UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

NUMERICAL INVESTIGATION OF HEAT TRANSFER ENHANCEMENT IN CORRUGATED CHANNELS USING VORTEX GENERATORS

Booklet of PhD Theses

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ABSTRACT

This thesis investigates thermal enhancement in semi-circular corrugated channels using vortex generators (VGs). Improving heat transfer while limiting pressure losses is an important challenge in compact heat exchangers and thermal systems. Corrugated channels and VGs improve heat transfer by increasing flow mixing and disturbing the thermal boundary layer. However, the combined interaction between these enhancement techniques remains insufficiently studied, particularly for semi-circular corrugated channels. In addition, limited studies have investigated the influence of VG shape, size, and streamwise position in semi-circular corrugated channels or compared curved single-body vortex generators with conventional winglet-type and multi-pair configurations. Therefore, the novelty of the present work lies in the combined investigation and optimization of VG geometry, size, and position together within the same corrugated channel configuration.

A numerical investigation was performed under turbulent steady-state conditions using the SST k−ω turbulence model. Different VG geometries, sizes, and positions were examined to evaluate their influence on the flow structure and thermal–hydraulic performance.

The results showed that vortex generators changed the flow behavior inside the corrugated channel by reducing the recirculation zones near the walls and improving fluid mixing. The results showed that the concave-up vortex generator (CUVG) provided the best overall performance among the investigated geometries. The size and position of the VG had a strong influence on the thermal behavior, where a 5 mm VG placed near the corrugation entrance (d=-2) produced the highest heat-transfer enhancement of approximately 121%. However, this configuration also caused the largest pressure-drop increase, reaching nearly 12.5 times that of the baseline channel. The maximum performance evaluation criterion (PEC) reached approximately 0.96, indicating a good balance between heat-transfer enhancement and pressure loss. The comparison between single-body and two-pair VG arrangements also showed that the single-body configuration provided better overall thermal–hydraulic performance.

Overall, the study demonstrates that combining optimized vortex generators in semi-circular corrugated channels can significantly improve thermal performance while maintaining acceptable hydraulic losses, making these configurations promising for compact heat exchanger applications.

1. INTRODUCTION

Improving heat-transfer performance while maintaining acceptable pressure losses remains a major challenge in thermal engineering, particularly in compact heat exchangers. Passive enhancement techniques are widely used because they improve thermal performance without requiring external energy input. Among the most common methods are corrugated channels and vortex generators (VGs), which enhance heat transfer through flow recirculation, vortex generation, and improved fluid mixing. Combining these techniques can further improve thermal–hydraulic performance; however, their interaction and overall effect on heat-transfer enhancement and pressure-drop penalty are not yet fully understood. This motivates the present study.

Corrugated channels are widely used for heat transfer enhancement because they significantly improve thermal performance. Many experimental and numerical studies have investigated their behavior, and the results consistently demonstrate that corrugated channels can effectively increase the heat transfer efficiency [1–5]. Ahmed et al. [6] reported that trapezoidal corrugations provide better thermal performance than sinusoidal geometries at low Reynolds numbers, whereas sinusoidal configurations become more effective at higher Reynolds numbers. Similarly, Naphon [7] showed that sharper corrugation edges intensify turbulence and heat transfer, while Islamoglu [8] demonstrated that smoothing the corrugation peaks reduces the enhancement because of weaker separation regions. Tokgoz and Sahin [9] and Dutta et al. [10] both concluded that corrugated channels outperform straight channels due to stronger recirculation and thermal boundary-layer disruption; however, Tokgoz and Sahin emphasized the role of vorticity concentration, whereas Dutta et al. mainly associated the enhancement with V-shaped corrugation geometry. In addition, Ajeel et al. [11] showed that combining corrugated geometries with nanoparticles further enhances thermal performance due to improved thermal conductivity and intensified mixing near the corrugated walls. Alfellag et al. [12] and Azman et al. [13] also reported that increasing corrugation height or decreasing pitch ratio enhances thermal mixing, but they noted that stronger recirculation zones significantly increase hydraulic resistance. These comparisons indicate that the reported thermal–hydraulic behavior strongly depends on corrugation geometry and operating conditions. The corrugated geometry generates recirculation zones within the fluid, which promote mixing and enhance thermal exchange. This effect can be further strengthened by incorporating vortex generators (VGs), which induce stronger flow disturbances and improve overall thermal performance.

The vortex generator is a solid body that can be designed in multiple ways. They help control and redirect the fluid flow by directing it toward specific regions, increasing the contact between the fluid and the surface, and improving the thermal efficiency [14–17]. Several studies have shown that vortex generators can improve heat transfer by enhancing fluid mixing and disturbing the thermal boundary layer. Xu et al. [18], Modi and Rathod [19], and Tanougast et al. [20] reported that curved VG geometries generally provide better thermal–hydraulic performance than straight winglets because they produce stronger and more stable vortices. Akcay [21] showed that perforated winglets can reduce pressure losses compared with solid VGs. Other studies [22,23] also reported improved performance in corrugated channels, although the PEC values varied depending on VG geometry, arrangement, and channel configuration. Overall, these studies indicate that the effectiveness of vortex generators strongly depends on their geometry and interaction with the channel flow. Vortex generators enhance heat transfer mainly by increasing near-wall mixing and repeatedly disturbing the thermal boundary layer. However, stronger vortices also increase wall shear stress and pressure drop. Therefore, achieving good thermal–hydraulic performance requires balancing heat-transfer enhancement with hydraulic losses.

Previous studies generally agree that corrugated channels and vortex generators enhance heat transfer by increasing flow separation, vortex formation, and near-wall mixing. However, contradictions exist regarding the optimal geometry and configuration. In many previous studies, the VG geometries were selected in a relatively conventional or random manner without considering geometric consistency with the corrugated channel profile or systematically evaluating the influence of VG size and streamwise position. Although semi-circular corrugated channels have demonstrated promising thermal performance and have been experimentally validated in several previous studies, their combined interaction with vortex generators remains insufficiently explored. In addition, the effects of VG size and streamwise position on flow structure and thermal–hydraulic behavior in semi-circular corrugated channels remain insufficiently explored. Furthermore, most previous studies focused mainly on conventional winglet-type or multi-pair VG arrangements, while direct comparisons with optimized single-body VG configurations are still limited.

2. NUMERICAL METHODOLOGY

In this chapter, the mathematical formulation used in the present study is introduced. It includes the governing equations such as the Navier–Stokes equations, the energy equation, the turbulence model, and evaluate key performance parameters. The geometry of the studied domain and its specific details, including boundary conditions, are also defined. In addition, the numerical procedure implemented in the ANSYS software is described, explaining how the computational setup was established to solve the governing equations within the defined domain.

2.1 Governing equations

Water was modeled as a viscous, Newtonian, and incompressible fluid with constant thermophysical properties. The flow was assumed to be steady and turbulent. A two-dimensional (2D) model was adopted because the vortex generators were extruded uniformly across the channel width, resulting in predominantly two-dimensional flow behavior. The governing equations for mass, momentum, and energy conservation were solved throughout the computational domain. [26]:

- Mass conservation equation:

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

The continuity equation ensures mass conservation throughout the computational domain and describes the incompressible nature of the flow inside the corrugated channel.

- Momentum conservation equation:

$$\frac{\partial(u_j \rho u_i)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j} - \rho\overline{u'_i u'_j}\right)\right). \tag{2}$$

The momentum equation governs the transport of fluid momentum and accounts for the effects of pressure gradients, viscous forces, and turbulence-induced momentum exchange generated by the corrugated geometry and vortex generators.

- Energy conservation equation:

$$\frac{\partial(\rho u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\left(\frac{\mu}{Pr} - \frac{\mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_i}\right). \tag{3}$$

The energy equation describes heat transport within the fluid domain and includes the combined effects of convection and thermal diffusion, which are strongly influenced by vortex-induced mixing near the heated walls.

Turbulence was modeled using the SST k–ω model, which combines the advantages of the k–ω formulation near the wall and the k–ε model in the free-stream region. The model was selected because of its ability to accurately predict near-wall flow behavior, thermal boundary-layer development, and flow separation in corrugated channels equipped with vortex generators [28].

$$-\rho\overline{u'_i u'_j} = \mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\rho k\delta_{ij} -\frac{2}{3}\mu_t\frac{\partial u_k}{\partial x_k}\delta_{ij}, \quad 4$$

- The turbulent kinetic energy (*k*)

$$\frac{\partial u_i k}{\partial x_i}=\frac{\partial}{\partial x_i}\left[(\mu+\mu_t\sigma_k)\frac{\partial k}{\partial x_i}\right]+ G_k - Y_k. \quad 5$$

- The specific dissipation rate (ω)

$$\frac{\partial u_i \omega}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\Gamma_\omega\frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + D_\omega. \quad 6$$

In these equations, G_k denotes the rate of turbulent kinetic energy generation resulting from the mean velocity gradients, whereas G_ω represents the production rate of ω associated with the mean flow. The terms Y_k and Y_ω account for the dissipation of k and ω due to turbulence effects. The turbulent viscosity μ_t is incorporated into the momentum and energy equations, influencing the Reynolds stresses and enhancing the effective thermal diffusion.

