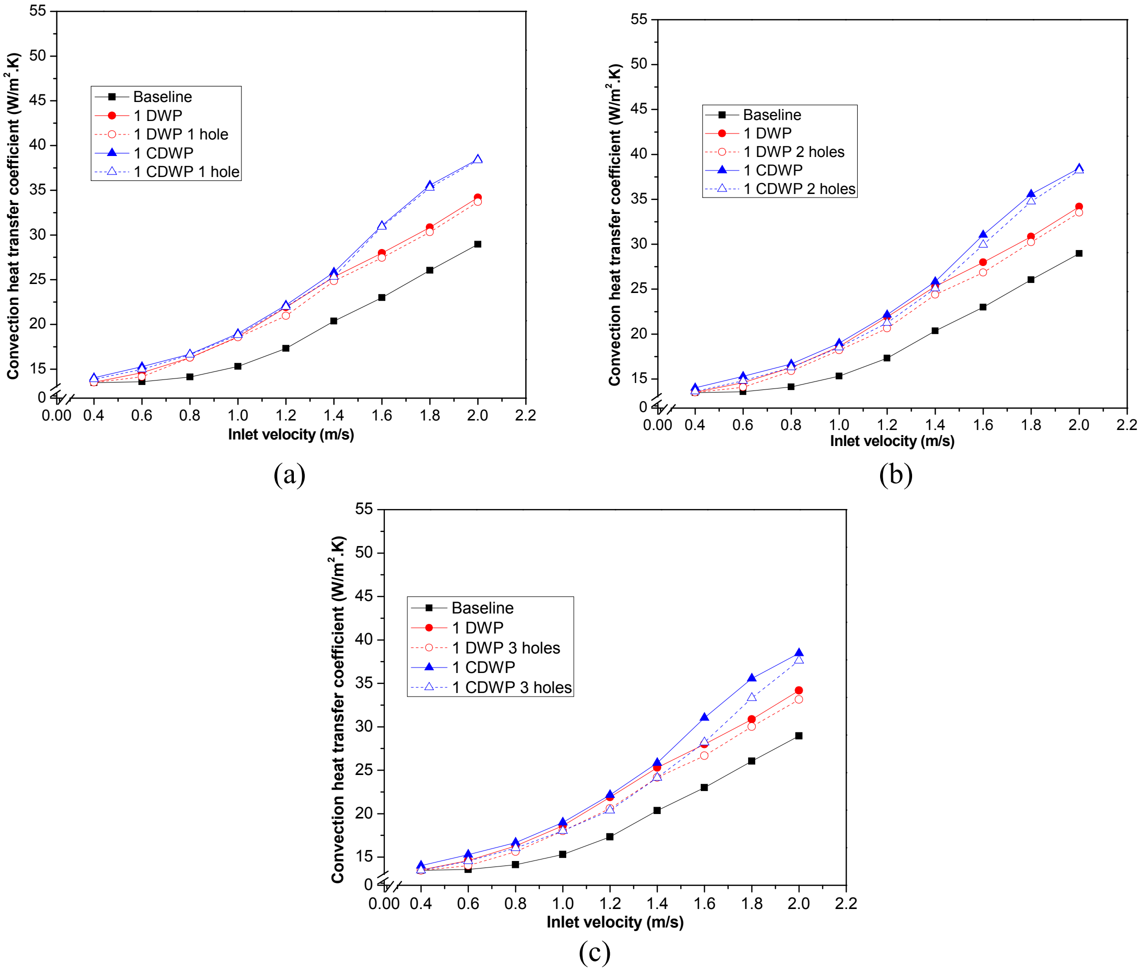
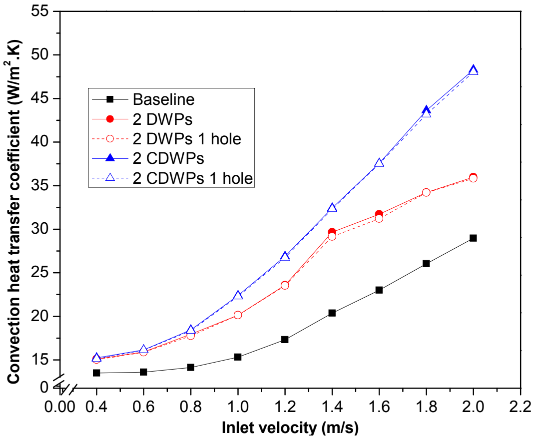


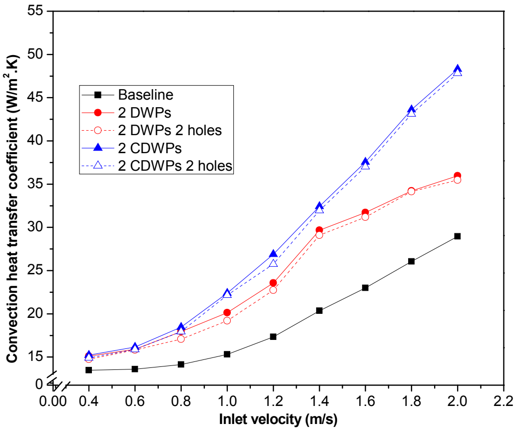
Figure 3. Convection heat transfer coefficient for plate mounted by one pair of VGs with (a) one hole, (b) two holes and (c) three holes

