NUMERICAL STUDY OF THE VORTEX GENERATORS EFFECTS IN A CORRUGATED CHANNEL FOR TURBULENT FLOW

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Abstract
Vortex Generators (VGs) are one of many techniques used to improve the efficiency of heat exchangers. In this paper, we will investigate in a numerical study a rectangular winglet and a long winglet VGs inside a corrugated channel with a change of Rynolds number from 5000 to 17500. The role of VGs is to manupilate flow, which increases the Nusselt number (Nu) and increases the friction coefficient, which are considered disadvantages. For that, we calculate the thermal performance coefficient PEC to see if VGs give us more heat compared to what we will lose from friction, and the results show a good PEC greater than 1, and comparing between rectangular and long VGs, we have almost the same results with a small difference in NU for rectangular VGs being higher than long VGs, and the coefficient of friction is smaller, which means we are battered. The results are discussed in detail in this paper.

Keywords: *Vortex Generators, heat transfer, turbulence, corrugations*

1. Introduction

Engineers and researchers work tirelessly to improve the performance and effectiveness of various structures in the realm of aerodynamics. The use of vortex generators is a noteworthy breakthrough that has drawn a lot of attention. The ability to regulate and manipulate the fluid flow around objects thanks to these tiny, carefully positioned devices has significantly improved aerodynamic properties. The power of vortices, whirling fluid patterns that have a substantial influence on the behavior of fluid flow, is harnessed by vortex generators. Engineers have unlocked a variety of advantages by incorporating these clever gadgets into the aerodynamic design, including higher lift, improved stability, less drag, and improved maneuverability. In his private studies on this topic, (Fiebig, 1998) published papers about the effect of transverse and longitudinal vortice generators on heat transfer. Transverse vortices are less effective in enhancing heat transfer than longitudinal vortices. Up to a maximum angle of attack, heat transfer enhancement increases with Reynolds number, increases for constant winglet aspect ratio with angle of attack, but it also increases up to limiting values with winglet height in relation to transverse and streamwise winglet spacing and in relation to boundary layer thickness. Henze et al. (Henze et al., 2010) employed TLC to determine the heat transfer distribution behind a tetrahedral, full-body vortex generator. They obtained the velocity field and wall heat transfer distributions for internal flows in the presence of longitudinal vortices. The typical heat transfer pattern shows the impact of the longitudinal vortices caused by the VG. The results from an ALTP heat flux sensor and TLC data were in excellent agreement, and this allowed for the evaluation of heat flux changes as well.To determine how sensitive the DU97-W-300 airfoil was to various vortex generator (VG) designs, wind tunnel research was done by Baldacchino et al. (Baldacchino et al., 2018). Rather than maximizing the VG geometry, the objective was to comprehend the significance of design factors. Findings supported the experimental approach by demonstrating a link between oil streak analysis and theory. Vane angle and length, two crucial characteristics, showed ideal values within the measured ranges. Base drag rose and lift decreased in the presence of a VG wake modulator, to varying degrees depending on how sensitive the airfoil was to airfoil roughness. The study highlighted how VGs affect dynamic load variations and offered suggestions for how to best optimize flow control devices for various environmental factors and performance measures. (Awais and Bhuiyan, 2018). Modern techniques for enhancing heat transfer efficiency and reducing pressure drop in tiny heat exchangers are evaluated via extensive experimental and computational study. Vortex generators (VGs), which protrude from heat transfer surfaces, improve heat transfer performance and help designers create effective heat exchangers. Longitudinal vortex generators (LVGs) increase downstream heat transmission, decrease wake zones, and stimulate heat transfer processes. Longitudinal vortices, staggered winglets, and precise VG positioning maximize heat transmission with little pressure loss. Ke et al. (Ke et al., 2019) study numerical analysis of heat transfer and fluid flow in a rectangular channel with delta-shaped winglet LGVs, Three distinct LVGs setups, including the common-flow-down setup, the common-flow-up configuration, and a new mixed configuration, were considered. The thermal boundary layer thickness and heat transport in LVGs channels are greatly influenced by longitudinal vortices. While bigger channel heights produce weaker vortices near the walls, mixed layouts improve fluid mixing and heat transport throughout the full cross-section at smaller channel heights. With common flow-up favored for lower ratios and common flow-down for bigger ratios, the ideal arrangement depends on the LVGs aspect ratio. Channel height improves overall performance, whereas additional LVGs rows and higher aspect ratios have the opposite effect. (Nfawa et al., 2019). Have numerically studied the turbulent flow in a trapezoidal corrugated channel with vortex generators for heat transfer enhancement. To achieve this objective, four amplitude heights were introduced: 1, 2, 3, and 4 mm. A constant heat flow is adopted as the thermal condition on the walls of the lower and upper corrugations, with a Reynolds number Re varying from 5000 to 17500. The results found show, that in the case of the configurations with vortex generators, a significant improvement in the Nusselt number but accompanied by an increase in the friction coefficient, is observed compared to the configuration without generators. Therefore, the vortex generator could be favorable in several heat transfer applications. Shlash and Koç. (Amer and Koc, 2022) Has investigated three different VG model kinds triangle, half circle, and quarter circle are the first three shapes. The simulations' Re range of 5,000–20,000 was used, which supported the original theory. The results show that the skin friction coefficient and the surface Nusselt number increase with step height and reach their maximum values at 4 mm. Additionally, the average Nusselt number rises as the Re number. The quarter circle VG beats the triangle VG in terms of thermal-hydraulic efficiency at a step height of 4 mm. (Jiang et al., 2023). The revolving wind turbines produce a three-dimensional rotational effect (TDRE). A TDRE modifies the inflow angle of vortex generators (VGs) installed on the blades by producing a spanwise velocity on the blade surface. This study analyzes the physical mechanisms of counter-rotating (CtR) and co-rotating (CoR) VGs. CtR VGs produce asymmetric vortices in the wake of incline inflow, but CoR VGs perform better. Vortex interaction is decreased when CoR VGs spacing is increased. Particularly with greater input angles, CoR VGs are more efficient at reducing separation and boosting pressure difference. The influence of a rectangular winglet vortex generator (VG) on the flow-induced particle resuspension created in a channel by Yu et al. (Yu et al., 2023) is investigated in the current study using high-fidelity CFD simulations. Enhanced particle removal forces are produced in areas with thinner boundary layers as a result of vortex generators (VGs), which redistribute kinetic energy and influence boundary layer thickness in channel flows. Where VGs obstruct the lower surface and are downstream of their trailing edge on the upper surface, force-enhanced zones appear. Particle resuspension is influenced by the VG angle of attack; bigger angles provide stronger forces and larger force-enhanced areas. Particle resuspension rates are often increased by VGs, particularly for tiny particles that are less impacted by regular channel flows.