2.3. Evaluation parameters

The pressure drop across the channel was determined using the following relation:

$$\Delta P = P_{in} - P_{out.} \quad 7$$

The average Nusselt number (*Nu*) is obtained as follows [29]:

$$Nu = \frac{h\,D_h}{K}, \quad 8$$

where h represents the convective heat transfer coefficient (W/(m²·K)), K is the thermal conductivity of the working fluid (W/(m·K)), and D_h denotes the hydraulic diameter (m) of the corrugated passage, expressed as [30]:

$$D_h = H + h. \quad 9$$

The friction factor (*f*) is calculated using the following equation [31]:

$$f = \frac{2\,D_h\,\Delta P}{L\,\rho\,u^2}. \quad 10$$

To quantify the increase in pressure loss caused by the VGs relative to that of a plain wavy channel, the pressure drop ratio (PR) is defined as [32]:

$$PR = \frac{\Delta P_{VGs}}{\Delta P_{WVGs}}, \quad 11$$

where ΔP_{VGs} and ΔP_{WVGs} are the pressure drops in channels with and without VGs, respectively.

The percentage enhancement (PE) quantifies the improvement in heat transfer when VGs are applied and is given by [33]:

$$PE\ (\%) = \frac{(Nu_{VGs} - Nu_{WVGs})}{Nu_{WVGs}} 100, \quad 12$$

where Nu_{VGs} and Nu_{WVGs} denote the Nu for channels with and without VGs.

The overall thermal–hydraulic performance was assessed using the Performance Evaluation Criterion (PEC) [34]:

$$PEC = \frac{Nu_{VGs}/Nu_{WVGs}}{\left(\Delta P_{VGs}/\Delta P_{WVGs}\right)^{\left(\frac{1}{3}\right)}}. \quad 13$$

2.2 Physical Model

The semi-circular corrugated channel used in this study is shown in Figure 2.1 The physical model.Figure 2.1. The channel consists of an inlet section, a corrugated test section, and an outlet section. The maximum and minimum channel heights are 10 mm and 5 mm, respectively, with a wavelength of 10 mm and a pitch diameter of 5 mm. In the first stage, three vortex-generator geometries were investigated: concave-up (CUVG), concave-down (CDVG), and straight (SVG) configurations. Based on the obtained thermal–hydraulic performance, the most effective geometry was selected for further analysis. In the second stage, the influence of VG size (2, 4, and 6 mm) and streamwise position (*d* = −2, 0, and +2 mm) was investigated using the selected VG geometry.

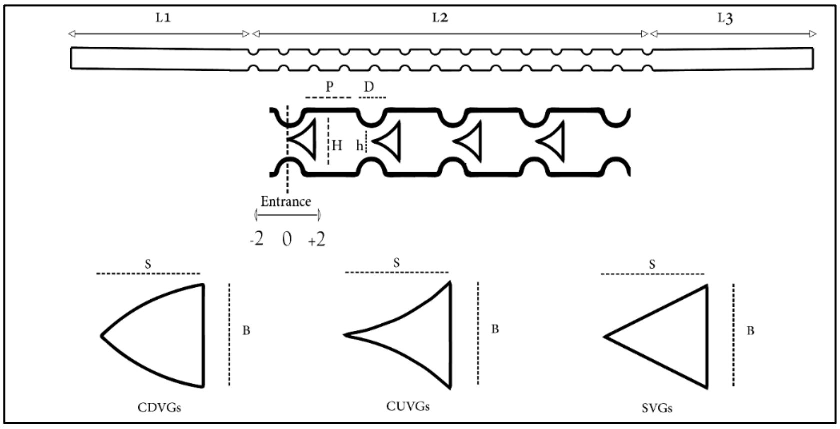


Figure 2.1 The physical model.

2.3 Boundary conditions

- Inlet:

T = 298 K, $u = \frac{Re\mu}{\rho D_h}$, Re = 10000-30000, I = 5%.

- Walls:

$u = v = 0$, $K_{cu} = 387.6$ W/m·K, $-k\frac{\partial T}{\partial y} = \begin{cases} 0, \text{smooth walls} \\ q_w = 10000\ \text{W/m}^2, \text{corrugated section} \end{cases}$

- Outlet:

$\frac{\partial u}{\partial x} = 0$; $\frac{\partial v}{\partial x} = 0$; $\frac{\partial T}{\partial x} = 0$; $P = P_{atm}$.

2.4 Numerical procedure

The numerical simulations were performed using ANSYS Fluent based on the Finite Volume Method (FVM), which solves the governing equations of mass, momentum, and energy over the computational domain. The Pressure-Based Coupled Solver (PBCS) was adopted to solve the governing equations simultaneously, providing improved stability and convergence for the present flow configuration. A second-order upwind discretization scheme was employed to ensure numerical accuracy. Convergence was achieved when the residuals satisfied the prescribed criteria and overall mass and energy balances were maintained.

3. MESH INDEPENDENCE AND MODEL VALIDATION

This chapter presents the mesh-independence study and validation of the numerical model. A grid-independence analysis was performed to ensure numerical accuracy, and the model was validated through comparisons with available experimental and numerical results. These assessments confirm the reliability of the numerical methodology used in the present study.

3.1 Mesh Independence Study

A mesh-independence study was performed using five different mesh configurations. The results showed a progressive reduction in numerical error with mesh refinement. Based on the average Nusselt number, a mesh containing 392,205 nodes was selected because it provided a good balance between numerical accuracy and computational cost. In addition, the Grid Convergence Index (GCI) analysis yielded a value of 2.12%, confirming low numerical uncertainty and mesh-independent behavior of the solution.

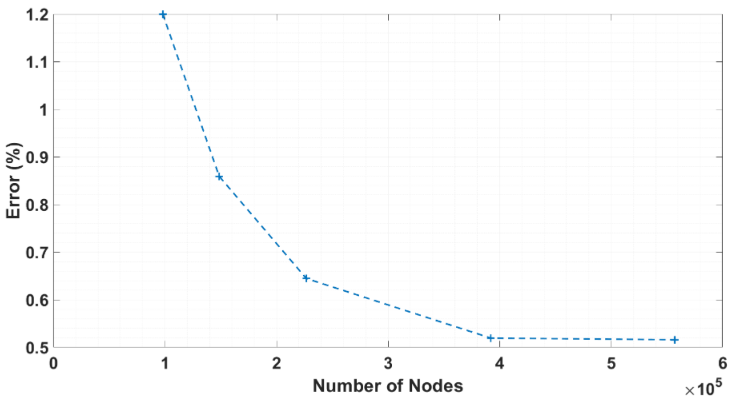


Figure 3.1 Variation of the relative error with the number of nodes.

3.2 Validation

The numerical model was validated against available experimental data for both thermal and hydraulic performance. Comparison with the experimental results of Ajeel et al. [11] showed good agreement for the average Nusselt number, with an average relative error of 5.31%. In addition, the predicted pressure-drop results agreed well with experimental data [36], with deviations below 13%. These results confirm the reliability of the numerical methodology adopted in the present study.

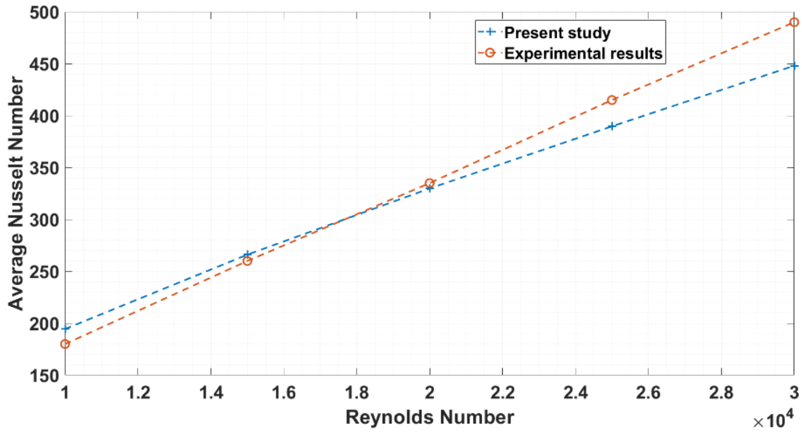


Figure 3.2 Validation of present CFD results against literature data: average Nu for channels without VGs.

Table 3.1 Validation of CFD pressure drop against experimental data for the baseline channel, showing percentage deviations.

