Volume 22 (2) 2023
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Mekanika: Majalah Ilmiah Mekanika

Effect of Hole Geometry Shape in Vortex Generators on Fluid Output Temperature: Computational Fluids Dynamics Validation

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Keywords:
Vortex generator
Computational fluid dynamics
Geometry

Abstract
Several methods to enhance heat transfer can be classified into three categories: active, passive, or hybrid. Among these methods, Vortex Generators (VGs) are one passive heat transfer enhancement device widely used in heat exchangers. This study aims to explore the geometric shapes of VGs equipped with longitudinal holes and examine their influence on the outlet temperature of the fluid. For the analysis in this research, a three-dimensional Computational Fluid Dynamics (CFD) simulation using ANSYS Fluent software was employed. The increased heat transfer and flow resistance in the VG geometry were evaluated based on previous research for validation. The study results demonstrate that the simulation produces fluid outlet temperature values and velocity contours that closely resemble the results obtained from the reference study. The validation error of this research was found to be only 0.02%, indicating high-quality and accurate simulation results. Furthermore, the study compared various geometries of the VG holes in the system. Among these geometries, hexagonal-shaped VG holes exhibited high-velocity contours on the VG side while achieving the lowest fluid outlet temperature at approximately 303.53 K. The findings of this study serve as a basis for further developments in enhancing the efficiency and performance of heat exchangers using VGs.

1 Introduction

Modern sectors such as energy, mechanical engineering, petroleum, chemical engineering, materials engineering, and metallurgy, among others, make use of improved heat transfer techniques, particularly in heat exchangers. Heat transfer augmentation methods are generally classified as active, passive, or multiple. The distinction between active and passive approach is whether or not external power is required. Surface alternatively, geometric changes made by inserts or enhancements are usually applied passively [1,2]. As a passive heat transfer enhancement device, a Vortex Generator (VG) has been widely used to promote heat transfer in heat exchangers. VG types, such as those in triangular and rectangular shapes or other combinations, are in high demand. However, despite the massive increase in heat transmission, the pressure drop remains relatively high [3,4].

https://dx.doi.org/10.20961/mekanika.v22i2.71340

Revised 25 August 2023; received in revised version 31 August 2023; Accepted 15 September 2023
Available Online 30 September 2023

2579-3144

Heat exchangers are divided into four categories as construction details: regenerators, extended surface heat exchangers, and tubular heat exchangers [5]. The plate-fin and tube-fin heat exchangers are the two most popular forms of extended surface heat exchangers. The expanded fin surface is frequently coated with VGs to boost further heat transfer. It works by reacting with and breaking the thermal barrier layer, separating the heat exchanger surface from the secondary fluid running over it. Two primary types of eddies produced are transverse and longitudinal, depending on the application and the design, size, and integration of VG devices. Longitudinal vortices frequently perform better at enhancing heat transfer than transverse vortices, with a minor increase in pressure drop [6,7]. In order to improve the heat transmission caused by the longitudinal eddies, four surface protrusion designs are often used, namely the rectangular wing, delta wing, rectangle winglet, and delta winglet, as shown in Figure 1. These VG geometric features, including their aspect ratio and angle of attack, can significantly affect how well heat transfers [8,9].

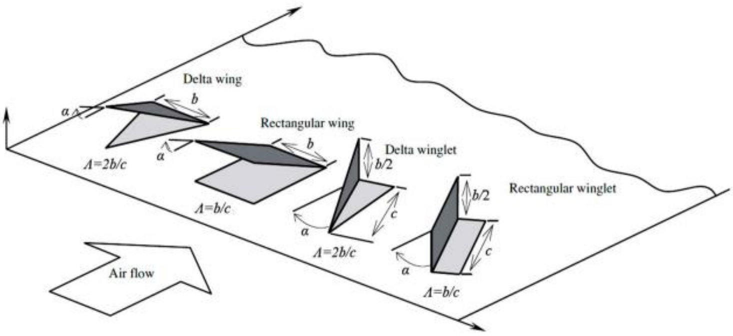


Figure 1. Model of vortex generators [10]

Besides the four main categories, other VGs have recently been suggested and researched. Specifically for use with finned tube heat exchangers, Wang et al. proposed annular wings and VG wave elements, as illustrated in Figure 2 (a) [11]. He et al. proposed using the V-deployed VG array, as shown in Figure 2 (b), to simulate animal locomotion in the wild [12]. Figure 2 (c) depicts the investigation of Zhou et al. into VG different straight and curved surface winglets with or without punched holes, including rectangular winglets, trapezoidal winglets, delta winglets, curved rectangular winglets, curved trapezoidal winglets, and curved delta winglets [13].