The main goal of this study is to find out how a vortex generator (VGS) within a corrugated channel affects on fluid and heat transfer. The study intends to improve fluid dynamics, decrease flow separation, and increase heat transmission. Depending on the particular application, this technique is used to improve mixing, reduce pressure losses, manage flow patterns, and promote energy efficiency. To increase efficiency and effectiveness in a variety of fluid-related processes, from heat exchange systems to aerodynamic designs to fluid transport systems, by incorporating VGS into the corrugated channel.

2. Assumptions and physical model

The study of a physical phenomenon is often formulated by laws expressed in the form of mathematical equations with partial derivatives that are elliptical and nonlinear on the one hand and complex and coupled on the other, linking the various parameters, namely speed, pressure, and temperature, which will be validated at each point of the field of study. These equations, obtained from the fundamental laws of mechanics and thermodynamics, are Navier-Stokes equations Nfawa et al. (Nfawa et al., 2019).

After Simplifying assumptions

- An incompressible fluid (ρ = constant).
- A viscous Newtonian fluid ($\mu \neq 0$).
- Constant physical properties.
- Steady state ($\frac{\partial}{\partial t}$ = 0).
- Two-dimensional simulation ($\frac{\partial}{\partial x_3} = 0$ and $u_3 = 0$).
- Negligible volume forces.
- Turbulent flow.

Continuity equation, momentum equation and energy equation that we used will be in this form

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial(\bar{u}_i \bar{u}_j)}{\partial \mathrm{x_j}} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(v\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) - \overline{\acute{u}_i \acute{u}_j}\right), \tag{2}$$

$$\frac{\partial(\rho C_p u_j \bar{T})}{\partial x_j} = \frac{\partial}{\partial x_j}\left(K\frac{\partial T}{\partial x_j} - \rho Cp\overline{\acute{u}_j \acute{t}}\right), \tag{3}$$

where the fluid velocity components u(x, y, t), pressure p(x, t), temperature T(x, y, t)) are the dynamical variables.

For turbulence model to close the systeme of quation k-epsilon are used.

The k-epsilon turbulence model was selected for our investigation because of its adaptability and ability to balance accuracy and processing simplicity while modeling a variety of turbulent flows.

2.1. k-epsilon model

The k-epsilon model is a two-equation model that gives a general description of turbulence using two transport equations, one for turbulent kinetic energy (k) and the other for dissipation (epsilon). The turbulent dissipation is the rate at which velocity fluctuations dissipate. This model uses the Boussinesq concept, based on the analogy between the exchange of momentum by molecular interaction at the microscopic scale and the exchange of momentum by turbulence at the macroscopic scale. In order to link Reynolds stresses to mean velocity gradients and turbulent viscosity, the k-epsilon model makes use of the gradient diffusion assumption

$$-\overline{u_i u_j} = v_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_i}{\partial x_j} \right) - \frac{2}{3} k \delta_{ij}, \quad (4)$$

$$\frac{\partial \rho}{\partial x_i} (\rho k u_j) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + G_k - \rho \varepsilon, \quad (5)$$

$$\frac{\partial \rho}{\partial x_i} (\rho k u_j) = \frac{\partial \rho}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \left(\frac{\varepsilon}{k} \right) G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}, \quad (6)$$

$$G_k = -\rho \overline{u_i' u_j'} \frac{\partial \bar{u}_j}{\partial x_i} = \rho v_t \left[\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right] \frac{\partial \bar{u}_i}{\partial x_j}, \quad (7)$$

where σ_ε and σ_k are the turbulent Prandtl numbers relating respectively to the rate of dissipation and turbulent kinetic energy.