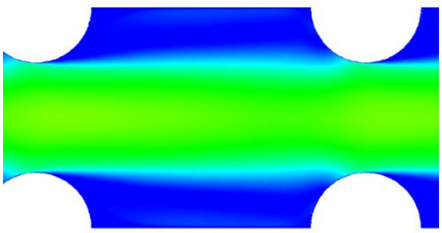
Re	**Friction Factor *f***	***ΔP* Numerical (Pa)**	***ΔP* Experimental (Pa)**	**Difference %**
10000	0.0204	148	132	12.1%
20000	0.0153	450	400	12.5%
30000	0.0131	872	800	9.0%

4. EFFECT OF VORTEX GENERATOR TYPE

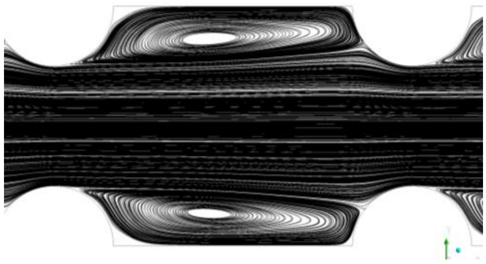
Chapter 4 investigates the influence of vortex-generator geometry on the thermal–hydraulic performance of a semi-circular corrugated channel. Three VG geometries were considered: straight, concave-down, and concave-up configurations. The objective was to evaluate how VG shape affects the flow structure, heat-transfer enhancement, and pressure-drop characteristics, and to identify the most effective geometry for improving overall thermal–hydraulic performance.

4.1 Flow field characteristics

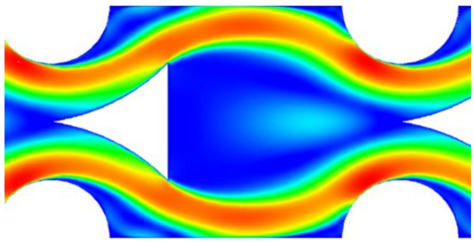
Figure 4.1 presents the velocity contours and streamlines for the different VG geometries. The flow is mainly concentrated in the channel core, while recirculation zones are formed within the corrugation valleys. The introduction of VGs redirects the flow toward the channel walls, enhancing fluid–wall interaction and heat transfer. Among the investigated configurations, the CUVG guides the flow more smoothly along the corrugated surface and produces smaller recirculation zones, resulting in stronger near-wall mixing and more effective thermal boundary-layer disruption. In contrast, the CDVG generates larger corner recirculation zones, while the SVG provides intermediate behavior. Overall, the VGs promote fluid mixing and enhance convective heat transfer, although at the expense of increased pressure drop [P1].



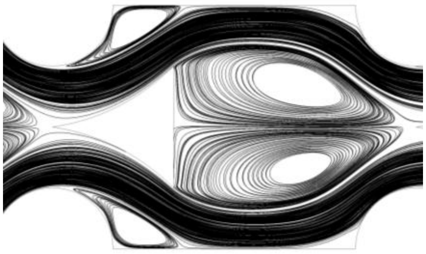
WVGs



WVGs



CUVGs



CUVGs

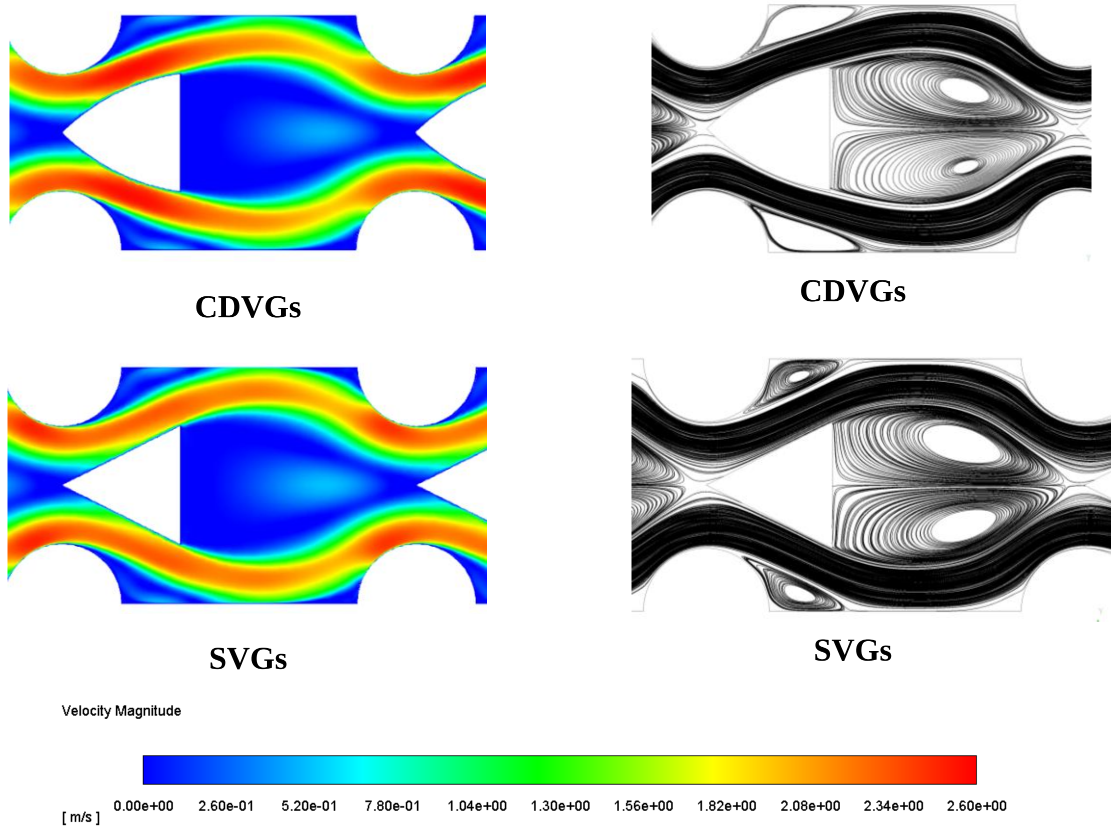


Figure 4.1 Velocity contours and streamlines for different VG types [P1].

4.2 Near-wall flow behavior

Figure 4.2 presents the wall shear stress along the bottom corrugated section as a function of *x* (m). For the channel without VGs, the shear stress is highest near the entrance, then decreases, reaching its lowest values at the corners after the pitch, which can be considered dead zones. The use of VGs increases the shear stress, especially at the middle of the channel. This increase is caused by stronger near-wall flow acceleration and enhanced momentum exchange generated by the vortical structures. This behavior is directly related to the local *h*: greater fluid contact with the wall produces higher shear stress, which enhances heat transfer (Figure 4.3). Higher wall shear stress also indicates thinning of the viscous and thermal boundary layers, allowing more efficient heat transfer between the wall and the fluid. The CUVGs increase the shear stress mainly at the middle of the corrugation, while the CDVGs produce higher shear stress near the entrance of each corrugation section. This difference reflects the distinct vortex distribution generated by each VG geometry and explains the variation in their thermal–hydraulic performance. [P1].

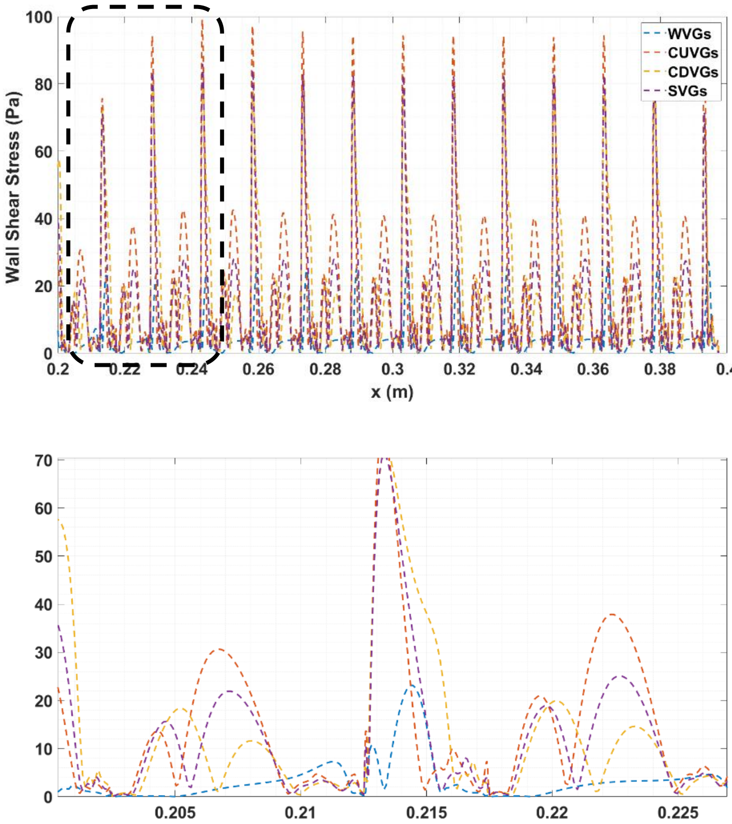
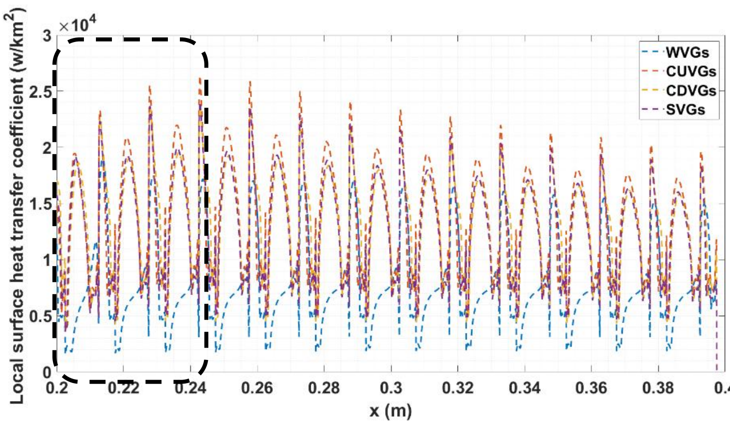


Figure 4.2 Distribution of wall shear stress along the corrugated section [P1].

