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Experimental investigation of perforated and non-perforated Delta Winglet pairs for heat transfer and pressure drop optimization

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Abstract

This study experimentally investigates the impact of Delta Winglet Pairs (DWPs) on heat transfer and friction factor in a rectangular duct. Configurations varied by the number of DWP pairs (one, two, and three) and the presence of perforations on the winglet. The performance was evaluated using the Nusselt number ratio (Nu/Nu_0) and friction factor ratio (f/f_0), compared to a smooth baseline. Results show that non-perforated DWPs enhanced heat transfer more effectively, with a maximum 27% higher Nusselt number than perforated ones. Increasing the number of DWP pairs improved thermal performance further, aided by higher airflow velocities that enhanced fluid mixing. In terms of pressure loss, the friction factor decreased with increasing velocity, while more DWPs increased pressure drop. Perforated DWPs reduced average friction by 47% compared to non-perforated ones, due to jet flow effects. Evaluation of the Thermal Enhancement Factor (TEF) revealed that although both configurations benefit from higher airflow, non-perforated DWPs achieved a 13.8% higher TEF than the perforated type. These results suggest that while non-perforated DWPs are optimal for maximum heat transfer, perforated DWPs offer a more favorable trade-off when pressure loss must be minimized.

Keywords:
Delta winglet pairs, friction factor, heat transfer, Nusselt number, thermal enhancement factor.

1 Introduction

Vortex Generators (VGs) have been widely used in various engineering applications to improve heat transfer, especially in systems that rely on forced convection such as heat exchangers, electronic cooling, and vehicle aerodynamics systems. Vortex generators induce longitudinal vortices that improve fluid mixing, thereby reducing wake regions and enhancing the heat transfer coefficient. For instance, simulations indicate that delta winglets can outperform other VG models, achieving notable increases in the Nusselt number (Nu) in fin-and-tube heat exchangers [1]. Experimental studies further confirm that perforated concave delta winglet VGs can increase Nu by up to 46.3% compared to baseline configurations [2]. Additionally, numerical analyses reveal that the optimal design and positioning of VGs can lead to substantial improvements in thermal performance, with specific configurations yielding thermal resistances as low as 0.98 K/W [3]. Overall, the integration of delta winglet VGs is pivotal for optimizing thermal management in high-temperature applications and compact electronic devices.

Several studies have explored the impact of vortex generators in different configurations and their effectiveness in improving thermal performance. Modifications to VG geometry, such as the inclusion of perforations, have been shown to significantly enhance heat transfer performance and fluid flow characteristics. Syaful *et al.* demonstrated that specific vortex configurations can increase the Nusselt number, a measure of heat transfer efficiency, compared to flows without VGs [4-5]. This is supported by Effendi *et al.*, who found that Perforated Concave Delta Winglet Vortex Generators (PCDWP VGs) can increase the Nusselt number by up to 46.3% in staggered arrangements compared to baseline configurations without VGs [6]. The use of perforations in VGs, such as delta winglets, is particularly effective as it reduces aerodynamic drag and enhances heat transfer efficiency by facilitating fluid interaction through the orifices. Additionally, Shukla *et al.* highlighted that different VG shapes, such as square and triangular, can optimize heat transfer depending on the Reynolds number, with square VGs performing better at lower to medium Reynolds numbers and triangular VGs excelling at higher Reynolds numbers [7]. Alqahtani *et al.* further emphasized the importance of VG shape and positioning, noting that triangular VGs with inclined back-faces significantly improve hydrodynamic performance by enhancing recirculation and flow velocity within heat exchanger channels [8]. These findings collectively underscore the potential of VG modifications, including perforations, to improve thermal performance and system efficiency in various industrial applications. However, one of the major challenges in the use of vortex generators is the increased friction factor, which can lead to a decrease in the overall energy efficiency of the system.

To address this challenge, several studies have explored modifications to the geometry of vortex generators, including the addition of perforations on their surface to reduce aerodynamic drag without sacrificing heat transfer enhancement.