The empirical coefficients are equal to : $C_{1\varepsilon} = 1.44$; $C_{2\varepsilon} = 1.92$.

G_k represents the generation of the kinetic energy of turbulence due to the gradients of average speed.

In the following, the different geometries, the generation of their mesh, and the incorporation of boundary conditions as developed in the Ansys-Fluent we used second order schem preprocessor are described.

ANSYS Fluent is a computational fluid dynamics (CFD) software package widely used for simulating fluid flow, heat transfer, and related phenomena. It provides engineers and researchers with powerful tools for analyzing and predicting fluid dynamics in various applications, including aerospace, automotive, energy, and environmental studies. With its robust solver capabilities and user-friendly interface, ANSYS Fluent aids in optimizing designs, enhancing performance, and solving complex fluid flow problems. ANSYS Fluent primarily uses the Finite Volume Method (FVM) for simulating fluid flow, heat transfer, and related phenomena by discretizing the computational domain into control volumes and solving governing equations within them.

If no significant change in the values of the dependent variables occurs, then said that the iterative process had reached convergence. Practically, the latter is expressed by a test for stopping the iterative process, based on the residuals of the mass, of the amount of motion, and temperature, which must be less than an arbitrary value. This is called: convergence criterion. For this study it is equal to 10^{-5}.

Figure 1 represents the physical model and shows the vortex generation inside this channel.

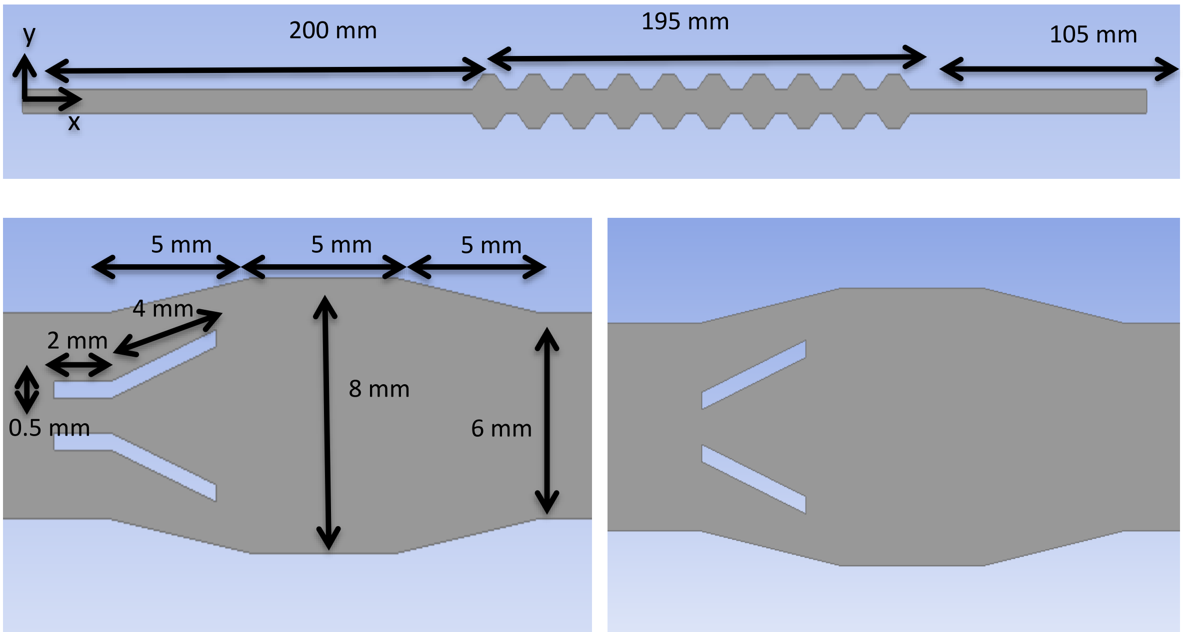

Figure 1. *Rectangular and Long VGs Inside Channel.*

The boundary types of the geometries considered in this work are summarized in the table below**.**

Table 1. *Types of boundaries.*

Region	Type
Input	Velocity
Output	Pressure
Wall (smooth channel)	Adiabatic
Wall (corrugations)	Heat flow
Vortex generator	Adiabatic

The fluid (water) brought to a temperature T = 298 K, enters with a deduced flow velocity of the Reynolds number included ranging from 5000 to 17500. At the corrugation part, the heat flow is imposed at an equal q=616 w/m^2.

2.2. Mesh independency

Figure 2 represent the pressure and velocity profiles at a position x=287.5 mm and y vary from -4 to +4 mm. The different curves were obtained with linear meshes with size of element 0.8 mm, 0.6 mm, 0.4 mm, 0.2 mm, 0.1 mm . The difference is not really important, and so for the present work the study was accomplished for a size of element 0.2 mm.