Figure 4.3 shows the variation of the local heat-transfer coefficient along the lower corrugated wall for the different VG geometries. The introduction of VGs increases the local heat-transfer coefficient and produces a more uniform heat-transfer distribution along the corrugated section. Among the investigated configurations, the CUVG achieved the highest local heat-transfer coefficients due to its stronger near-wall mixing and more effective thermal boundary-layer disruption. The CDVG and SVG also improved heat transfer compared with the baseline case, but to a lesser extent. Overall, the results confirm the strong influence of VG geometry on local thermal performance [P1].



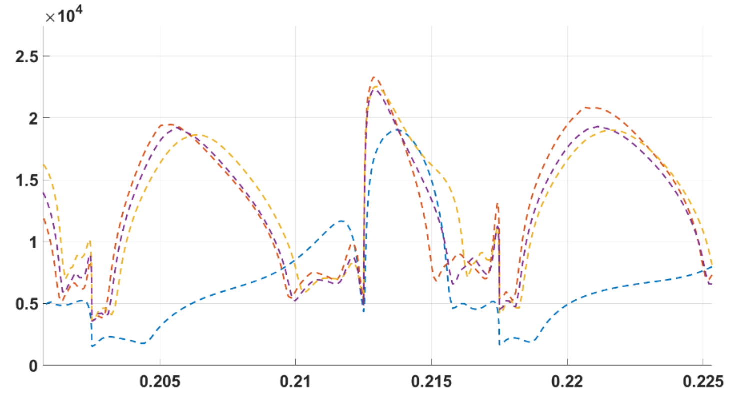


Figure 4.3 Distribution of local heat transfer coefficient along the corrugated section [P1].

4.3 Velocity and turbulence characteristics

Figure 4.4 presents the x-velocity and turbulent kinetic energy profiles across the channel height. The presence of VGs redistributes the flow, reducing the core velocity and increasing the velocity near the walls, which enhances fluid–wall interaction. In addition, the VGs increase the turbulent kinetic energy within the channel, promoting stronger mixing and thermal boundary-layer disruption. Among the investigated configurations, the CUVG produced the highest velocity levels and stronger mixing, while the SVG generated the lowest turbulence intensity [P1].

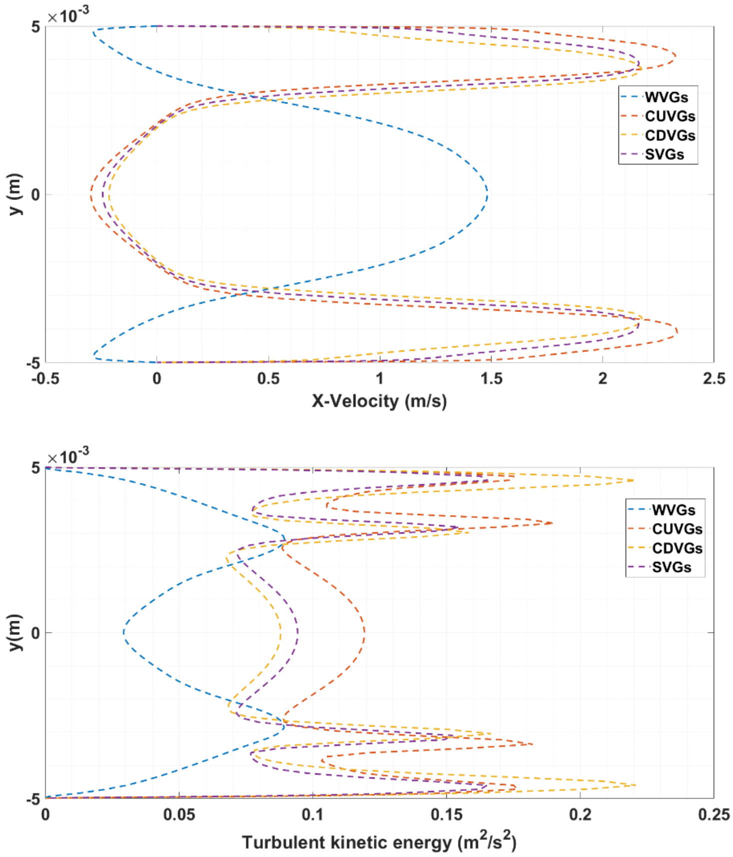


Figure 4.4 Profiles of x-velocity and turbulent kinetic energy along a vertical line at the mid-length of the corrugated section [P1].

4.4 Performance enhancement and pressure ratio

Figure 4.5 compares the heat-transfer enhancement and pressure-drop ratio for the different VG geometries. All VGs improved heat transfer compared with the baseline channel, with the CUVG providing the highest enhancement (up to 77%). However, the improved thermal performance was accompanied by increased pressure losses due to flow blockage and vortex generation. Among the investigated configurations, the CUVG achieved the best balance between heat-transfer enhancement and hydraulic penalty [P1].

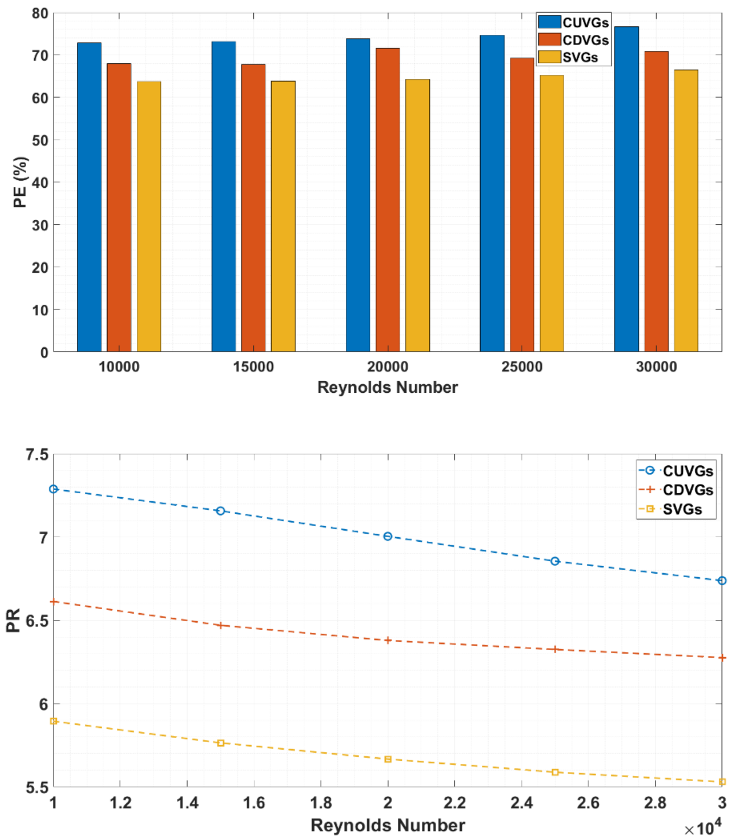


Figure 4.5 Variation of PE and PR with Re for different VG types [P1].

4.5 Overall performance evaluation

Figure 4.6 presents the variation of the PEC with Reynolds number for the different VG geometries. The PEC increased with increasing Reynolds number, indicating improved thermal–hydraulic performance at higher flow rates. All configurations achieved PEC values close to unity, demonstrating a favorable balance between heat-transfer enhancement and pressure-drop penalty. The SVG provided the highest overall PEC values, while the CUVG and CDVG offered greater heat-transfer enhancement at the expense of higher hydraulic losses [P1].