With two holes in the VGs, a similar tendency is found for the heat transfer augmentation as shown in Figure 3(b). A high increase of heat transfer coefficients is found on the use of CDWP VGs with/without holes at velocities above 1.4 m/s. The highest increase of heat transfer coefficient is observed for the use of CDWP VGs without holes compared to the baseline, which is about 32.9%. In the presence of two holes in VGs at 2 m/s, the heat transfer coefficient is slightly lower at 1.9% and 0.7% from CDWP and DWP VGs without holes, respectively. Significant increase in heat transfer coefficients are found on the use of CDWP VGs with/without holes at flow velocities greater than 1.4 m/s.

Figure 3(c) describes the heat transfer coefficient for the baseline, one pair of CDW and DW VGs without/with three holes at various flow velocities. From this figure it is also observed that the heat transfer coefficient is increased against the flow velocity for all cases. Three holes on CDWP VGs contribute to a 2.2% reduction in the heat transfer coefficient of CDWP VGs at the highest velocity. While the addition of three holes on the DWP VGs decreases the heat removal coefficient of 3.1% of DWP VGs without holes at a velocity of 2 m/s.



(a)



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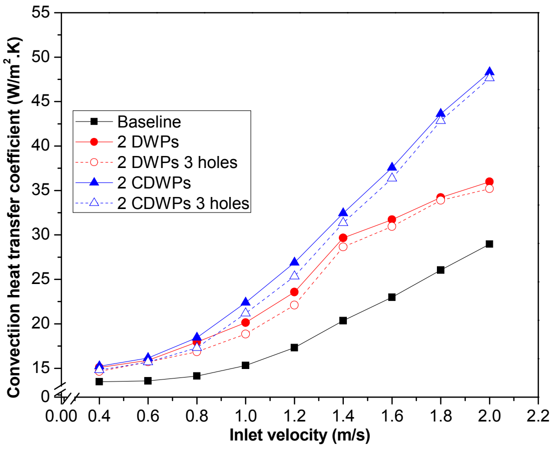


(c)

Figure 4. Convection heat transfer coefficient for plate mounted by two pairs of VGs with (a) one hole, (b) two holes and (c) three holes

Figures 4 (a) to (c) show the value of the heat transfer coefficient by the installation of two pairs of CDW and DW VGs with/without holes at various flow velocities. From Figure 4 (a) it can be described that the heat transfer coefficient increases with increasing flow velocity for all cases. Comparing Figures 4 (a) and 3 (a), the addition of VGs pairs may increase heat transfer because stronger LVs are formed in the downstream on the second and third rows of VGs [18]. The heat transfer coefficient increases sharply at velocities above 0.8 m/s as expressed in Figure 4(a). This indicates that the improvement of heat transfer increases significantly by mounting VGs at velocities greater than 0.8 m/s. The highest heat transfer improvement is 66.8% of the baseline observed for the case using CDWP VGs without the hole at a velocity of 2 m/s. While the use of DWP VGs without hole enhances the 24.2% heat transfer from the baseline at the same velocity. By adding one hole on the VGs the heat transfer coefficient value decreases slightly by 0.4% and 0.5% for the use of DWP and CDWP VGs, respectively.

Figure 4 (b) describes heat transfer augmentations through the use of two pairs of CDW and DW VGs without/with two holes. By comparing Figures 4 (b) and (a), a similar tendency for improvement of heat transfer is found. The sharp rise of the heat transfer coefficient is found above the velocity of 0.8 m/s through the installation of CDWP and DWP VGs. The use of CDWP VGs without and with two holes at the highest velocity provides an increase in heat transfer coefficient of 66.8% and 65.2% of the baseline, respectively. While the installation of DWP VGs without and with two holes enhances the heat transfer coefficients of 24.2% and 22.5% of the baseline, respectively, at the same velocity of 2 m/s.

This explains that the holes effect of VGs is not having a significant impact on changes in heat transfer coefficient generated by VGs without holes.

Figure 4 (c) shows heat transfer augmentation using CDWP and DWP VGs without/with three holes. The same things as described in Figures 4 (a) and (b) are also found in Figure 4(c) in which the baseline is used as a reference to evaluate the increase in heat transfer resulted by the installation of VGs. The heat transfer coefficient increases significantly with the use of VGs after a velocity of 0.6 m/s especially in the case of CDWP VGs with/without holes. By installing two pairs of CDW VGs with three holes on the heated plate, the heat transfer coefficient increases 64.5% from the baseline at a velocity of 2 m/s. This value is 35.4% higher than using two pairs of three-hole DW VGs at a velocity of 2 m/s.