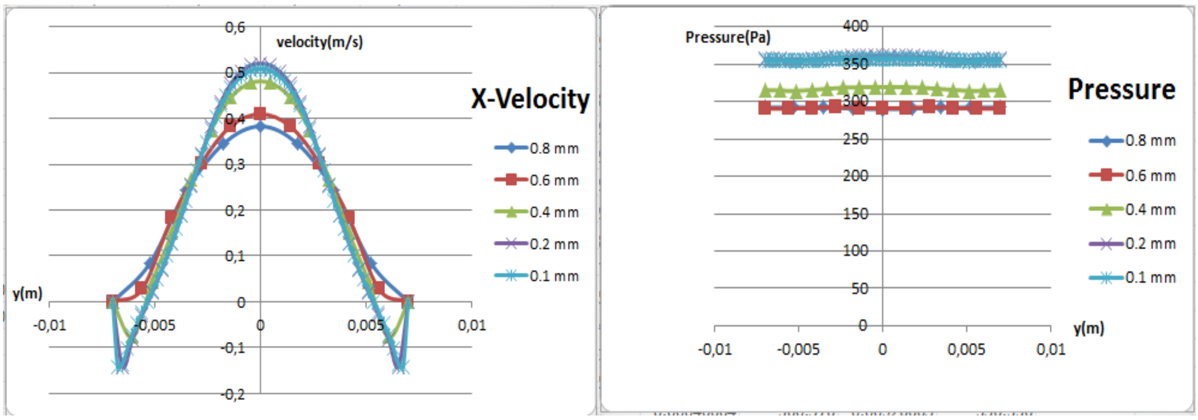

Figure 2. *Pressure and Velocity profile on a line at the 5th corrugation.*

2.3. Validation

Code validation was conducted by comparing the data from Shlash and Koç (Amer and Koc, 2022). As depicted in Fig. 3, the average Nusselt number (Nu) closely matched their results, while the coefficient of skin friction showed a notable similarity, which is good.

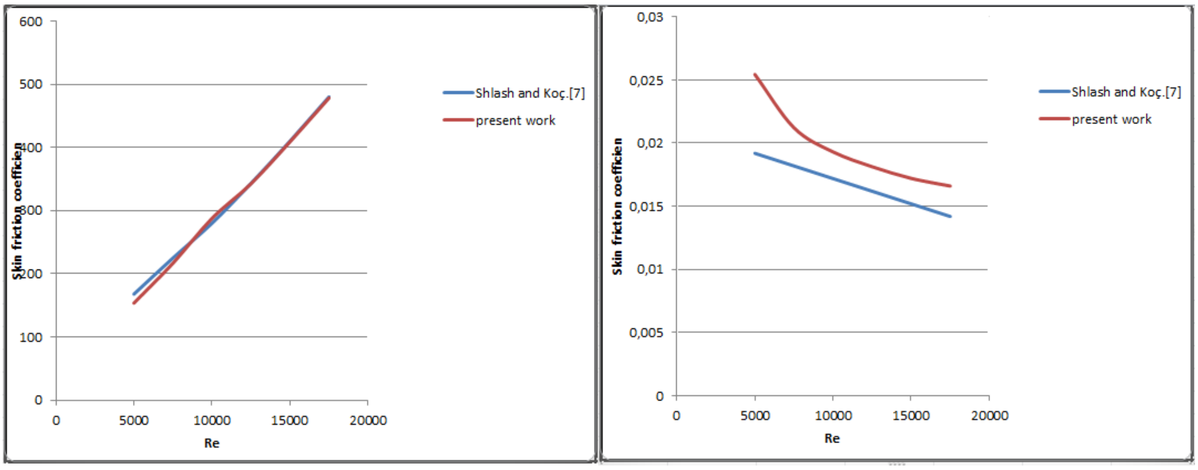

Figure 3. *Validation of the present CFD results with numerical data from previous studies: average Nusselt number and Skin friction coefficient.*

3. Results and discussion

This chapter displays the research's numerical results in numbers. Examining the turbulent flow and heat transfer via a corrugated channel with a VGs for Re varying from 5000 to 17500 is the main objective of this computational investigation.

The first section of the study describes the mathematical outcomes of forced convective fluid flow and heat transfer across channel mixed with various VGs (rectangular and long winglet). The impacts of Re and VG shape on hydraulic and thermal efficiency are presented and explained in this section. The results of this investigation support earlier results by Nfawa et al. (Nfawa et al., 2019).

The installation of vortex generators in the channels greatly affects the fluid flows and heat transfer. You can notice this in Fig. 4 for Re = 5000 with and without vortex generators. We notice that the velocity is parabolic in the middle and changes direction until it becomes negative under the effect of the vortex generator both of, and both vortex generators have the same effect on velocity. Also in temperature, we see how the change of temperature is in the wall of the channel, and the VGs decrease this change, which means the thermal boundary layer becomes thinner.