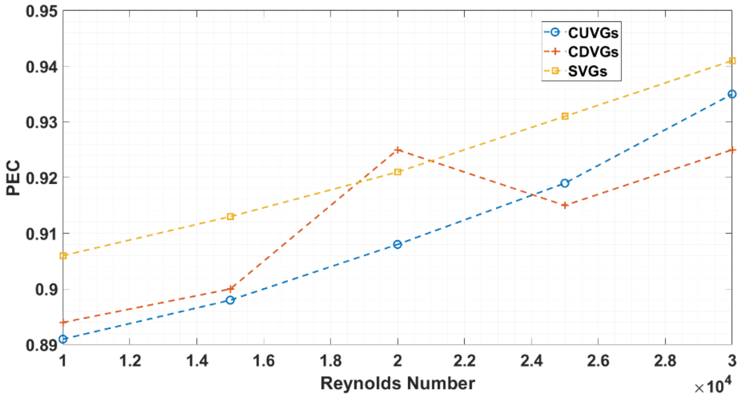


Figure 4.6 Variation of PEC with Re for different VG types [P1].

The results demonstrate that vortex generators can significantly improve the thermal performance of semi-circular corrugated channels by enhancing fluid mixing and disrupting the thermal boundary layer. Among the investigated configurations, the CUVG achieved the highest heat-transfer enhancement due to its more effective flow redirection toward the corrugated wall and stronger vortex generation. The findings also highlight the importance of geometric consistency between the VG shape and the corrugated channel profile in improving thermal–hydraulic performance.

5. EFFECT OF VORTEX GENERATOR SIZE

Chapter 5 investigates the influence of vortex-generator size on the thermal–hydraulic performance of a semi-circular corrugated channel. After identifying the most effective VG geometry in the previous chapter, the VG size was varied to evaluate its effect on flow behavior, heat-transfer enhancement, and pressure-drop characteristics. The objective was to identify a suitable VG size that provides improved thermal performance while maintaining acceptable hydraulic losses.

5.1 Isothermal and flow visualization

Figure 5.1 presents the isotherm contours and streamlines for the baseline channel and the VG configuration with S = 4 mm. The introduction of the vortex generator reduced the size of the recirculation zone and produced a thinner thermal boundary layer compared with the baseline channel. This behavior enhanced fluid mixing and improved heat transfer by increasing fluid–wall interaction. The results demonstrate the effectiveness of the selected VG size in modifying the flow structure and promoting thermal enhancement [P10].

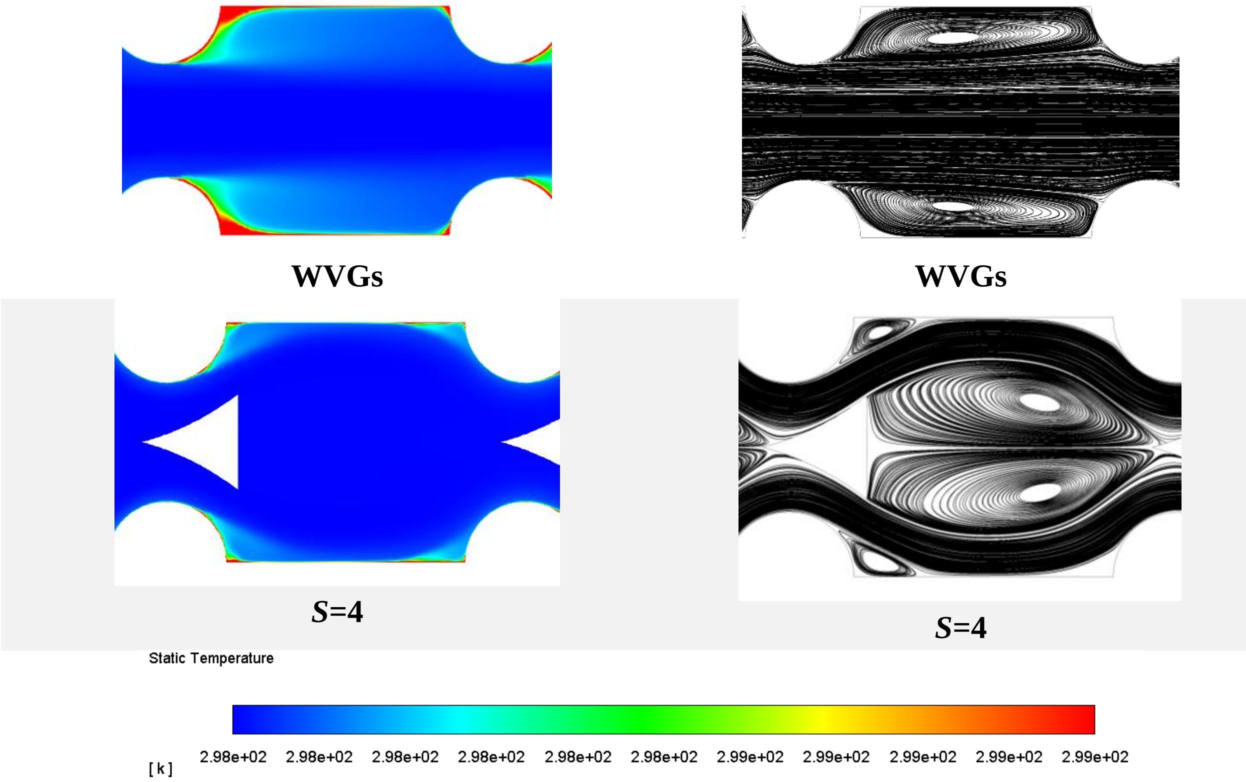


Figure 5.1 Isotherm contours and streamlines showing the effect of different VG sizes [P10].

5.2 Performance Enhancement and Pressure Ratio

Figure 5.2 presents the heat-transfer enhancement and pressure ratio for the investigated VG sizes. Increasing the VG size improved heat-transfer performance, with the largest VG providing the highest enhancement. However, this improvement was accompanied by a substantial increase in pressure drop due to stronger flow blockage and wall shear stress. These results highlight the trade-off between thermal enhancement and hydraulic penalty associated with increasing VG size [P10].

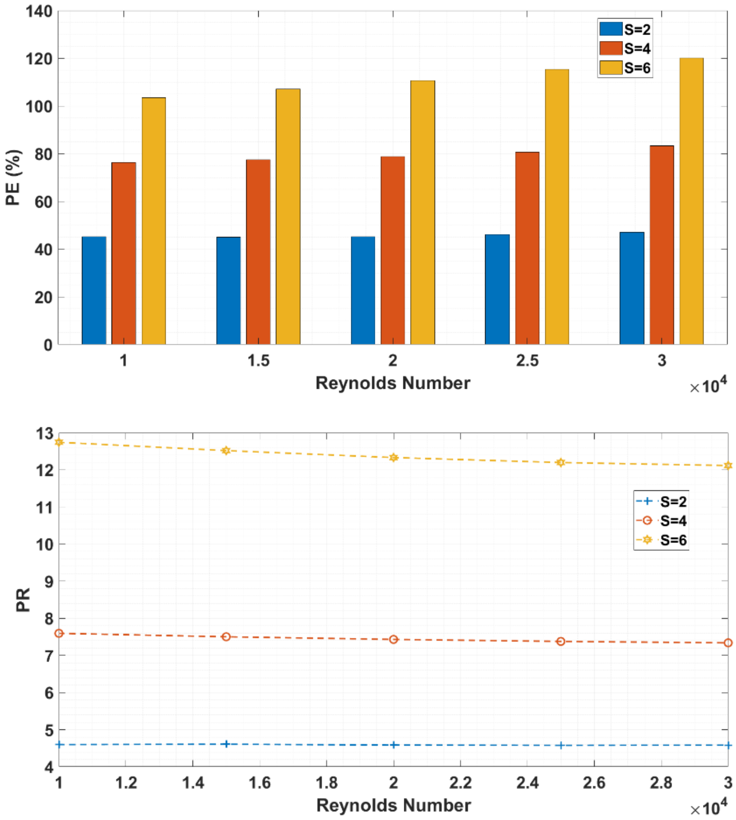


Figure 5.2 Variation of PE and PR with Re for different values of VG size [P10].

5.3 Overall performance evaluation

Figure 5.3 presents the variation of the PEC with Reynolds number for the investigated VG sizes. The PEC increased with increasing Reynolds number, indicating improved thermal–hydraulic performance at higher flow rates. Among the investigated configurations, the largest VG size achieved the highest PEC value (≈0.95), demonstrating the most favorable balance between heat-transfer enhancement and pressure-drop penalty [P10].

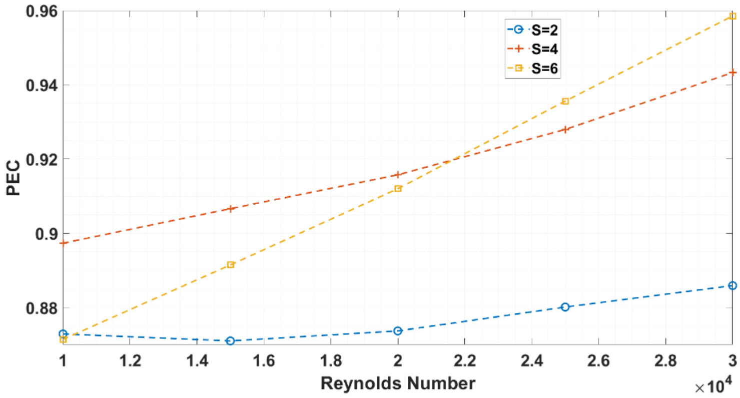


Figure 5.3 Variation of PEC with Re for different VG sizes [P10].