Figure 5 shows the heat transfer coefficient by installing three pairs of CDW and DW VGs for one to three holes. From Figure 5 (a) it is clearly observed that CDWP VGs are able to improve heat transfer better than DWP VGs. By comparing Figures 5 (a) and 4 (a) it is found that the addition of the number of VGs pairs enhances the heat transfer coefficient because of the stronger vortices formed in the downstream of VGs. The use of three pairs of CDW VGs with one hole increases the heat transfer coefficient by up to 78.9% of the baseline at a velocity of 2 m/s. While the use of three pairs of DW VGs with one hole increases the heat transfer coefficient of up to 40.6% of the baseline at a velocity of 2 m/s. This shows that the use of concave VGs enhances better heat transfer than plain VGs.

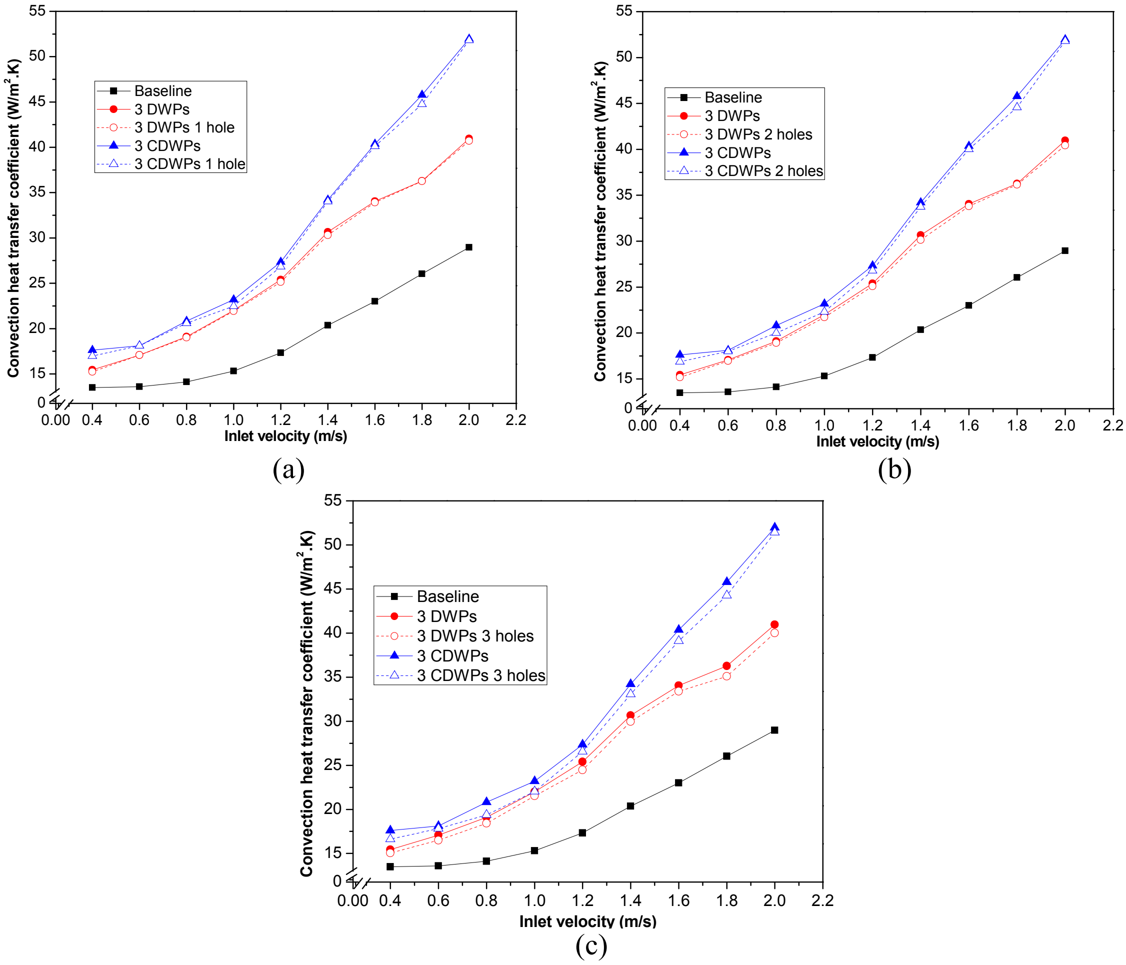


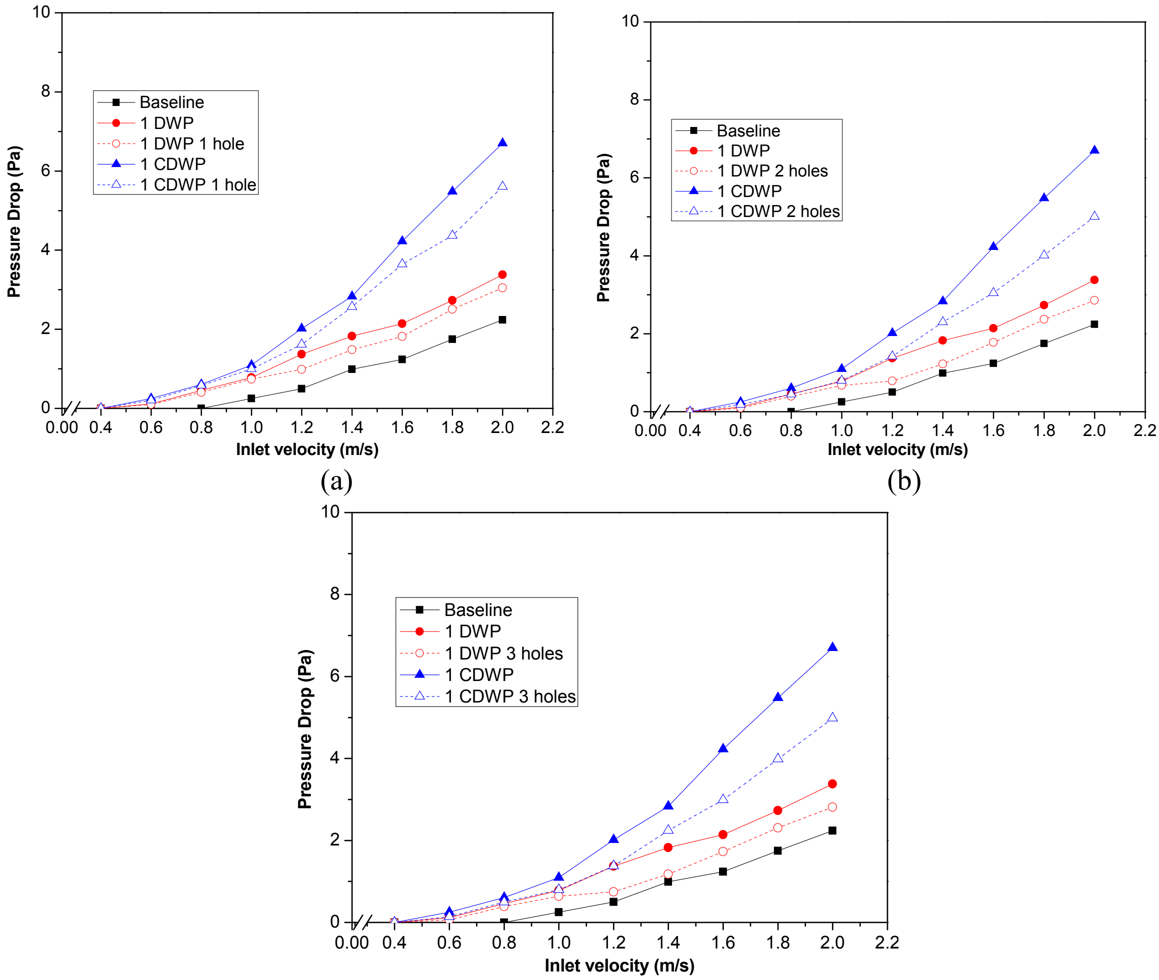
Figure 5. Convection heat transfer coefficient for plate mounted by three pairs of VGs with (a) one hole, (b) two holes and (c) three holes

An increase in the nearly equal heat transfer coefficient is observed by assigning two holes to the VGs as expressed in Figure 5 (b). At the lowest velocity, the use of three pairs of CDWP VGs with two holes provides an incentive for 25.2% heat transfer improvement against the baseline. While at the highest velocity of 2 m/s, the installation of three pairs of CDW VGs with two holes can enhance heat transfer up to 78.8% of the baseline. At this highest velocity, three pairs of DW VGs with two holes can only increase heat transfer by 39.6% to the baseline.

The use of three pairs of CDW VGs with three holes results in a slightly lower heat transfer improvement compared to the two holes as shown in Figure 5(c). At a velocity of 2 m/s, the heat transfer coefficient increases by 77.5% from the baseline. Likewise, with the use of three pairs of DW VGs with three holes, the heat transfer coefficient increases 38.2% to the baseline at a velocity of 2 m/s.

3.2 Effect of the Concave and Plain Delta Winglet Vortex Generators on Pressure Drop

Figure 6 shows the pressure drop value with the presence of CDWP and DWP VGs with/without holes. Figure 6 (a) shows the comparison of pressure drop values for baseline, one pair of CDW and DW VGs with one hole cases. From Figure 6 (a) to (c) it can be revealed that the pressure drop increases with increasing flow velocity in the channel for all cases. This is due to an increase in the formed drag when the flow velocity increases [15]. At the same flow velocity, insertion of VGs results in an increase in pressure drop due to the increasing flow resistance [20]. From the study results show that the use of CDW VGs produces a larger pressure drop compared to DW VGs at the same velocity. This is due to the wider cross flow surface of CDW VGs compared to DW VG as well as the interaction between stronger LV generated by CDW and main flow resulting in increased pressure drop [15, 21].