The analysis of heat transfer and pressure drop characteristics in convex-louver fin-and-tube heat exchangers reveals several critical insights. Wang *et al.* found that the number of rows minimally impacts the Colburn *j* factor at Reynolds numbers below 1,000, indicating that design parameters like fin spacing and configuration are more influential at lower flow rates [9]. Additionally, Ionescu study highlighted the importance of geometric parameters, such as louver pitch and fin length, in optimizing thermal performance, particularly in applications like automotive cooling systems [10]. Furthermore, Feleke *et al.* demonstrated that variations in louver edge design significantly affect pressure drop and heat transfer efficiency, with horizontal edges yielding better performance [11]. Collectively, these findings underscore the complex interplay between design features and operational conditions in enhancing the efficiency of heat exchangers [12].

Despite the demonstrated potential of delta winglet vortex generators, limited research exists on the performance of perforated Delta Winglet Pairs (DWPs), especially in terms of pressure drop behavior and thermal enhancement under varying airflow velocities. Most previous studies have focused either on numerical analyses or on different VG shapes and arrangements, leaving a gap in experimental validation for perforated DWPs. This study aims to experimentally investigate the thermal and aerodynamic performance of perforated and non-perforated DWPs installed at a fixed 20° angle of attack in a rectangular test duct. Key performance metrics include the Nu, heat transfer enhancement ratio (Nu/Nu_0), friction factor ratio (f/f_0), and Thermal Enhancement Factor (TEF). The effect of varying the number of DWP pairs and airflow velocities is also examined. The results are expected to provide valuable insights into the trade-offs between heat transfer enhancement and pressure loss, and to evaluate the feasibility of using perforated DWPs in compact heat exchanger systems where thermal efficiency and low pressure drop are both critical.

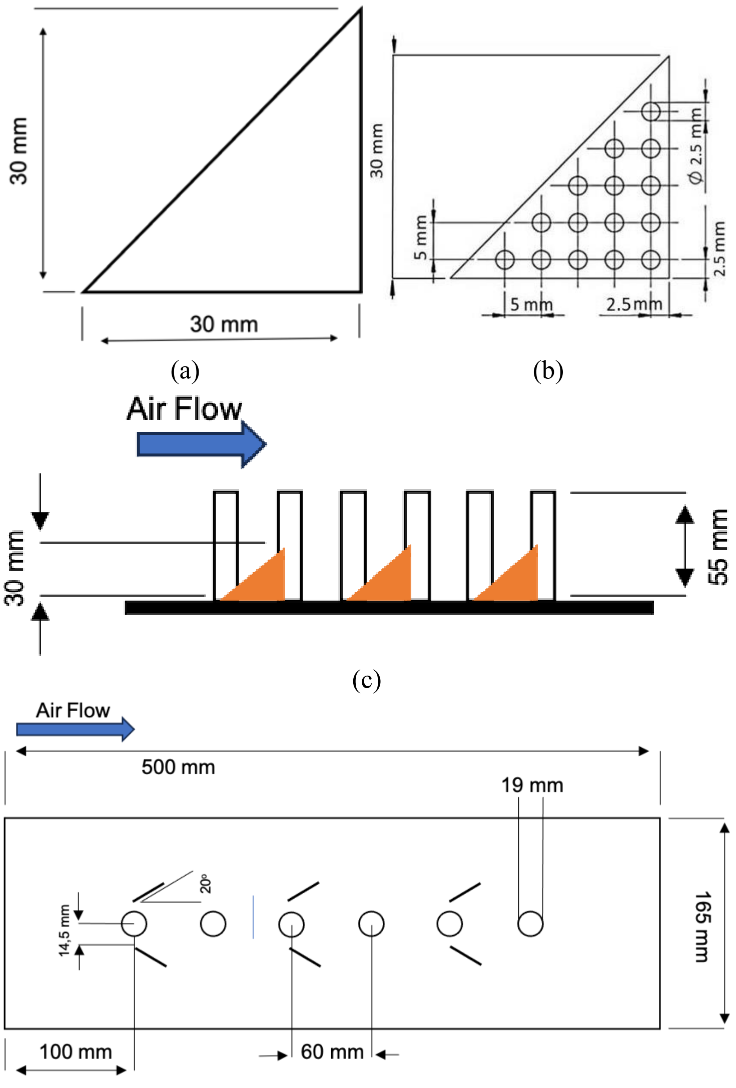
2 Methods

2.1 Test specimens

The test specimens used in this study consisted of six cylindrical tubes, each with a diameter of 19 mm and a height of 55 mm, arranged in an in-line configuration, as depicted in Fig. 1(c) and Fig. 1(d). These cylinders served as the primary heat transfer elements within the experimental setup.