The results demonstrate that VG size strongly influences the thermal–hydraulic performance of the corrugated channel. Increasing the VG size enhanced fluid mixing and heat transfer but also increased pressure losses. Among the investigated configurations, the larger VG sizes provided the best overall performance, highlighting the importance of VG size optimization in corrugated heat exchangers. Based on the obtained results, a VG size of 5 mm was selected for the subsequent investigation of VG position.

6. EFFECT OF VORTEX GENERATOR POSITION

Chapter 6 investigates the influence of vortex-generator streamwise position on the thermal–hydraulic performance of a semi-circular corrugated channel. With the VG geometry and size selected from the previous chapters, different streamwise locations were examined to evaluate their effect on flow structure, heat-transfer enhancement, and pressure-drop characteristics. The objective was to identify the VG position that provides the best overall thermal–hydraulic performance.

6.1 Isothermal and flow visualization

Figure 6.1 presents the isotherm contours and streamlines for the selected VG position (d = 0 mm). The vortex generator modified the recirculation pattern inside the corrugated channel and reduced the thermal boundary-layer thickness compared with the baseline channel. The generated vortices enhanced fluid mixing and fluid–wall interaction, leading to improved heat-transfer performance. These results demonstrate the influence of VG position on the flow structure and thermal behavior of the corrugated channel [P11].

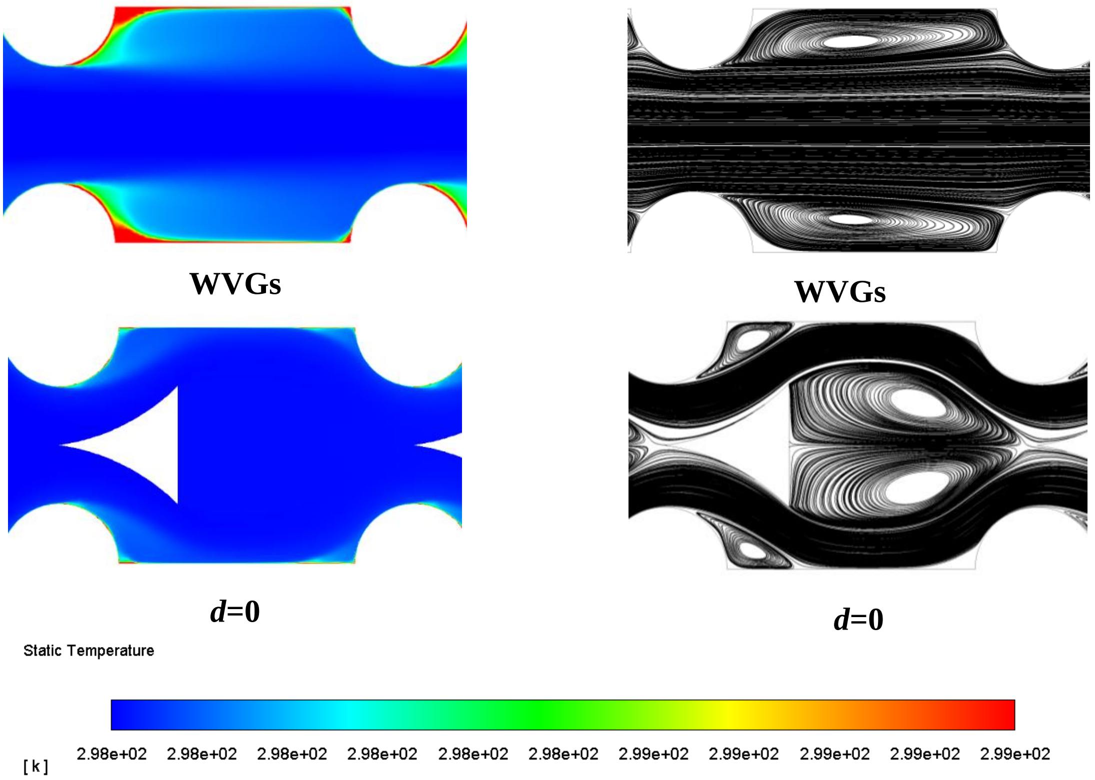


Figure 6.1 Isotherm contours and streamlines showing the effect of different VG positions [P11].

6.2 Performance Enhancement and Pressure Ratio

Figure 6.2 presents the heat-transfer enhancement and pressure ratio for the investigated VG positions. The VG located at *d* = –2 mm achieved the highest heat-transfer enhancement (≈121%) due to its stronger interaction with the corrugation-induced flow structures. However, this configuration also produced the highest pressure-drop penalty. The results demonstrate that VG position has a significant influence on the thermal–hydraulic performance of the corrugated channel [P11].

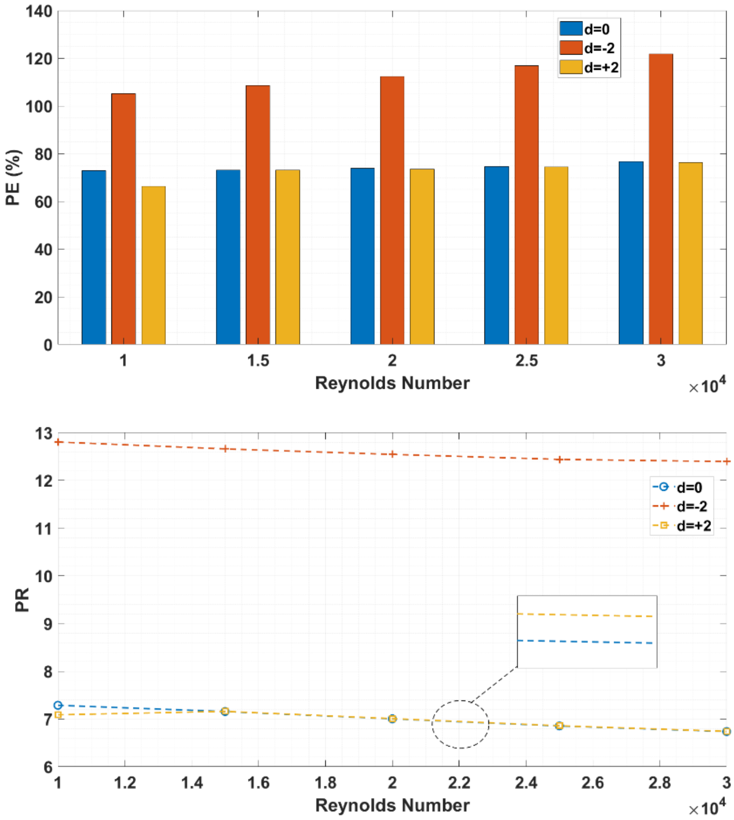


Figure 6.2 Variation of PE and PR with Re for different VG positions [P11].

6.3 Overall performance evaluation

Figure 6.3 presents the variation of the PEC with Reynolds number for the investigated VG positions. The configuration with *d* = –2 mm achieved the highest PEC value (≈0.96), indicating the most favorable balance between heat-transfer enhancement and pressure-drop penalty. These results identify *d* = –2 mm as the optimal VG position for improving the overall thermal–hydraulic performance of the corrugated channel [P11].

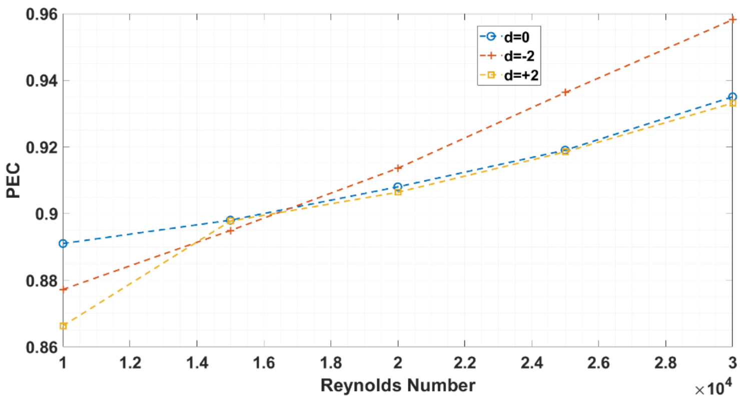


Figure 6.3 Variation of PEC with Re for different VG positions [P11].

The results demonstrate that the streamwise position of the vortex generator strongly influences the thermal–hydraulic performance of the corrugated channel. Placing the VG near the corrugation entrance (*d* = –2 mm) provided the highest heat-transfer enhancement and PEC by promoting stronger fluid mixing and reducing recirculation zones near the walls. These findings highlight the importance of VG positioning as a key design parameter for optimizing thermal performance in corrugated channels.