(a) (b) (c)

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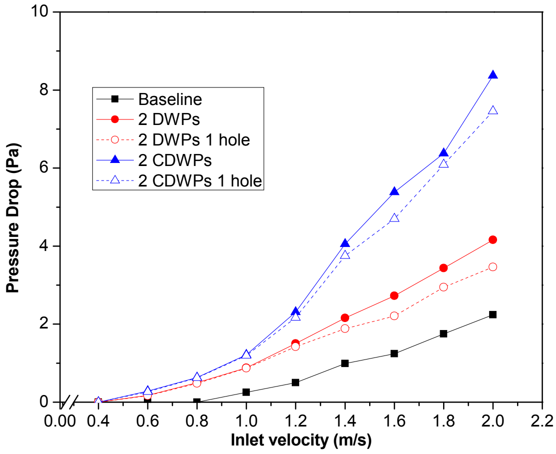
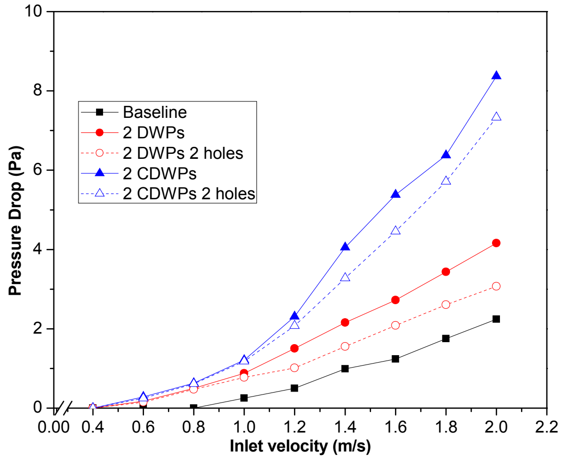
Figure 6. Pressure drop for plate mounted by one pair of VGs with (a) one hole, (b) two holes and (c) three holes

With one hole in one pair DW VGs can reduce the 9.8% pressure drop from the one without a hole at a velocity of 2 m/s as shown in Figure 6(a). In the same condition, the use of one pair of CDW VGs with one hole can reduce pressure drop by 16.4% from those without holes. This indicates that the effect of the hole on the decrease in pressure drop is more significant in the case of CDW VGs than the DW VGs. At low velocities, the impact of holes in VG on the pressure drop is not significant as denoted in Figures 6 (a) to (c). For the cases of DW and CDW VGs with two holes, the pressure drop is reduced up to 15.5% and 25.3%, respectively, from those without holes at a velocity of 2 m/s as can be seen in Figure 6 (b). Pressure drop can be lowered up to 16.7% and 25.7% of one without hole at a velocity of 2 m/s, respectively for DW and CDW VGs as expressed in Figure 6(c).



(a)



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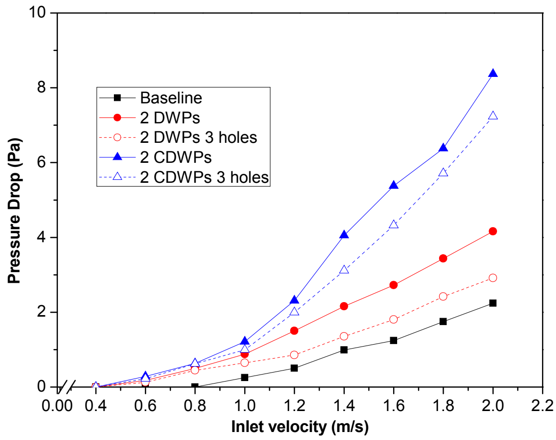

(c)

Figure 7. Pressure drop for plate mounted by two pairs of VGs with (a) one hole, (b) two holes and (c) three holes

Conversely, a decrease in pressure drop is found to be greater in the case of two pairs of DW VGs with one hole compared to two pairs of CDW VGs with one hole, which is 16.8% with 10.9% at a velocity of 2 m/s as shown in Figure 7(a). Similar tendencies are also shown in Figure 7 (b) that the pressure drop values for two pairs of DW and CDW VGs with two holes decreases 26.2% and 12.4% against the no-hole at the highest velocity, respectively. The greater the number of VG rows causes an increase in pressure drop due to the form drag of VGs [4]. Similar results are also observed in the case of two pairs of VGs with three holes, pressure drop on perforated DW VGs use decreased by 42.7% and perforated

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Figure 8. Pressure drop for plate mounted by three pairs of VGs with (a) one hole, (b) two holes and (c) three holes

CDW VGs decreased by 15.7% against DW and CDW VGs without holes, respectively, as denoted in Figure 7(c).