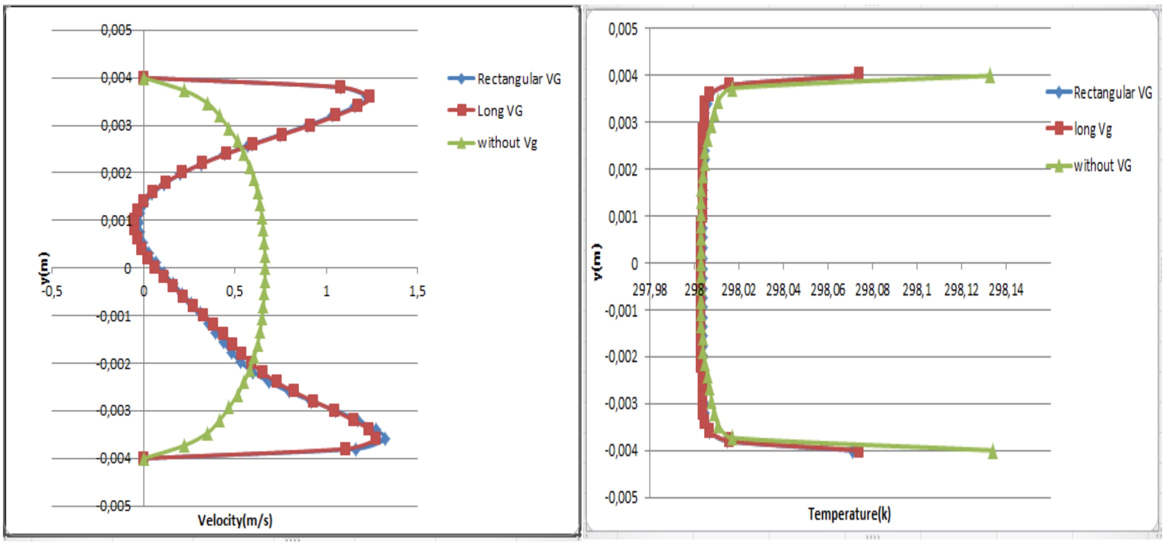

Figure 4. *Profile of velocity and temperature in line in the middal of corrugation (x = 287.5 mm).*

Figure 5 represents the contour velocity at Re = 5000 with and without vortex generators. In the case of corrugations without vortex generators, an acceleration of the fluid is noted at the central section of the channel, which weakens as one moves away from and towards the wall. On the other hand, in the case of corrugations with vortex generators, there is elimination of the stagnation zone of the fluid at the wall to concentrate in the middle. At the level of the upper and lower walls, the behavior is almost identical.

Figure 6 shows the temperature contours for a Reynolds number of 5000 with and without vortex generators. It is clear that the vortex generators have an influence on the temperature gradient in the walls, the thermal boundary layer becomes thinner, and the heat transfer is better. The temperature contour shows the difference between the temperature of fluids, which is uniform, and the temperature of walls.

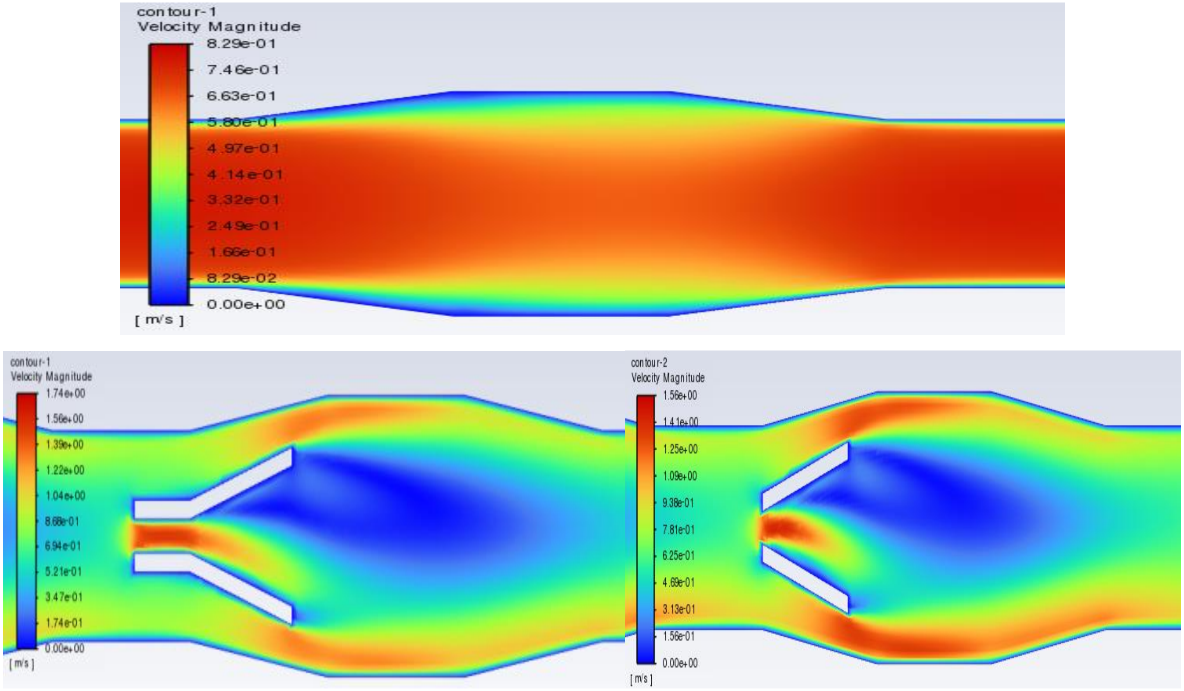

Figure 5. *Velocity distribution with and without vortex generators (Re = 5000).*