To enhance heat transfer performance, VGs were integrated into the system. The VGs were mounted on aluminum fins with a thickness of 1 mm, a length of 500 mm, and a width of 165 mm. These fins provided a structural foundation for the installation of the VGs. The vortex generators were designed in the form of DWPs, which were further categorized into two types: those with perforations (holes) and those without. The VGs were positioned at an angle of attack of 20°, ensuring optimal flow interaction and turbulence generation. The angle of attack (20°) was selected based on prior studies indicating that this angle effectively balances vortex generation and pressure loss.

The study explored variations in the number of VG pairs, specifically one, two, and three pairs, all arranged in an in-line configuration. Fig. 1(a) and Fig. 1(b) illustrate the side-view representation of the test specimen incorporating DWPs with and without three pairs of holes in an in-line arrangement.



(a) (b) (c) (d)

Fig. 1. Geometry details. (a) side view of DWPs VGs, (b) side view of PDWPs VGs, (c) side view of test specimen, and (d) top view of in-line VGs.

2.2 Experimental set-up

A rectangular air duct with dimensions of 370 cm in length, 8 cm in width, and 18 cm in height, along with a hydraulic diameter of 0.0922 m, was utilized in this experiment. The duct was constructed from glass with a thickness of 1 cm. To measure temperature variations, type K thermocouples, which have an accuracy of ±0.5°C within a temperature range of 200°C to 1250°C, were installed at both the inlet and outlet of the duct. These thermocouples were connected to a data acquisition system, allowing real-time temperature recording and storage on a computer.

Air circulation within the duct was facilitated by a Wipro YS7112 blower, which was positioned at the duct's outlet. Before entering the test section, the airflow passed through pipes and a wire mesh, ensuring a more uniform velocity profile. An inverter (Mitsubishi Electric FR-D700) with a precision of 0.01 was employed to regulate the airspeed, which was varied from 0.4 m/s to 2.0 m/s in increments of 0.2 m/s. The velocity of the airflow was monitored using a Lutron AM-4204 hotwire anemometer with an accuracy of 0.1 m/s. The airflow velocity range (0.4–2.0 m/s) was chosen to represent low to moderate Reynolds number regimes, which are typical in compact heat exchangers and small-scale cooling systems such as electronics or battery thermal management. This range allows for the observation of how the vortex generators behave under varying flow conditions, from laminar to transitional flow regimes, enabling comprehensive evaluation of thermal-hydraulic performance

In the test section, the airflow interacted with six cylindrical tubes arranged in line, each subjected to a constant heat input of 40 W. Additionally, VGs were installed on the fins located on both sides of the tubes to enhance heat transfer characteristics. A Fluke 922 pressure micromanometer with an accuracy of 0.05 was integrated with a Pitot tube at the inlet and exit of the test section to monitor the pressure drop across the setup. Fig. 2 provides a schematic diagram illustrating the experimental apparatus.

2.3 Testing parameters

In this study, various parameters were used to evaluate heat transfer performance and fluid flow characteristics within the system. The analysis focused on the Nusselt number Nu/Nu_0, pressure drop (ΔP), friction factor (f/f_0), and TEF. These parameters were assessed to determine the effectiveness of VGs in enhancing heat transfer while also considering their impact on airflow resistance.

2.3.1 Nusselt number

The Nusselt number represents the ratio of convective to conductive heat transfer in a fluid. It is a crucial parameter in assessing the efficiency of heat transfer within the system. The Nusselt number is calculated using the Eq. (1).

$$Nu = \frac{h\, D_h}{\lambda} \tag{1}$$

D_h is the hydraulic diameter (m), h is the convective heat transfer coefficient (W/m²K), and λ is the thermal conductivity of air (W/mK).

2.3.2 Pressure drop

The pressure drop (ΔP) across the system was determined by measuring the difference in average pressure between the inlet and outlet of the test section. This parameter is essential for evaluating changes in flow characteristics due to the presence of VGs. The pressure drop is calculated using the Eq. (2).

$$\Delta P = \bar{P}_{in} - \bar{P}_{out} \tag{2}$$

$\bar{P}_{in}$ represents the average pressure at the inlet (Pa), and $\bar{P}_{out}$ represents the average pressure at the outlet (Pa).