Figures 8 (a) to (c) show pressure losses from flow due to the installation of three pairs of DW and CDW VGs without/with three holes. The increase in pressure drop with the installation of three pairs of DW and CDW VG against the baseline is found 1.7 and 5.9 times at a velocity of 2 m/s as expressed in Figure 8(a). This is triggered by the stronger the longitudinal vortices that are formed resulting in a higher drag form. The addition of one hole in DWP and CDWP VGs is only able to reduce pressure drop by 15.7% and 3.4% from VGs without holes, respectively, as can be seen in Figure 8(b). By giving two holes to VGs, the pressure drop can be reduced to 19.9% and 7.7% from without holes for DWP and CDWP VGs, respectively, as expressed by Figure 8(c). While the three holes in VG results in a decrease in pressure drop by 35.4% and 11.6% of the three pairs of DW and CDW VGs without holes, respectively.

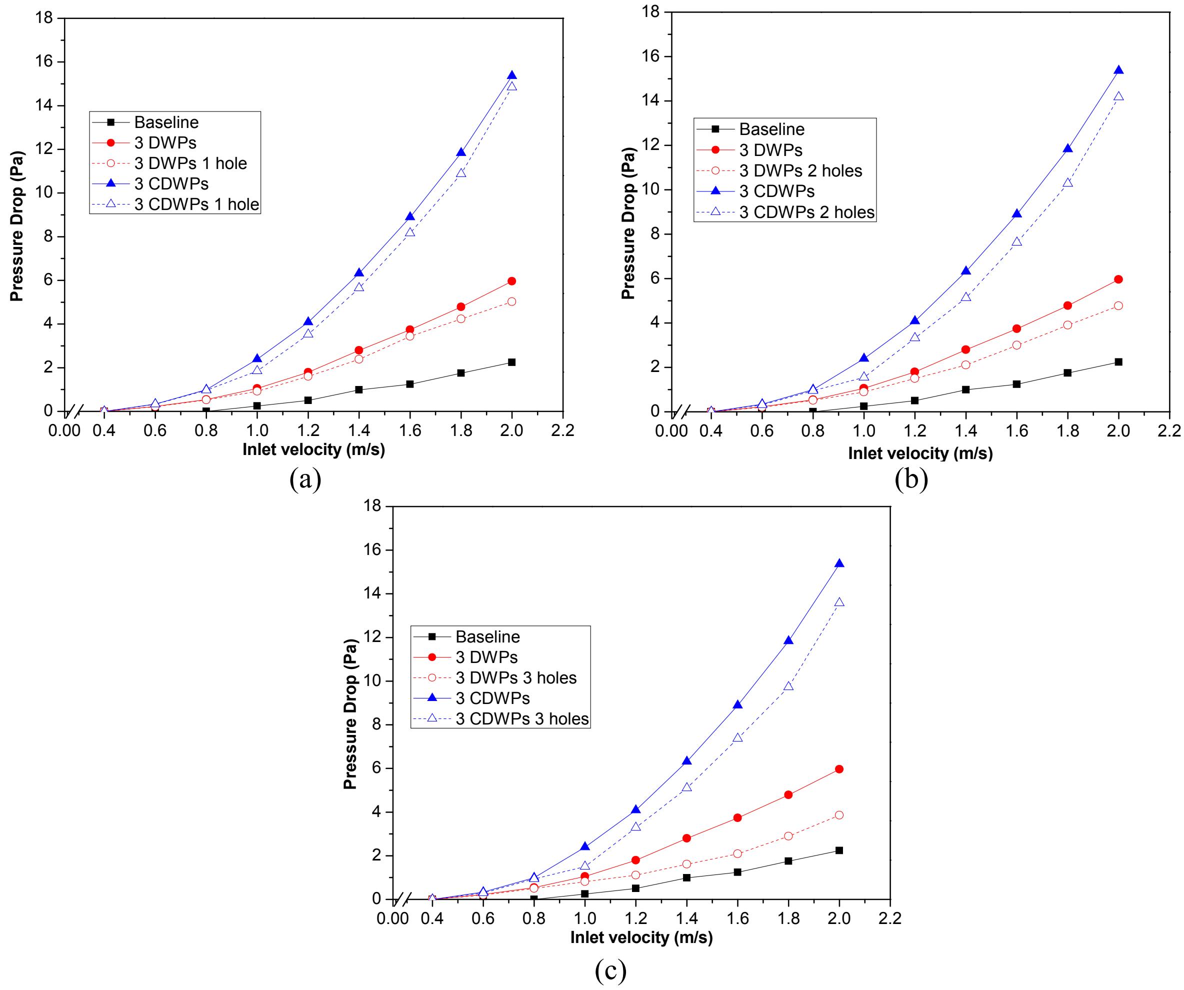
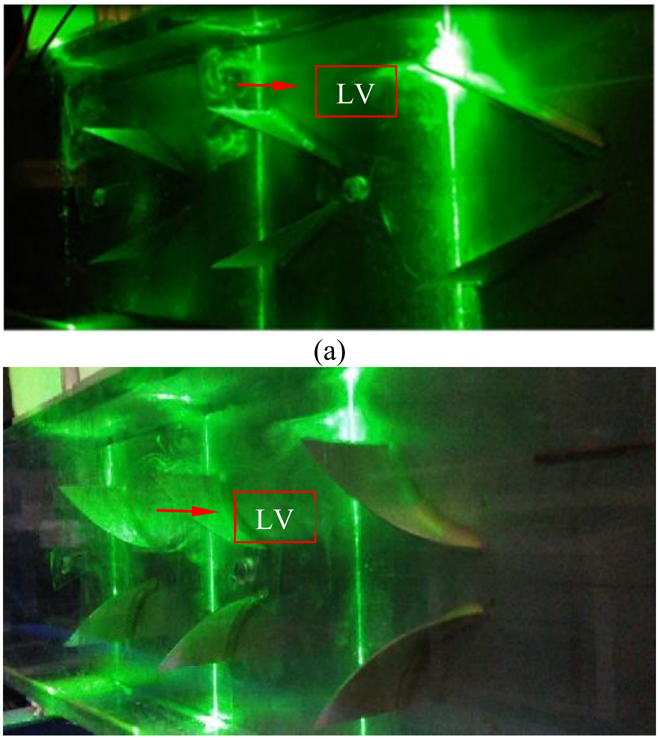