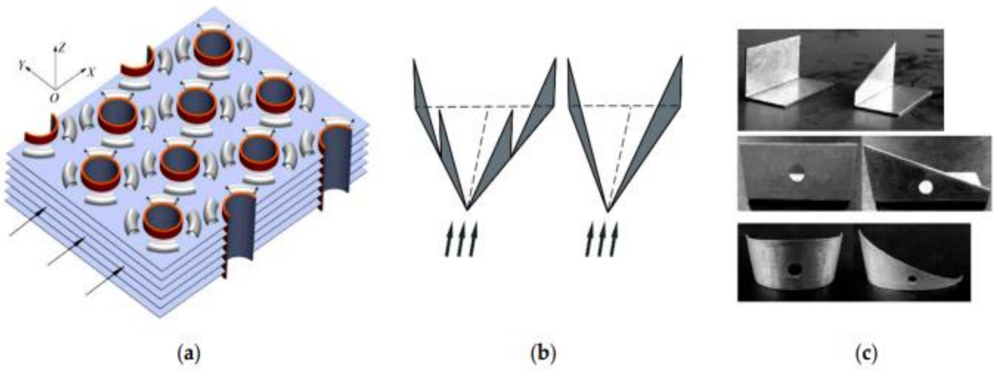


Figure 2. Latest vortex generator design [11-13]

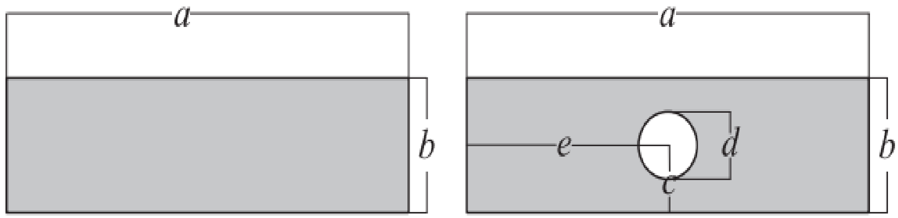
Three-row tube heat exchanger elements with delta wings were the subject of experimental research conducted by Fiebig et al. According to the findings, the friction factor has increased by 20-45% while the heat transmission augmentation has increased by 55-65% [8]. He et al. investigated how a fin-and-tube heat exchanger with a punctured winglet-type vortex generator array can improve heat transmission. He claims intermittent winglets significantly improve heat transmission, increasing the heat transfer coefficient to 33.8-70.6%. That is achieved with a pressure drop penalty ranging from 43.4 to 97.2% [12]. Han et al. studied by simulation and experiment related to adding holes in the longitudinal vortex generator. There is a difference in the temperature of the fluid output in the fluid heat transfer with the vortex generator [14]. According to the studies cited above, VG, which can produce longitudinal vortices, is frequently used to improve heat exchanger heat transfer. This study explores the geometric shape of the VG with longitudinal holes to determine its effect on the outlet temperature of the fluid research analysis using Computational Fluid Dynamics (CFD) 3D simulation using ANSYS Fluent. Validation of simulation simulations was performed based on previous research to test the validity of the simulation of increased heat transfer and flow resistance in the form of VG geometry.