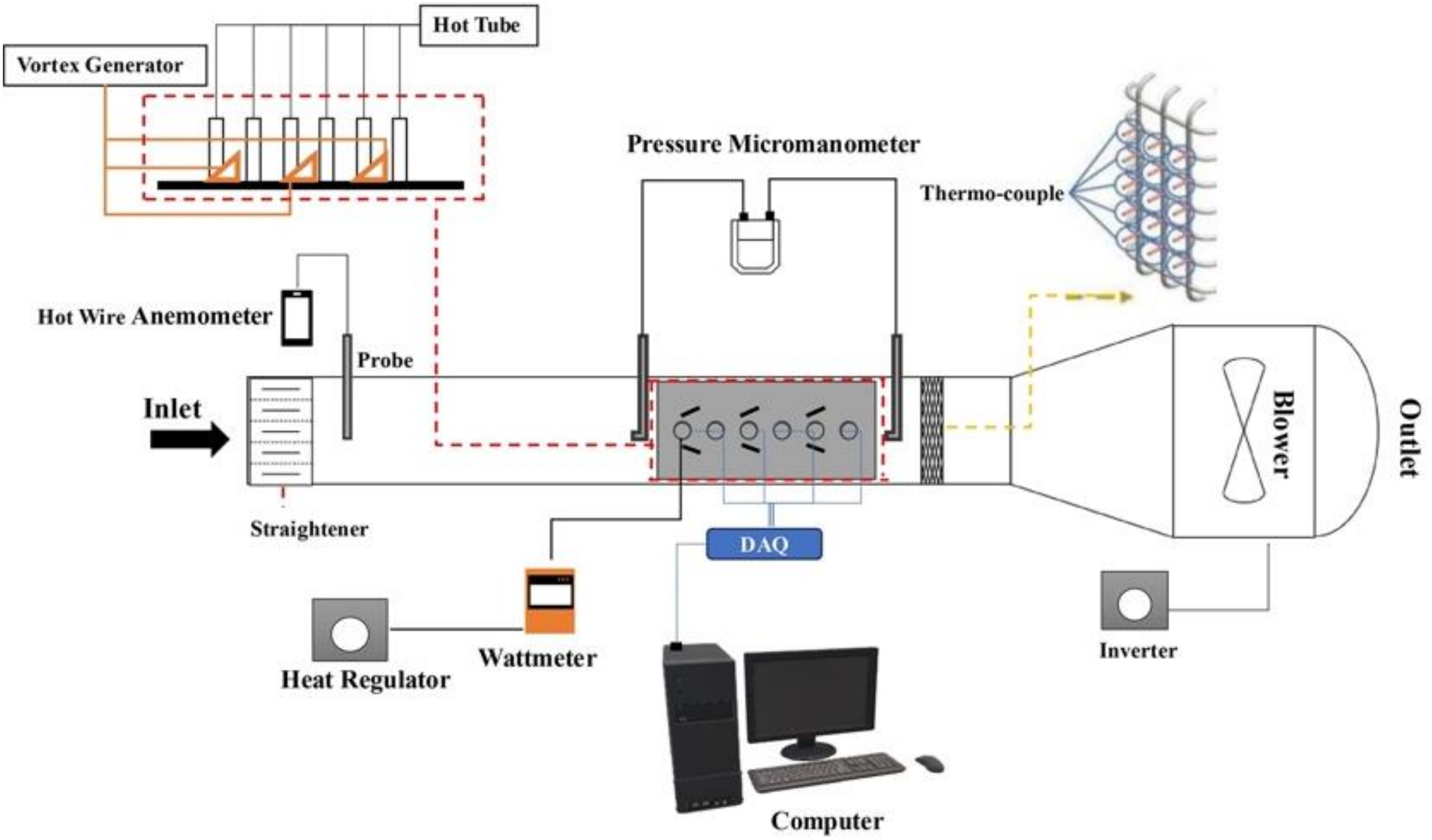


Fig. 2. Heat transfer rate and pressure drop testing scheme.

2.3.3 Friction factor

The friction factor (f/f_o) is used to quantify the resistance experienced by the airflow as it moves through the test section. It serves as an indicator of how VGs influence flow resistance. The friction factor is determined using the Eq. (3).

$$f = \frac{2\,\Delta P\, D_h}{\rho\, V^2\,(L + 6D)} \tag{3}$$

ρ is the air density (kg/m³), V is the inlet airflow velocity (m/s), and L is the length of the test specimen (m).