Figure 8. Pressure drop for plate mounted by three pairs of VGs with (a) one hole, (b) two holes and (c) three holes

3.3 Longitudinal vortex visualization in rectangular channel

Figure 9 (a) and (b) show the visualization of longitudinal vortices formed in the downstream of three pairs of DW and CDW VGs. Longitudinal vortices form in the wake area of DWP VGs as can be seen in Figure 9 (a). The number of longitudinal vortices formed in the wake area causes better fluid mixing in the area which leads to an increase in local heat transfer. By installing CDWP VGs, longitudinal vortices formed in the wake area have a larger radius than those formed by DWP VGs as denoted in

Figure 9(b). This indicates that the increase in heat transfer rate due to installation of CDWP VGs is higher than that of the installation of DWP VGs.



(b)

Figure 9. Flow visualization of longitudinal vortex generated (a) DWP, (b) CDWP VGs

4. Conclusion

Experimental studies of perforated delta winglet concave effects on thermal and hydraulic performance have been carried out. Installation of vortex generators had a good impact on the improvement of heat transfer. However, the use of vortex generators was also accompanied by an increase in pressure drop. Hole in vortex generators can reduce pressure drop by 35% for DWP VGs and 17% for CDWP VGs. Longitudinal vortices generated from CDWP VGs were greater than those generated by DWP VGs based on visualization results.

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References

[1] J.M. Wu and W.Q. Tao, "Numerical study on laminar convection heat transfer in a rectangular channel with longitudinal vortex generator. Part A: Verification of field synergy principle", International Journal of Heat and Mass Transfer, vol. 51, 2008, pp. 1179–1191, doi: 10.1016/j.ijheatmasstransfer.2007.03.032.

[2] J.M. Wu and W.Q. Tao, "Numerical study on laminar convection heat transfer in a rectangular channel with longitudinal vortex generator. Part B: Parametric study of major influence factors", International Journal of Heat and Mass Transfer, vol. 51, 2008, pp. 3683–3692, doi: 10.1016/j.ijheatmasstransfer.2007.03.031.

[3] A. Joardar and A.M. Jacobi, "Heat transfer enhancement by winglet-type vortex generator arrays in compact plain-fin-and-tube heat exchangers", International Journal of Refrigeration, vol.

31, 2008, pp. 87–97, doi: 10.1016/j.ijrefrig.2007.04.011.

[4] Ya-Ling He, Pan Chu, Wen-Quan Tao, Yu-Wen Zhang and Tao Xie, "Analysis of heat transfer and pressure drop for fin-and-tube heat exchangers with rectangular winglet-type vortex generators", Applied Thermal Engineering, vol. 61, 2013, pp. 770-783, doi: 10.1016/j.applthermaleng.2012.02.040.

[5] Pankaj Saha, Gautam Biswas and Subrata Sarkar, "Comparison of winglet-type vortex generators periodically deployed in a plate-fin heat exchanger – A synergy based analysis", International Journal of Heat and Mass Transfer, vol. 74, 2014, pp. 292–305, doi: 10.1016/j.ijheatmasstransfer.2014.03.015.

[6] Guobing Zhou and Zhizheng Feng, "Experimental investigations of heat transfer enhancement by plane and curved winglet type vortex generators with punched holes", International Journal of Thermal Sciences, vol. 78, 2014, pp. 26-35, doi: 10.1016/j.ijthermalsci.2013.11.010.

[7] M. Khoshvaght-Aliabadi, O. Sartipzadeh and A. Alizadeh, "An experimental study on vortex-generator insert with different arrangements of delta-winglets", Energy, vol. 82, 2015, pp. 629-639, doi: 10.1016/j.energy.2015.01.072.