2 Research Validation

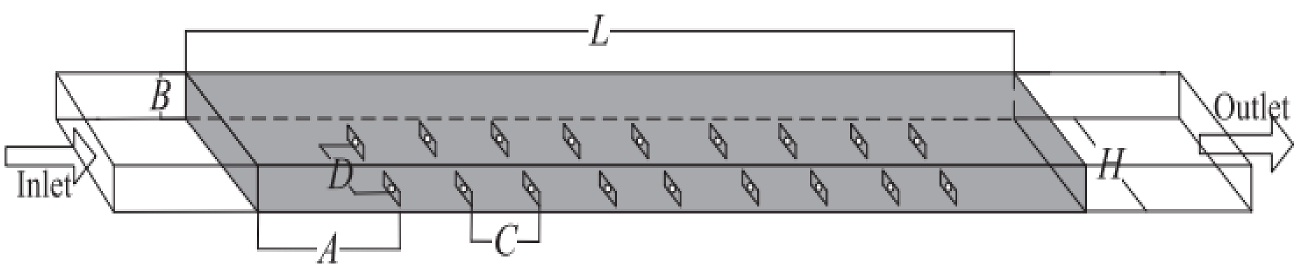
2.1 Design of vortex generators models

This study involves three-dimensional simulations in a rectangular channel. The study utilizes a heat transfer enhancement device known as Vortex Generator (VG). The VG used in the study has a length of *a* = 25 mm, height of *b* = 6 mm, and is made of aluminum. For the analysis and focus on the research's main aspects simplification, the VG winglet's thickness should be addressed in large-scale simulation experiments. It is important to note that the VG surface has holes at various locations. The diameter of these holes is *d* = 3 mm. Additionally, the width of the holes from the center to the side is *e* = 12.5 mm, while the height from the center to the bottom edge is *c* = 3 mm.

Figure 3 (a) illustrates the dimensions of the rectangular VG, both with and without holes. The simulation stages in this study are a crucial foundation for understanding the characteristics and performance of VG in enhancing heat transfer in the rectangular channel. This research can evaluate various VG configurations to optimize the VG design and enhance heat transfer efficiency by considering the dimensions of the Vortex Generator (VG), including its holes. This information can serve as a basis for further development and implementation of VG in heat exchangers and piping systems, potentially improving overall system efficiency and performance.



(a)



(b)

Figure 3. Vortex generators model design: (a) VG, and (b) System [14]

Furthermore, the simulations were conducted in a computational domain that includes winglets integrated into the channel, as depicted in Figure 3 (b). Ensuring that the fluid can form the largest jet as it exits the opening, the primary channel has dimensions of 1000 mm x 100 mm x 8.5 mm. The VGs are arranged symmetrically about the axis, with a common- flow-down arrangement, comprising two rows and nine columns with a 90° angle of attack. At position A = 140 mm from the channel inlet, the transverse distance between the leading edges of the winglet pairs with a value of D = 20 mm is measured. Additionally, there is a distance of C = 79 between the two vortex generators in the channel. These stages serve as crucial foundations in the research to understand the influence of VG and winglet geometry in enhancing heat transfer in the rectangular channel.

Comprehensive simulations in this computational domain use a series of mathematical models and specialized software to simulate in detail the behavior and performance of Vortex Generators (VG) and winglets in manipulating fluid flow and heat transfer. In these simulations, parameters such as VG and winglet geometry, fluid flow velocity, and temperature are considered to understand how VG and winglets interact with the flow and affect heat transfer. Measurements and observations are conducted at various positions within the system to validate the simulation results with experimental data. The outcomes of both the simulation and measurement processes allow researchers to analyze the effectiveness of VG and their potential for practical applications in heat exchangers. Researchers can identify more efficient designs to enhance heat transfer in heat exchangers by understanding the complex interactions between VG, winglet, and fluid flow.

2.2 Vortex generators system simulation

Pure water is used as the working fluid in the channel, and a 3D steady flow is simulated using it; the fluid characteristics are shown in Table 1. The parameters are assumed to be constant and are assumed to be incompressible. The flow may be laminar or turbulent depending on the range of Re. FLUENT offers a wide selection of turbulence models. The flow structure induced by VG has been successfully simulated using the model of the Re-Normalisation Group (RNG). Addressing the adjacent wall area, the researchers selected a better wall treatment. The computational region in this article uses the RNG turbulent and laminar models. Continuity, momentum, and the equations governing energy are satisfied in the computational domain. Assuming that body forces and viscous are neglected, the governing expression (Equations 1-4).