2.3.4 Thermal Enhancement Factor

The TEF is used to evaluate the improvement in heat transfer performance due to VGs compared to the baseline condition (without VGs). TEF is calculated using the Eq. (4). Nu_0 is the Nusselt number under baseline conditions, and f_0 is the friction factor under baseline conditions.

$$TEF = \frac{\frac{Nu}{Nu_o}}{\left(\frac{f}{f_0}\right)^{\frac{1}{3}}} \tag{4}$$

By analyzing the TEF, the effectiveness of VGs in enhancing heat transfer can be assessed, along with their impact on flow resistance. This parameter serves as a key performance metric for evaluating the thermal-hydraulic efficiency of the system.

To ensure the accuracy and clarity of the experimental analysis, it is essential to classify the variables involved in the study. Each variable plays a distinct role in influencing or responding to the experimental conditions. The variables in this experiment are categorized into four types: independent, dependent, controlled. The classification of variables used in this study is summarized in Table 1.

Table 1. The classification of variables

Type	Variable
Independent	Number of DWP pairs (1, 2, or 3), VG type (perforated vs. non-perforated), air velocity (0.4 m/s–2 m/s)
Dependent	Nu, pressure drop (ΔP), friction factor (f), TEF
Controlled	Tube dimensions, fin material and size, heat input (40 W per tube), angle of attack (20°)

3 Results and discussion

3.1 Effect of perforated delta winglet pairs on heat transfer performance

Heat transfer from the tube surface to the airflow in the duct is affected by flow characteristics, one of which is the turbulence structure. Turbulent flow can increase heat transfer significantly due to more intense fluid mixing between the near-surface layer and the main flow. One method to improve heat transfer is to install VGs on the fin. The performance evaluation of VGs in this experiment was carried out by comparing the Nusselt number of test specimens fitted with VGs against the baseline condition (without VGs).

In this study, the variations of VGs include configurations with and without holes and the number of VGs pairs, namely one, two, and three pairs. The effect of VGs installation on heat transfer was analysed in different airflow velocity ranges. The experimental results show that an increase in airflow velocity contributes to an increase in the Nusselt number for both perforated and unperforated VGs configurations.

From the test results, it is seen that the installation of VGs in the test channel effectively enhances heat transfer. This is due to the formation of the Longitudinal Vortex (LV) generated by the VGs, which promotes the mixing between the hot fluid around the tube surface and the cooler fluid in the main flow. In addition, the number of pairs of VGs installed also affects the heat transfer enhancement. The more pairs of VGs applied, the higher the Nusselt number ratio obtained.

However, compared to VGs without holes, the configuration of VGs with holes shows a lower Nusselt number ratio. This phenomenon can be explained by the presence of jet flow generated by the VGs holes, which tends to weaken the formation of longitudinal vortex. The jet flow can also reduce the stagnation area behind the VGs, which can improve the local heat transfer [13-14]. From these experimental results, it was found that the average Nusselt number of the DWP configuration without holes was 27% higher than that of the perforated DWP configuration.

Overall, the heat transfer rate increased with the increase in the number of VGs pairs and airflow velocity. This shows that the installation of VGs is an effective method in improving heat transfer efficiency, although the configuration without holes shows better performance compared to the one with holes. A key strength of this analysis lies in the systematic comparison between perforated and un-perforated DWPs over a range of velocities and VG configurations, providing a clear understanding of the thermal impact of geometric modifications. However, limitations exist, including the study's focus on in-line configurations only and the absence of numerical flow visualization to corroborate vortex structure development. Future studies can incorporate Computational Fluid Dynamics (CFD) simulations or flow visualization (e.g., smoke-wire technique or PIV) to better understand flow dynamics and validate the experimental trends.

3.2 Impact of perforations on friction factor

The friction factor is an important parameter in heat transfer analysis, especially in applications that involve increasing the heat transfer rate with the use of VGs. While VGs can improve heat transfer, their presence can also lead to increased pressure loss due to flow disturbance. Therefore, friction factor analysis becomes essential to evaluate the balance between the heat transfer enhancement and the resulting pressure penalty.