7. SINGLE VG VS. TWO-PAIR VG CONFIGURATION

Chapter 7 presents a comparison between an optimized single-body vortex generator and a two-pair VG arrangement in a semi-circular corrugated channel. The objective was to evaluate the influence of the number of vortex generators on flow behavior and overall thermal–hydraulic performance, and to determine whether a two-pair configuration offers advantages over a single optimized VG design.

7.1 Flow field visualization

Figure 7.1 shows the velocity contours. The velocity is concentrated in the middle of the channel, while dead zones appear near the corrugation corners because of the corrugation pitch. The use of VGs redirects the flow toward the walls, increasing the near-wall velocity and improving fluid–wall interaction. As the distance between the VGs increases, the velocity near the walls becomes higher. This indicates that wider VG spacing allows the generated vortices to develop more effectively before interacting with adjacent flow structures. At A = 6 mm, the near-wall velocity is the highest, resulting in better contact between the fluid and the wall [P5].

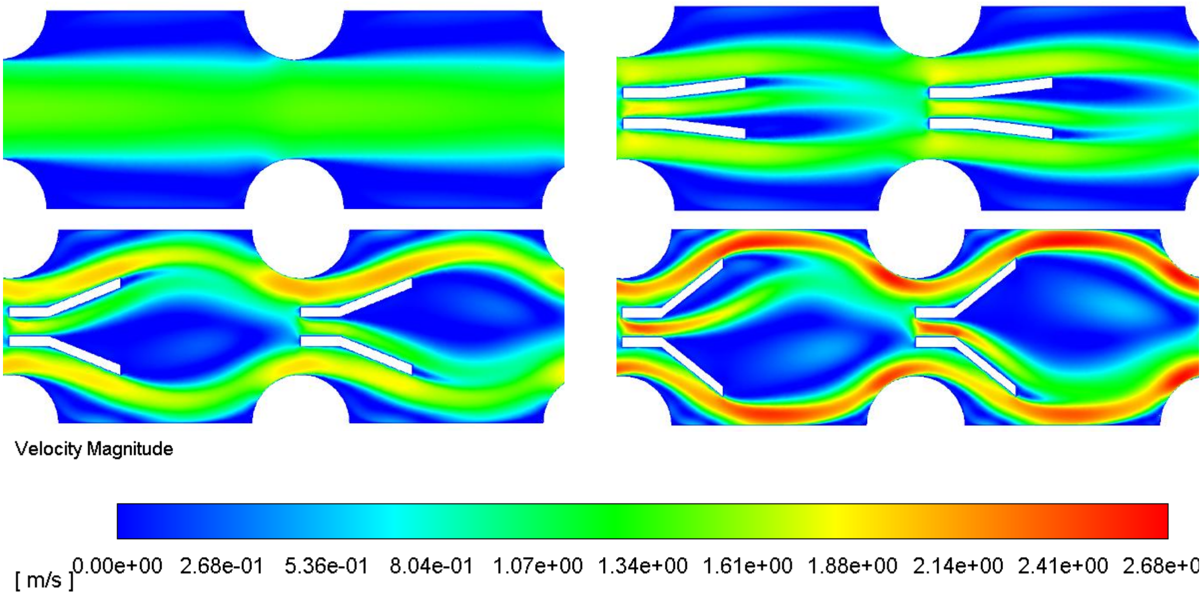


Figure 7.1 Velocity contours for the two-pair VG configuration [P5].

Figure 7.2 presents the velocity streamlines. The dead zones correspond to fluid recirculation regions that reduce the local heat transfer efficiency near the corrugated walls. The VGs reduce the recirculation zones near the wall but generate a larger recirculation region in the middle of the channel, which contributes to additional pressure loss. The spacing between the VGs also affects the flow structure. Increasing the VG distance reduces the recirculation near the corrugated wall while enlarging the central recirculation region. This behavior suggests that wider spacing allows stronger vortex development in the channel core, leading to enhanced mixing but also greater momentum dissipation [P5].

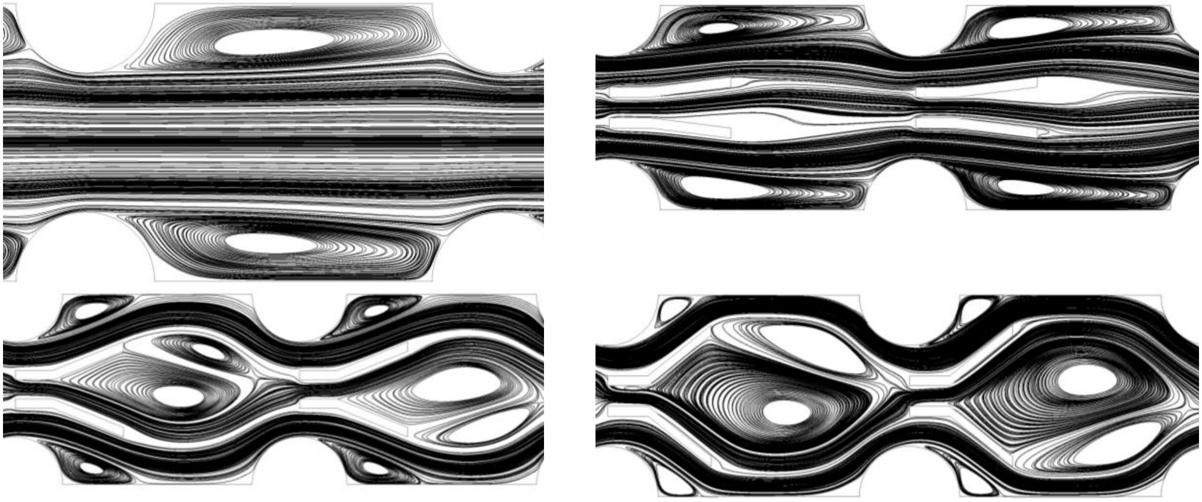
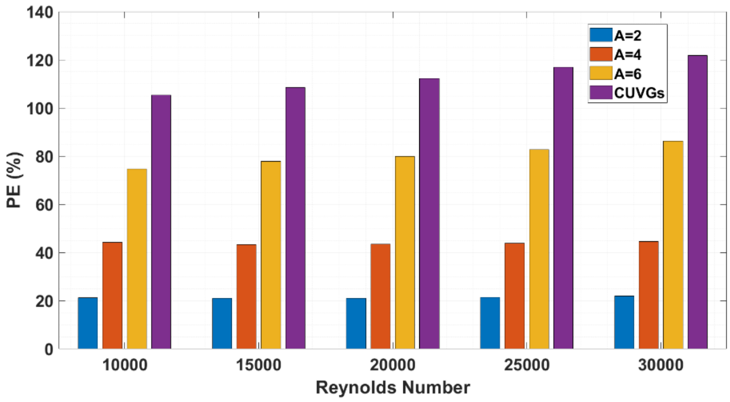


Figure 7.2 Streamlines for the two-pair VG configuration [P5].

7.2 Heat transfer enhancement and pressure ratio

Figure 7.3 present the PE (Equation (12)) and PR (Equation (11)) varying with *Re*. The VGs show a good effect on heat transfer enhancement, which increases respectively with the increase of the distance. The highest value is for *A* = 6 mm, about 86%, while the lowest is for *A* = 2 mm, about 22%. *A* = 4 mm shows average performance. The improved enhancement at larger spacing is associated with stronger development of the generated vortices and a wider interaction region between the flow core and the heated walls. The pressure drop increases more than 9 times at the largest distance, while it is about 5 times and 4 times for *A* = 4 mm and *A* = 2 mm, respectively.

For comparison, the best configuration of the single-body VGs (CUVGs) yielded a higher heat-transfer enhancement of around 121%, though with a larger pressure penalty of nearly 12.5 times. This indicates that the single-body VG produces stronger and more concentrated flow disturbance than the two-pair configurations, resulting in greater thermal enhancement but also higher momentum loss [P5].



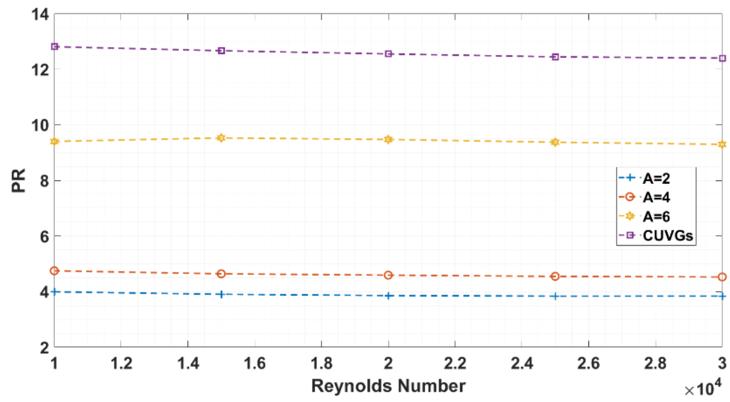


Figure 7.3 Variation of PE and PR with Re for the two-pair VG configuration.