- Continuity equations

$$\frac{\vartheta}{\vartheta x_i}(\rho u_i) = 0 \tag{1}$$

- Momentum equation

$$\frac{\vartheta}{\vartheta x_i}(\rho u_i u_j - \mu \frac{\vartheta u_j}{\vartheta x_i}) = \frac{\vartheta P}{\vartheta x_j} \tag{2}$$

- Energy equation

$$\frac{\vartheta}{\vartheta x_i}(\rho u_i T) = \frac{\vartheta P}{\vartheta x_i}\left(\frac{k}{C_p}\frac{\vartheta T}{\vartheta x_i}\right) \tag{3}$$

- Reynolds Number

$$Re = \frac{uD}{V} \tag{4}$$

Table 1. Material characteristics [15]

Material	**Density (kg/m3)**	**Specific Heat (J/kgK)**	**Thermal Conductivity (W/mK)**	**Viscosity (kg/ms)**
Water	998.2	4182	0.6	0.001003
aluminum	2719	871	202.4	

The fluid enters the channel at a uniform velocity and constant temperature because the inlet boundary condition in the simulation process is velocity inlet. Tin is 299.5 K, and the inflow velocity is 0.1-0.5 m/s, translating to a Reynolds number between 1400 and 2400. The outflow limit condition is set to the outlet. The surface temperature of the bottom wall of the main section of the channel is set at Tw = 318 K. This analysis assumes that the existing wall and the enlarged section wall are adiabatic, meaning there is no heat exchange through these walls. It implies that the heat generated by the fluid flow will not be absorbed or released by these walls. This assumption simplifies the mathematical model and allows researchers to concentrate on the vortex generator influence on the flow and heat transfer within the system.

2.3 Validation method

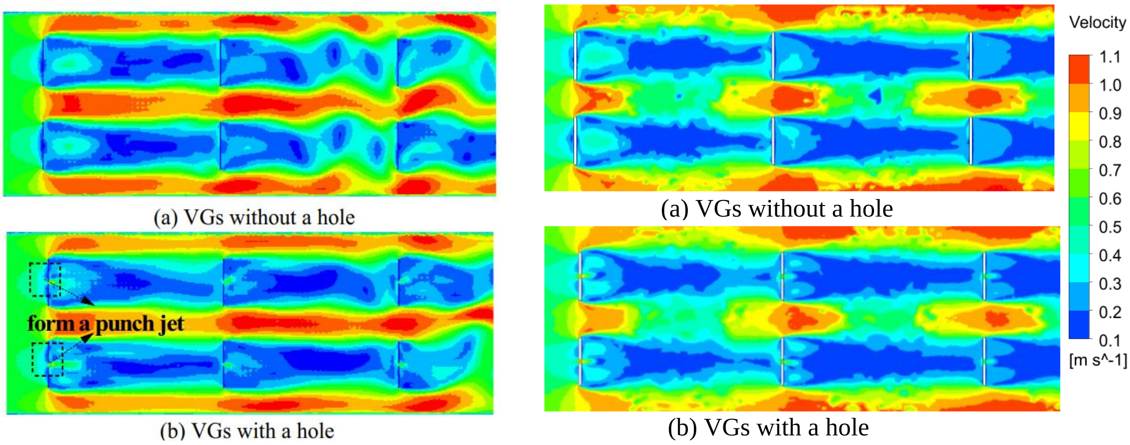
This study examined the heat transfer characteristics of rectangular ducts with rectangular and perforated Vortex Generators (VGs) using a commercial Computational Fluid Dynamics (CFD) application, specifically ANSYS Fluent. The Finite Volume Method (FVM) was employed to discretize and solve the system's governing equations for fluid flow and heat transfer. The relationship between pressure and velocity was determined using the coupled method, which allows for a more accurate and robust coupling of the pressure and velocity fields in the numerical simulation. The usual approximation was utilized to discretize pressure, and the simulation algorithm was considered to have converged when the residuals of the continuity, momentum, and energy equations were smaller than 10^{-6}. It shortens computation time while maintaining precision [16,17].