In this experiment, the friction factor was analysed for various configurations of VGs, both those with perforations and those without. The data presented in Fig. 3 shows the ratio of friction factor (f/f_o) to airflow velocity (Reynolds number) for configurations of one, two, and three pairs of VGs.

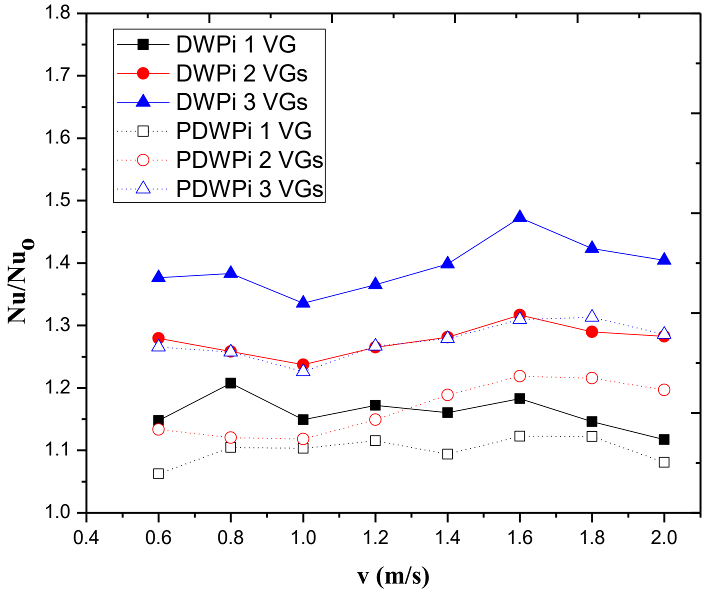


Fig. 3. Ratio of Nu/Nu_0 for the installation of one, two, and three pairs of DWP VGs, both with and without holes, in an in-line configuration under varying airflow velocities.

From the experimental results in Fig. 4, it can be seen that the friction factor decreases as the airflow velocity increases. This is because the drag effect produced by the VGs becomes smaller relative to the fluid inertial force at higher Reynolds numbers. However, the friction factor remains higher in configurations with a greater number of VGs, indicating that an increase in the number of VGs increases pressure loss.

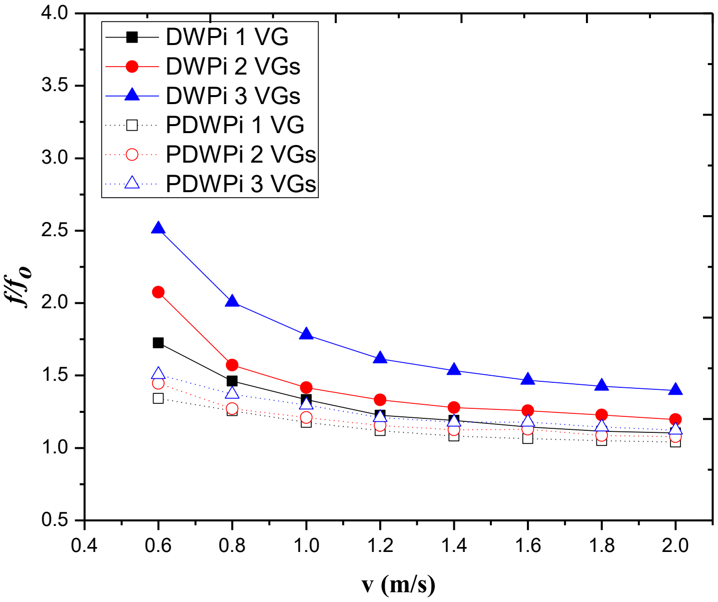


Fig. 4. Ratio of f/f_0 for the installation of one, two, and three pairs of DWP VGs, both with and without holes, in an in-line configuration under varying airflow velocities.

In addition, when comparing VGs with and without perforations, it is seen that the configuration with perforations has an average friction factor 47% lower than the configuration without perforations. This can be explained by the jet stream formed from the holes on the VGs, which helps to reduce the stagnation area behind the VGs and reduces aerodynamic drag [15, 16]. In other words, the perforations on the VGs contribute to reducing pressure loss, albeit with a slight decrease in heat transfer effectiveness compared to VGs without perforations.