7.3 Overall Performance Evaluation

To balance between heat transfer enhancement and pressure drop, the thermal hydraulic performance coefficient was measured, as shown in Figure 7.4. The smallest distance has a lower PEC compared to the other two distances. The cases A = 4 mm and A = 6 mm range between 0.83 and 0.88, which is close to one, with each having an advantage within a specific Reynolds number range. A = 4 mm shows higher values for *Re* between 10,000 and 26,000, while A = 6 mm performs better above 26,000. This indicates that larger spacing becomes more effective at high flow rates, where the stronger flow momentum supports better vortex development with a relatively lower hydraulic penalty.

For comparison, the single-body configuration exhibits higher PEC values across most *Re*. At *Re* = 30,000, the PEC reaches approximately 0.96, which is very close to the ideal value of one, indicating a stronger overall balance between heat-transfer enhancement and pressure drop than the two-pair cases. This behavior is consistent with its higher heat-transfer performance reported earlier. Based on these results, the single-body VG (CUVGs) provides the best overall thermal–hydraulic performance among the configurations studied.

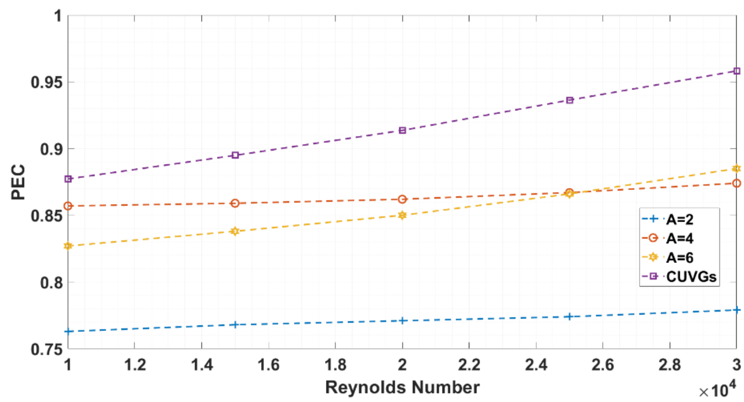


Figure 7.4 Variation of PEC as a function of Re for the two-pair VG configuration.

The results demonstrate that the optimized single-body CUVG provided better overall thermal–hydraulic performance than the two-pair VG arrangement. Although the two-pair configuration increased flow disturbance, it also produced higher pressure losses, resulting in a less favorable performance balance. In comparison, the optimized single CUVG (S = 5 mm, d = –2 mm) achieved a maximum heat-transfer enhancement of approximately 121%, compared with approximately 112% reported for paired winglet vortex generators in previous studies. These findings highlight the importance of geometric consistency between the VG shape and the corrugated channel profile in achieving effective thermal enhancement.

8. NEW SCIENTIFIC RESULTS – THESES

This thesis presented a comprehensive numerical investigation of heat transfer enhancement in a semi-circular corrugated channel using combined passive enhancement techniques, including vortex generators. The study systematically examined the influence of VG geometry, size, and streamwise position. The main original contributions and findings of the thesis are summarized as follows:

T1. A novel contribution of this thesis is that I investigated three different vortex generator geometries in relation to the corrugated channel shape, which has received limited attention in previous studies. The geometry of the vortex generators strongly influences the flow behavior and heat transfer characteristics in corrugated channels. Concave-up vortex generators generate stronger and more stable vortical structures, which enhance fluid mixing and effectively disrupt the thermal boundary layer, resulting in the highest heat transfer enhancement among the investigated designs. Concave-down and straight vortex generators also improve heat transfer compared to the baseline configuration, but with relatively weaker vortex intensity. These findings demonstrate that VG geometry plays a key role in controlling vortex strength and heat transfer performance [P1] [P2].

T2. This thesis demonstrates the influence of vortex generator size on the thermal–hydraulic performance of corrugated channels. In this work, I investigated the effect of VG size on flow disturbance, thermal boundary-layer development, and pressure-drop behavior. The results demonstrate that increasing the vortex generator size significantly enhances heat transfer in corrugated channels by intensifying flow disturbance, thinning the thermal boundary layer, and promoting stronger fluid mixing. This leads to higher local and average Nusselt numbers. However, the thermal improvement is accompanied by an increase in wall shear stress and pressure drop. Among the investigated configurations, moderate VG sizes (S = 4–6 mm) provide the most favorable thermal–hydraulic compromise, achieving PEC values close to unity, which indicates efficient performance without excessive hydraulic penalties. This finding highlights the importance of VG size optimization in corrugated channels, which has received limited attention in previous studies [P10] [P2].

T3. This thesis demonstrates the importance of vortex generator streamwise position on the flow structure and thermal–hydraulic performance in a corrugated channel. In particular, I studied the influence of VG placement relative to the corrugation geometry. The position of the vortex generator plays a critical role in determining overall performance. Locating the VG near the corrugation entrance ($d = -2$) produces the highest heat transfer enhancement due to stronger mixing and suppression of recirculation zones, resulting in a maximum PEC of approximately 0.96. Although this configuration induces a higher pressure drop, it offers the best overall thermal–hydraulic balance. This confirms that strategic placement of VGs is as important as their size in achieving optimal heat exchanger performance. This result highlights that accurate VG positioning within corrugated channels is a key design parameter, and its systematic assessment has received less attention compared to VG geometry and size in previous studies [P11].

T4. Another contribution of this thesis is the direct comparison between a two-pair vortex generator configuration with a single-body concave-up vortex generator (CUVG) to determine which arrangement provides better thermal–hydraulic performance in a corrugated channel. In this part of the work, I compared the thermal enhancement produced by paired and single-body VG configurations under identical operating conditions. Many previous studies have employed two-pair vortex generator configurations in corrugated channels. The results show that although the two-pair configuration enhances heat transfer, its maximum improvement (approximately 86%) remains lower than that achieved by the single-body CUVG, which reaches about 121%. This indicates that a properly designed single-body VG can outperform more complex multi-VG configurations. This demonstrates that a well-designed single VG can outperform more complex multi-VG configurations while avoiding unnecessary geometric complexity [P5] [P2].

LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

(P1) Tanougast, A., Bessaih, R., & Hriczó, K. (2025). Comparative study of different vortex generator designs in corrugated channels for turbulent heat transfer enhancement. *Results in Physics*, 108450.

(P2) Tanougast, A., & Hriczó, K. (2025). Enhanced heat transfer in wavy channels with vortex generators: A CFD investigation. *International Journal of Thermofluids*, *30*, 101405.

(P3) Tanougast, A., & Hriczó, K. (2025). Advancements in Heat Exchangers for Improved Engine Cooling: A Comprehensive Literature Review. *Periodica Polytechnica Transportation Engineering*, *53*(4), 431-439.

(P4) Tanougast, A., Omle, I., & Hriczó, K. (2025). Turbulent Hybrid Nanofluid Flow in Corrugated Channels with Vortex Generators: A Numerical Study. *Fluids*, *10*(10), 249.

(P5) TANOUGAST, A., & HRICZÓ, K. (2025). Effect of Winglet-Designed Vortex Generators on Heat Transfer Performance in Corrugated Channels. *Applied Scientific Research*, *5*(2), 5-14.

(P6) Tanougast, A., & Hriczó, K. (2025, September). Numerical modeling of unsteady heat convection in turbulent flow. In *AIP Conference Proceedings* (Vol. 3315, No. 1, p. 180006). AIP Publishing LLC.

(P7) Tanougast, A., & Hriczó, K. (2025). Comparison of Turbulence Models in the Simulation of Fluid Flow in Corrugated Channel. *Advances in Science and Technology*, *165*, 53-64.

(P8) Tanougast, A., & Hriczó, K. (2023). Numerical study of the vortex generators effects in a corrugated channel for turbulent flow. *MULTIDISZCIPLINÁRIS TUDOMÁNYOK: A MISKOLCI EGYETEM KÖZLEMÉNYE*, *13*(4), 30-41.

(P9) TANOUGAST, A., Hriczo, K. (2023). Numerical simulation of nanofluid flow through a corrugated channel with vortex generator - In: Gép, ISSN 0016-8572, 2023. (vol. 74), 2-3. no., 72-77 p.

(P10) Tanougast, A., Bessaih, R., & Hriczó, K. Effect of vortex generator size on thermal–hydraulic performance in a corrugated channel. Pollack Periodica. **Accepted**

(P11) Tanougast, A., & Hriczó, K. Numerical Investigation of Vortex Generator Position Effects on Thermal–Hydraulic Performance in a Corrugated Channel. Design of Machines and Structures. **Accepted**

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