The results from this study were contrasted with experimental data and theoretical data to validate the simulation technique. The channel simulation results serve as an illustration of model validation and have been successfully used to simulate the VG flow structure based on the grid mesh that has been carried out. Empirical correlations were compared to the results of the smooth duct simulation. Experimental findings in the same size laminar channels under the same conditions are compared to simulated data from smooth channels. In the channel with pure water as the working fluid at Re = 1400, a comparison of the research and reference simulation results reveals that the highest relative error is less than 0.02%, as shown in Table 2.

Table 2. Research validation results

Reynolds Number	**Grid Mesh (10^{-6})**		**Fluid Output Temperature (K)**		
	Research Simulation	**Reference Simulation [14]**	**Research Simulation**	**Reference Simulation [14]**	**Reference Experiment [14]**
1400	1.70	1.50	303.82	303.89	303.68

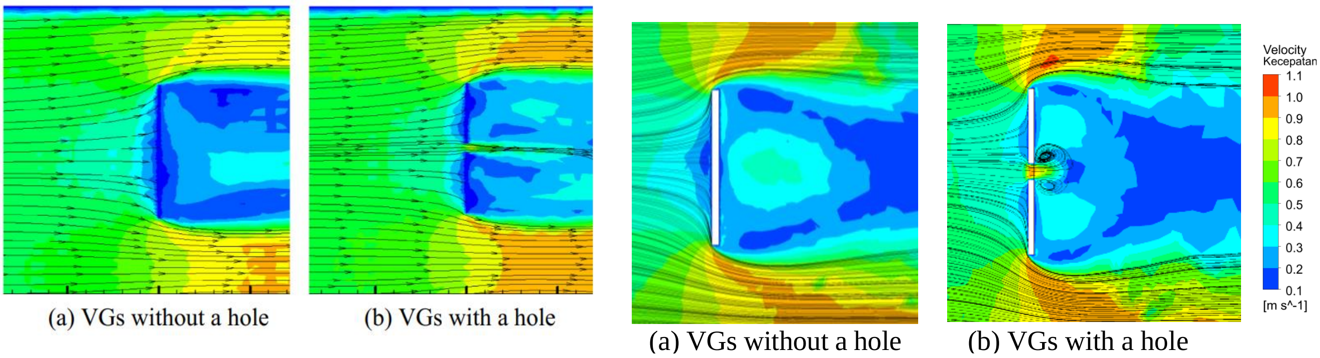
The simulation results in this research show a remarkable similarity to the reference simulation results based on the analysis of the velocity contour in the system for Re = 6500 fluid flow. The velocity color contours obtained from the research closely match those from the reference study, indicating that the Computational Fluid Dynamics (CFD) simulation was accurate and reliable. Overall, the simulation results provide valuable insights into the behavior of the VG system at Re = 6500 fluid flow and demonstrate its ability to predict the velocity distribution accurately. The research findings lay a strong foundation for further understanding and optimizing the VG system’s performance in heat transfer applications and they can guide future engineering design and optimization efforts. However, validating these simulation findings with experimental data is essential to ensure their applicability in real-world scenarios. Figure 4 shows that the flow patterns in the reference and research simulations are generally similar and comparable. Although there are slight variations in velocity contours, the overall flow patterns in both simulations exhibit noticeable similarities. The addition of the VG hole results in a lower velocity contour indicated by the number of blue contours after the VG. It also affects the velocity contours of the VG behind it.



(a) (b)

Figure 4. Speed contour of three VGs at *X* = 2.25 mm at *Re* = 6500: (a) Reference [14], and (b) Research

Figure 5 illustrates the holes on the VG that allow for flow separation in the fluid. As seen in the reference simulation results, there are high velocities between the VG holes, and this phenomenon is also observed in the research simulation results. The velocity contours show consistency between the reference simulation and research simulation results. Furthermore, it is observed that there is an increase in velocity at the end of each VG. This phenomenon indicates that VG can increase the fluid flow velocity, particularly around its trailing edge. This increase in velocity can positively impact heat transfer and system efficiency as it directs the flow more forcefully and effectively. This increase in velocity can positively impact heat transfer and system efficiency as it directs the flow more forcefully and effectively.