Overall, the experimental results show a trade-off between heat transfer enhancement and pressure loss. Although the addition of VGs can significantly improve heat transfer, its effect on pressure loss also needs to be taken into account in the design of an optimised thermal system. The use of VGs with perforations can be a more efficient alternative to reduce the pressure penalty without sacrificing too much heat transfer performance. The study clearly delineates the heat transfer–pressure drop trade-off, a critical factor in thermal system design. However, only friction factor was measured, and further exploration of local pressure distributions and drag coefficient measurements would provide a more detailed understanding. Incorporating uncertainty analysis and error bars in figures would strengthen the conclusions.

3.3 Thermal Enhancement Factor analysis

TEF is an important parameter used to evaluate the balance between heat transfer enhancement and pressure loss enhancement due to the installation of VGs. TEF is calculated by comparing the ratio of heat transfer enhancement to the ratio of friction factor enhancement.

From the data displayed in Fig. 5, it can be seen that the TEF increases as the airflow velocity increases, especially for configurations with a greater number of VGs. This indicates that at higher airflow velocities, the effect of heat transfer enhancement is more dominant than the pressure penalty, thus maintaining thermal efficiency [17, 18].

When comparing VGs without holes (DWP) and VGs with holes (PDWP), it is seen that the TEF for the configuration without holes is 13.8% higher. This is in line with previous findings that although perforations in VGs can reduce pressure loss, their effect in improving heat transfer is not as great as VGs without holes. The study provides comprehensive data on TEF variations with configuration and flow velocity, contributing valuable insight into the optimization of VG geometry. Nevertheless, it assumes uniform inlet conditions and neglects long-term fouling or thermal fatigue effects, which may alter performance over extended operation.

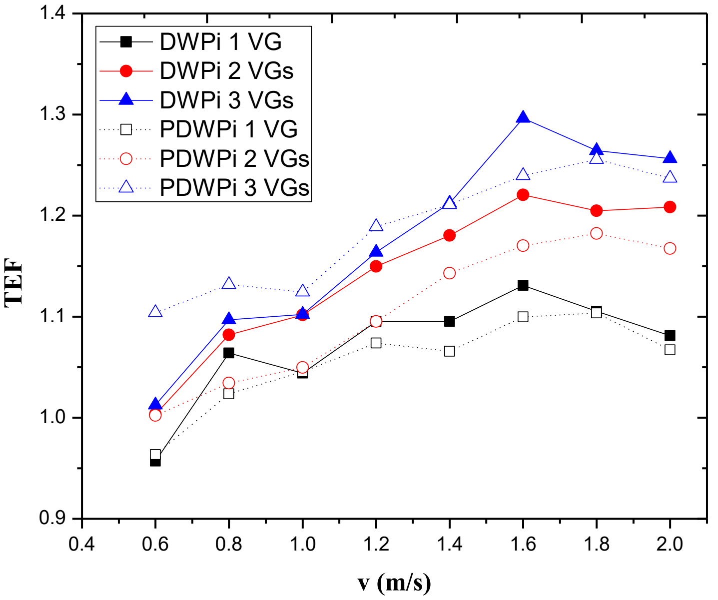


Fig. 5. TEF for the installation of one, two, and three pairs of DWP VGs, both with and without holes, in an in-line configuration under varying airflow velocities.

4 Conclusions

The study confirms that installing DWPs enhances heat transfer by generating longitudinal vortices that improve fluid mixing near the heated surface. The main conclusions are: 1) All DWP configurations significantly improved heat transfer over the smooth duct. Non-perforated DWPs yielded up to 27% higher Nusselt numbers than perforated ones. More DWP pairs and increased airflow velocity further enhanced heat transfer. 2) Higher velocities led to a decrease in the friction factor due to the dominance of inertial forces. However, adding more DWPs increased pressure loss. Notably, perforated DWPs reduced friction by an average of 47%, attributed to jet flow through the holes mitigating flow resistance. 3) TEF was improved with airflow velocity in all cases. Non-perforated DWPs had a 13.8% higher TEF than perforated ones, making them more effective for maximizing thermal performance, while perforated DWPs offer a viable solution for minimizing frictional losses. 4) These results contribute data for the design of compact, high-efficiency thermal systems. Limitations include the absence of numerical flow visualization. Future work should incorporate computational fluid dynamics validation and alternative arrangement for long-term operational analysis to optimize the design and application of vortex generators in thermal systems.

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