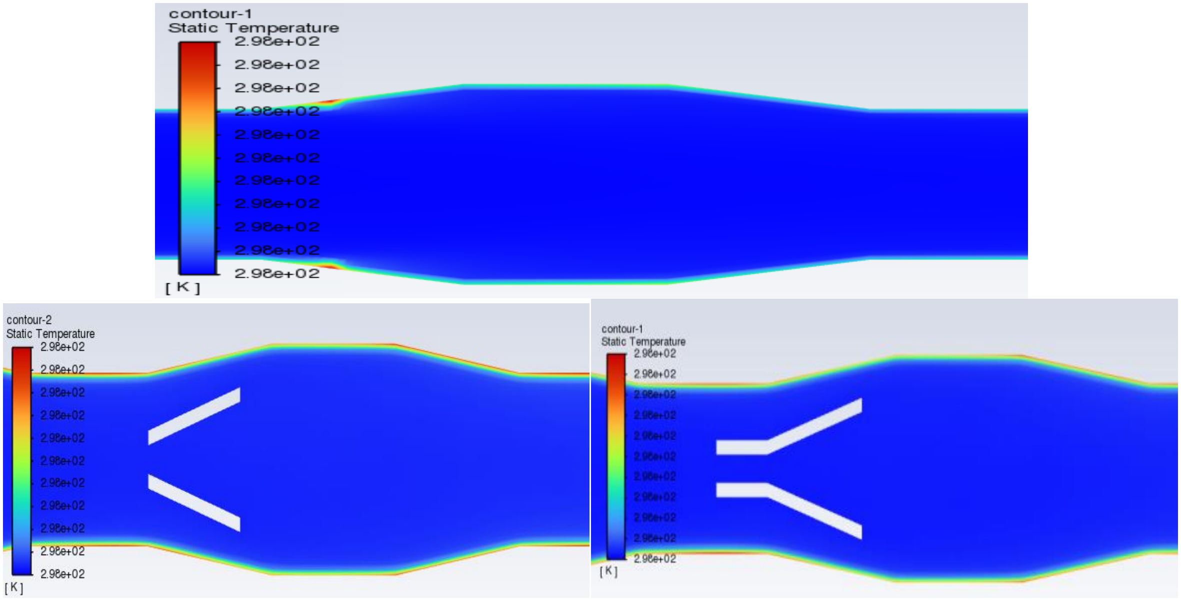

Figure 6. *Temperature contours (Re = 5000).*

Figure 7 represents the profile of gradient x-velocity with changing of y with Reynolds number 5000. It shows that there is a large difference in velocity around the walls of the channel because VGs say that every time we go to the middle of the channel, the gradient will be null, and almost the velocity in the middle is the same.

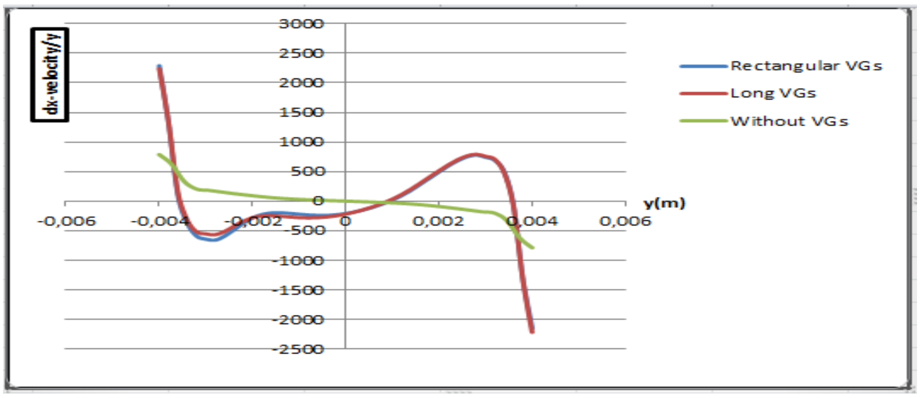

Figure 7. *Profile of the derivative of x-velocity (Re = 5000).*

Figure 8 presents the Turbulence intensity at Re = 5000 in line in the middle of the corrugation. On the turbulence intensity distribution, the effect of VGs forms is shown. The graphic demonstrates that the channel without VGs has the least amount of disturbance. Additionally, the pattern of these two VGs' turbulence intensity is nearly identical. Moreover, the turbulence is higher around the wall because of the high velocity there.