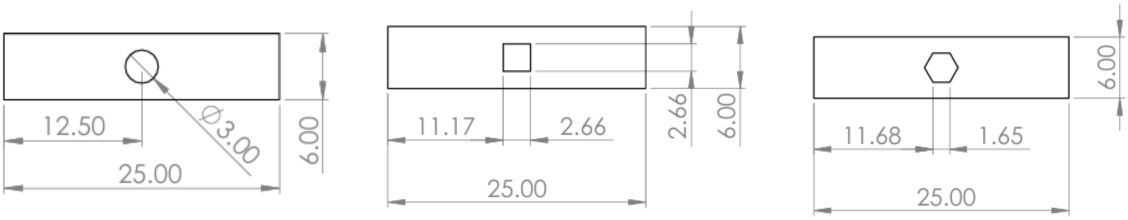
(a) (b)

Figure 5. Streamline VG contour at *X* = 2.25 mm at *Re* = 6500: (a) Reference [14], and (b) Research

These results confirm that VG is an effective device for manipulating fluid flow and enhancing heat transfer in the rectangular channel. These findings provide crucial guidance for using VG in various applications, such as designing and developing more efficient heat exchangers and improving the performance of piping systems. This finding indicates that the research simulation results are valid and consistent with the reference simulation results. Despite minor differences, the VG heat transfer enhancement device successfully creates flow patterns similar to the reference results. It confirms the quality and accuracy of the research in understanding the flow phenomena and heat transfer occurring in the rectangular channel with the use of VG.

3 Case Study

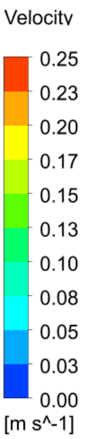
This study modifies the geometry of the holes on the VG. The hole can be shaped into a circle, square, or hexagon. The area of the plane has the same value so that the best geometry shape in the VG regarding the decrease in fluid outlet temperature can be determined. VG dimensions with holes, as shown in Figure 6; the hole is located in the middle of the VG diagonal.

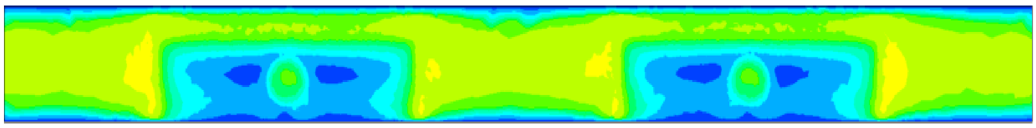


(a) (b) (c)

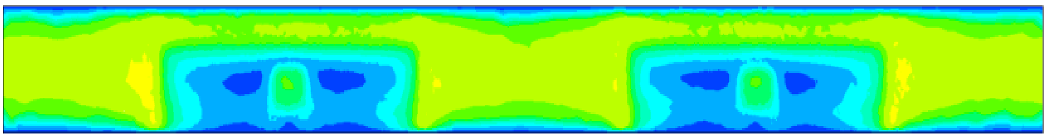
Figure 6. Hollow VG design: (a) Circle, (b) Square, and (c) Hexagon

Simulation on the VG system with hole modification using Computational Fluid Dynamics ANSYS Fluent. All boundary conditions use settings based on the simulation validations that have been carried out. Research using *Re* = 1400 with a hydraulic diameter of 0.01407 m. It is known that there are differences in the contours of the VG system with the hole modifications made. Top speed is seen on the side of each VG. Contour differences on the right and left VG, as shown in Figure 7. A hexagonal hole geometry has the highest speed on the right and left VG, indicated by a wider yellow contour, compared to the other geometric shapes.