[8] P.S.B. Zdanski, D. Pauli and F.A.L. Dauner, "Effects of delta winglet vortex generators on flow of air over in-line tube bank: A new empirical correlation for heat transfer prediction", International Communications in Heat and Mass Transfer, vol. 67, 2015, pp. 89–96, doi: 10.1016/j.icheatmasstransfer.2015.07.010.

[9] Syaiful, Rochman Jalil, Imam Hambali and Myung-whan Bae, "Numerical Simulation of Concave Delta Winglet Vortex Generator Effect on Heat Transfer Augmentation in Airflow inside A Channel", Proceedings of the Seventh International Symposium on Mechanics, Aerospace and Informatics Engineering 2015 (ISMAI10), Sep. 2015.

[10] Syaiful, Geny Reviansyah and Myung-whan Bae, "Attack Angle Effect of Concave Delta WInglet Vortex Generator on Heat Transfer Augmentation in Fin-and-Tube Heat Exchanger for EGR Cooler Application by Numerical Simulation", FISITA 2016 World Automotive Congress, Sep. 2016.

[11] L.H. Tang, W.X. Chu, N. Ahmed and M. Zeng, "A new configuration of winglet longitudinal vortex generator to enhance heat transfer in a rectangular channel", Applied Thermal Engineering, vol. 104, 2016, pp. 74–84, doi: 10.1016/j.applthermaleng.2016.05.056.

[12] Babak Lotfi, Bengt Sundén and Qiuwang Wang, "An investigation of the thermo-hydraulic performance of the smooth wavy fin-and-elliptical tube heat exchangers utilizing new type vortex generators", Applied Energy, vol. 162, 2016, pp. 1282–1302, doi: 10.1016/j.apenergy.2015.07.065.

[13] Syaiful, Gladys Sugiri, Maria F. Soetanto, and Myung-whan Bae, "Effect of concave rectangular winglet vortex generator on convection coefficient of heat transfer", American Institute of Physics (AIP), 1788, 030025, 2017, doi: 10.1063/1.4968278

[14] Hung-Yi Li, Wan-Rong Liao, Tian-Yang Li and Yan-Zuo Chang, "Application of vortex generators to heat transfer enhancement of a pin-fin heat sink", International Journal of Heat and Mass Transfer, vol. 112, 2017, pp. 940–949, doi: 10.1016/j.ijheatmasstransfer.2017.05.032.

[15] Syaiful, Astrid Ayutasari, Maria F. Soetanto, Ahmad Indra Siswantara and Myung-whan Bae, "Thermo-Hydrodynamic Performance Analysis of Fluid Flow through Concave Delta Winglet Vortex Generators by Numerical Simulation", International Journal of Technology, vol. 8, 2017, pp. 1276-1285, doi: 10.14716/ijtech.v8i7.706.

[16] M.J. Li, H. Zhang, J. Zhang, Y.T. Mu, E. Tian, D. Dan, X.D. Zhang and W.Q. Tao, "Experimental and numerical study and comparison of performance for wavy fin and a plain fin with radiantly arranged winglets around each tube in fin-and-tube heat exchangers", Applied Thermal Engineering, vol. 133, 2018, pp. 298–307, doi: 10.1016/j.applthermaleng.2018.01.012.

[17] Syaiful, Imam Syarifudin, Maria F. Soetanto and Myung-whan Bae, "Numerical simulation of heat transfer augmentation in fin-and-tube heat exchanger with various number of rows of

concave rectangular winglet vortex generator", MATEC Web of Conferences, 159, 02012, 2018, doi: 10.1051/matecconf/201815902012.

[18] Syaiful, M. S. K. Tony S. U., Agus Saryanto, and Myung-Whan Bae, "Improvement of hydrodynamic performance of heated plate mounted by perforated concave delta winglet vortex generator in airflow channel: An experimental study", AIP Conference Proceedings, 1983, 020004, 2018, doi: 10.1063/1.5046200.

[19] Syaiful, Bambang Yunianto, Agus Saryanto, and Myung-Whan Bae, "Pressure loss penalty improvement of airflow through heated plate mounted by delta winglet vortex generator: An experimental study", AIP Conference Proceedings, 1984, 020033, 2018, doi: 10.1063/1.5046617.

[20] Y. Xu, M.D. Islam and N. Kharoua, "Experimental study of thermal performance and flow behaviour with winglet vortex generators in a circular tube", Applied Thermal Engineering, vol. 135, 2018, pp. 257–268, doi: 10.1016/j.applthermaleng.2018.01.112.

[21] Amin Ebrahimi, Ehsan Roohi and Saeid Kheradmand, "Numerical study of liquid flow and heat transfer in rectangular microchannel with longitudinal vortex generators", Applied Thermal Engineering, vol. 78, 2015, pp. 576-583, doi: 10.1016/j.applthermaleng.2014.12.006.