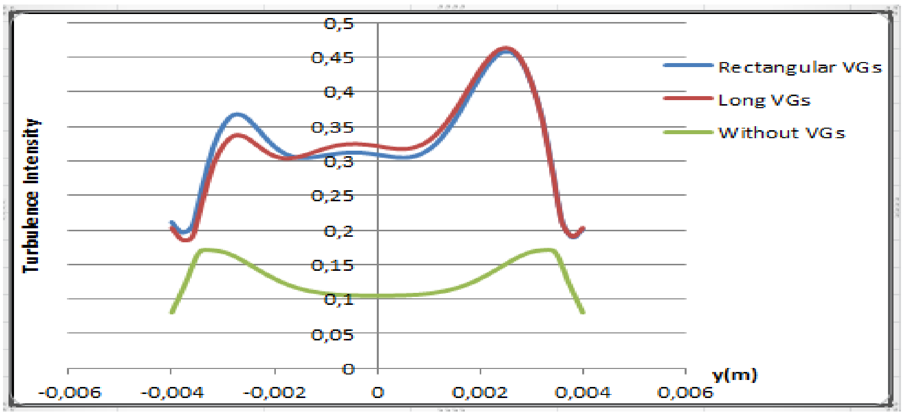

Figure 8. *Profile of the Turbulence Intensity (Re = 5000).*

Figure 9 reveals that the ratio between the Nusselt number of a channel with VGs and the Nusselt number without VG increases after using VG. This is because the vortex generator produces vortices, which improve the heat transmission ratio.

$$N_u = \frac{h\,Lc}{\lambda},$$

where **h** is the convective heat transfer coefficient of the flow, ***Lc*** is the characteristic length, and $\boldsymbol{\lambda}$ is the thermal conductivity of the fluid.

The skin friction coefficients for all VGs show an increase, primarily attributed to the presence of VGs

$$f = \frac{\tau_w}{0{,}5.\rho.u^2},$$

where τ_w is shear stress, ρ is density and u is the velocity.

Which leads to the pressure drop loss in energy, but comparing the enhancement in Heat transfer with the loss in energy is described in the thermal performance coefficient, as shown in Fig. 10

$$PEC = \frac{\left(\frac{Nu}{Nu_0}\right)}{\left(\frac{f}{f_0}\right)^{1/3}},$$

where f and f_0 is the skin friction coefficients for VGs and without VGs respectively, Nu and Nu_0 is the Nusselt number for VGs and without VGs respectively.

We notice that this factor increases with the increase in Reynolds number, and if the value is greater than one, it means that VGs have a good effect compared to the loss for both VGs almost is the same. The rectangular VGs have a higher Nusselt number than LVGs and lower skin friction, which means batter heat transfer with lower losses.

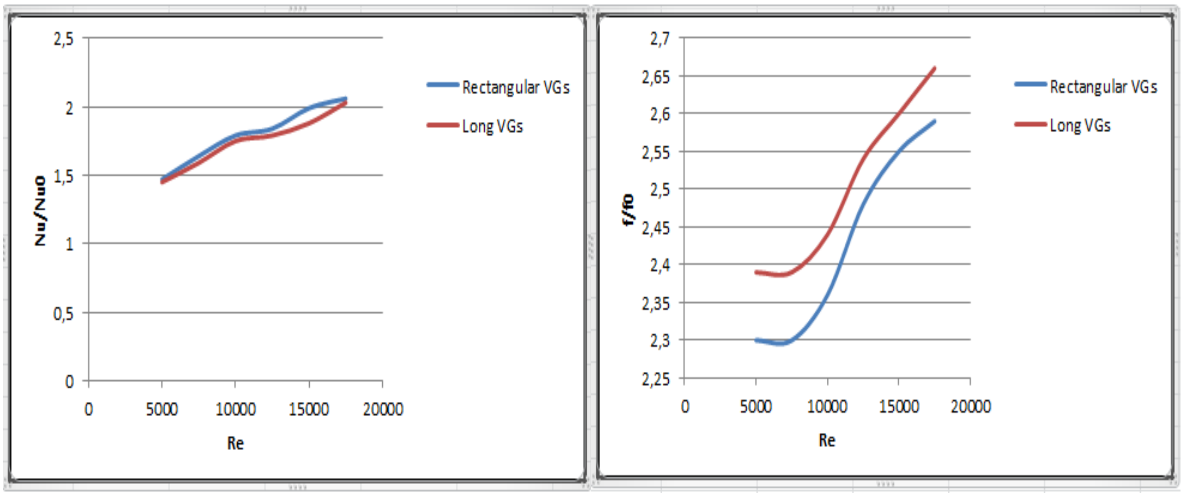

Figure 9. *Variation of the Nusselt number and friction coefficient as a function of the Reynolds number.*