(a)



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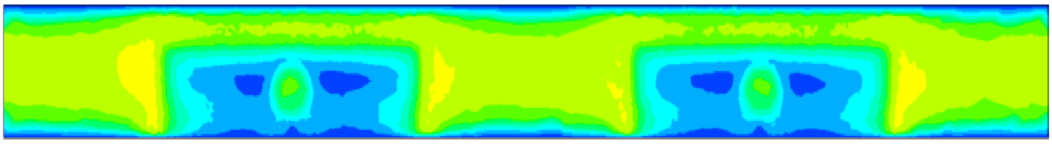

(c)

Figure 7. Contours of the front side of the VG system with holes: (a) Circle, (b) Square, and (c) Hexagon

Using a hexagonal hole geometry shape on the Vortex Generator (VG) leads to the lowest fluid outlet temperature of 303.53 K, as illustrated in Figure 8. It is attributed to the high velocity generated on the VG side. The geometric shape of the VG significantly influences flow resistance, consequently enhancing heat transfer between the VG and the fluid. The unique design of the hexagonal holes facilitates the generation of higher fluid velocities, promoting more efficient heat exchange and contributing to the observed lower fluid outlet temperature.

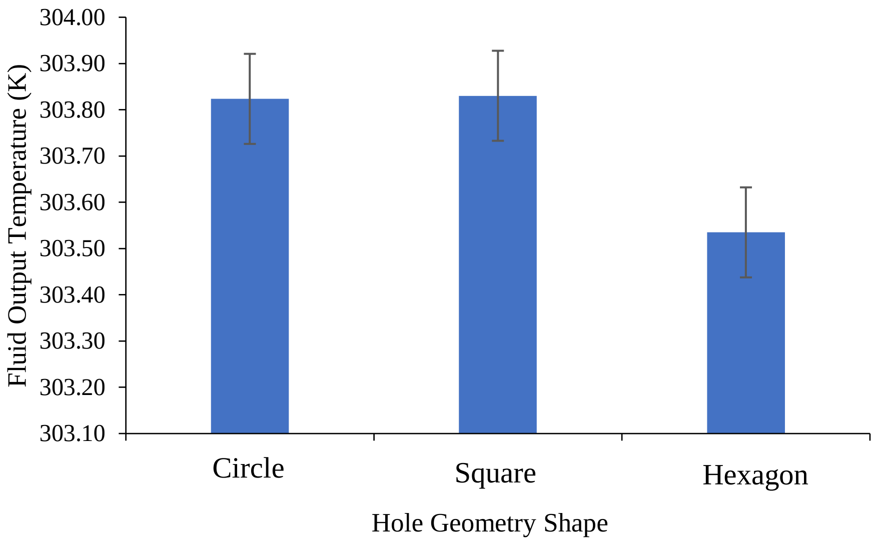

Figure 8. Fluid outlet temperature in the VG system

4 Conclusions

The research investigating the vortex generator system using 3D Computational Fluid Dynamics (CFD) with ANSYS Fluent has been successfully conducted. The investigation studied heat transfer and flow resistance in rectangular ducts with perforated VGs. The research validated its findings by successfully reproducing fluid outlet temperature values and velocity contours similar to those found in the reference study conducted by Han et al. The validation error for the research was calculated at 0.02% using the Relative Absolute Error (RAE) method. Furthermore, the research compared various geometries of VG holes in the system. Among these geometries, the use of a hexagonal hole geometry shape resulted in high-velocity contours on the VG side and the lowest fluid outlet temperature recorded at 303.53 K. These findings provide valuable insights into the potential application of VGs as a passive heat transfer enhancement method in heat exchangers. It is found that the study identifies the most effective VG hole geometries for enhancing heat transfer within the system. The research results provide a solid foundation for future advancements in improving the efficiency and performance of heat exchangers utilizing VGs. The findings provide valuable knowledge and recommendations for designing and optimizing VG systems to enhance heat transfer, potentially leading to more efficient heat exchanger designs in various industrial applications.

5 Acknowledgments

This research was fully supported by the PNBP grant from the Sebelas Maret University, Indonesia, with contract number 228/UN27.22/PT.01.03/2023 of the Penelitian Unggulan Terapan (PUT-UNS) scheme.

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