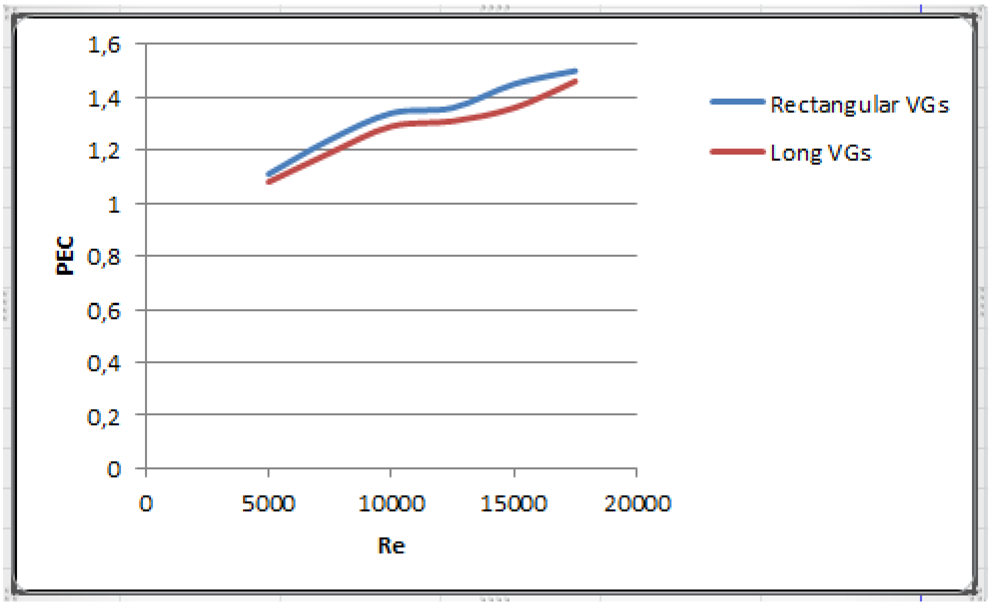

Figure 10. *Variation of the performance criterion as a function of the Reynolds number.*

4. Conclusion

The numerical study of the turbulent through a corrugated channel with a trapezoidal base with and without vortex generators was the objective of the present work.

- The effect of Reynolds number on the thermal and dynamic fields is direct link.
- In the case of corrugations with vortex generators, there is an elimination of the stagnation zone of the fluid at the wall, the thermal boundary layer becomes thinner, and the heat transfer is better.
- The ratio of Nusselt number and coefficient of friction is increasing, which means vortex generators are increasing heat transfer and also creating more friction.
- The dependence of x-velocity on the change of y has big values around the walls of the channel, and that is because VGs change directions of flow, which lead to big differences in velocity around walls and also increase turbulence intensity.
- The PEC factor increases with increasing Reynolds numbers, and the value of PEC is always greater than one, which means that vortex generators have a good effect on heat transfer.
- Comparing between rectangular and Long VGs, the rectangular ones are better because they have a higher Nu and a lower friction coefficient.
- The size of VGs has an effect, as longer VGs create more friction.

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References

[1] Fiebig, M. (1998). Vortices generators and heat transfer. *Trans IChemE*, 76, 108–123. **https://doi.org/10.1205/026387698524686**

[2] Henze, M., von Wolfersdorf, J., Weigand, B., Dietz, C. F., Neumann, S. O. (2010). Flow and heat transfer characteristics behind vortex generators – A benchmark dataset. *International Journal of Heat and Fluid Flow*, 32, 318–328. **https://doi.org/10.1016/j.ijheatfluidflow.2010.07.005**

[3] Baldacchino, D., Ferreira, C., Tavernier, D. D. (2018). Experimental parameter study for passive vortex generators on a 30% thick airfoil. *Wind Energy*, 21, 745–765. **https://doi.org/10.1002/we.2191**

[4] Awais, M., Bhuiyan, A. A. (2018). Heat transfer enhancement using different types of Vortex Generators (VGs): A review on experimental and numerical activities. *Thermal Science and Engineering Progress*, 5, 524–545. **https://doi.org/10.1016/j.tsep.2018.02.007**

[5] Ke, Z., Chen, C. L., Li, K. (2019). Vortex dynamics and heat transfer of longitudinal vortex generators in a rectangular channel. *International Journal of Heat and Mass Transfer*, 132, 871–885. **https://doi.org/10.1016/j.ijheatmasstransfer.2018.12.064**

[6] Nfawa, S. R., Talib, A. R. A., Masuri, S. U., Basri, A. A., Hasini. H. (2019). Heat transfer enhancement in a corrugated-trapezoidal channel using winglet Vortex Generators. *CFD letters*, 11, 69–80.

[7] Amer, B., Koc, I. (2022). Turbulent fluid flow heat transfer enhancement using novel Vortex Generator. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 96(1), 36–52. **https://doi.org/10.37934/arfmts.96.1.3652**

[8] Jiang, R., Zhao, Z., Liu, Y. (2023). Effect of vortex generator orientation on wind turbines considering the three-dimensional rotational effect. *Ocean Engineering*, 267, 113307. **https://doi.org/10.1016/j.oceaneng.2022.113307**

[9] Yu, D., Lin, J. L., Xie, J. H. (2023). Investigation on the influence of vortex generator on particle resuspension. *Particuology*, 86, 126–136. **https://doi.org/10.1016/j.partic.2023.04.009**