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Effect of Winglet-Designed Vortex Generators on Heat Transfer Performance in Corrugated Channels

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Abstract

This study focuses on improving heat transfer within corrugated channel. These channels are used to improve fluid mixing and heat transfer, but they typically result in recirculation zones inside. The study's goal is to reduce the amount of space that recirculates around the walls. To achieve this, we introduce vortex generators (VGs), where solid bodies are inserted to manipulate and change the flow direction. Winglet designs are used for the vortex generators at different angles, represented by the change in distance between the upper and lower winglets (D=2, 4, and 6 mm). This study is compared with a channel without vortex generators. The work is simulated using commercial software ANSYS Fluent based on conservation laws under different Reynolds numbers and turbulent flow. The SST k-omega model is commonly used due to its higher accuracy around walls. Parameters such as Nusselt number, pressure drop, pressure ratio, and performance enhancement factor are evaluated in detail.

INTRODUCTION

The vortex generator is a passive heat transfer enhancement technique used to manipulate and change the direction of the flow. The VGs are used in many applications such as heat exchangers, solar radiators, or heating and cooling systems. It increases the heat transfer efficiency but is combined with a pressure drop [1]. Many researchers have investigated the corrugated channels where they found that it increases heat transfer because of the larger area compared to a smooth channel and helps in fluid mixing and increased turbulence [2, 3, 4].

Mohammad and Davood [5] investigated six different shapes of vortex generators in a fin-plate heat exchanger with a triangular channel cross-section. Simple rectangular vortex generators improved heat transfer in the sample heat exchanger by 7%. The vortex generators' effectiveness in enhancing heat transfer increases with greater height and an optimal angle of attack. Ruifang et al. [6] investigated the ideal design of VGs that take into account the three-dimensional rotational effect in order to increase the aerodynamic performance of wind turbines. The results indicate that vortex generators (VGs) can enhance wind turbine power output by delaying airflow separation along the blade surface. In a periodic corrugated channel with discrete V-type winglets, Selma [7] examined the hydraulic and thermal performance of pulsing flow. Three distinct channel flows were taken into consideration: non-winglet, solid winglet, and perforated winglet configurations. The results showed that perforated winglets reduced the friction factor compared to solid winglets, and that the thermal performance significantly improved with increasing pulsation amplitude. Khamis et al. [8] studied rectangular channels equipped with transverse corrugations and longitudinal winglet vortex generators. Corrugated channels form static transverse vortices that confine fluid particles, thereby restricting heat transfer particularly in the diverging regions. At a Reynolds number (Re) of 20,000, corrugated channels with winglets exhibit Nusselt numbers that are 167.7% and 61.8% greater than those of smooth and corrugated channels, respectively. However, this enhancement in heat transfer comes with an increased pressure drop. An innovative sinusoidal wavy winglet type vortex generator was presented by Jiafeng et al. [9] to increase the fin-and-tube heat exchangers' air-side heat transfer capacity. Longitudinal vortices are induced within the channel to improve convective heat transfer. The surface goodness factor, friction factor ratio, and Nusselt number ratio in this study fall within the following ranges: 1.09 to 1.52, 1.09 to 2.31, and 1.06 to 1.24.

Based on previous studies, corrugated channels have shown improved heat transfer compared to smooth channels. However, the corrugation can create recirculation zones that hinder flow performance. To address this, vortex generators are introduced to help reduce these zones. In this study, a semi-circular corrugated channel is investigated using winglet-shaped vortex generators [10, 11] with varying distances between them at different Reynolds numbers.

2. Mathematical Model

2.1. Governing Equations

The fundamental equations governing the flow include the conservation of mass, momentum, and energy, and their respective mathematical expressions are presented in [3]:

- The mass conservation equation

$$\nabla.(\rho\vec{u}) = 0. \tag{1}$$

- The momentum equation

$$\nabla.(\rho\vec{u} \otimes \vec{u}) = -\nabla p + \nabla\tau. \tag{2}$$

- The energy equation

$$\nabla.(\rho\vec{u}C_pT) = \nabla.(k\nabla T - C_p\rho\overline{uT}). \tag{3}$$

The k-ω turbulence model characterizes turbulence using two transport equations: one for turbulent kinetic energy (k) and another for the specific dissipation rate (ω). Turbulent dissipation refers to the rate at which the velocity fluctuations diminish [12, 13].

$$\nabla.(\rho\vec{u}k) = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + G_k - Y_k, \tag{4}$$

$$\nabla.(\rho\vec{u}\omega) = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\nabla \omega\right] + G_\omega - Y_\omega + D_\omega. \tag{5}$$

$\mathrm{G_k}$ is kinetic energy production rates and $\mathrm{G_\omega}$ production rates of ω. Y_k and Y_ω are the loss rates k and ω due to turbulence.

The pressure difference across the channel from inlet to outlet is given by:

$$\Delta p = p_{in} - p_{out.}$$

The average Nusselt number is determined using the following expression:

$$Nu = \frac{h\,D_h}{k},$$

where h denotes the convective heat transfer coefficient $(\mathrm{W/(m^2\,K)})$, k is the thermal conductivity of the fluid $(\mathrm{W/(m\,K)})$. D_h is the hydraulic diameter (m) corrugated channel which can be defined:

$$D_h = H + h.$$

To describe the increase in pressure drop in a wavy channel due to vortex generators (VGs), the pressure drop ratio (PR) is defined as [14]:

$$PR = \frac{\Delta p_{VGs}}{\Delta p_{WVGs}},$$

where Δp_{VGs} is the pressure drop with vortex generators and Δp_{WVGs} without vortex generators.

The enhancement in heat transfer due to the VGs is expressed as the percentage increase compared to a channel without VGs [14]:

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

where Nu_{VGs} is the Nusselt number with vortex generators and Nu_{WVGs} without vortex generators.

The thermal-hydraulic performance coefficient is used to assess the effect of different vortex generator spacing (PEC) [15]:

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

2.2. Boundary Conditions

The Navier-Stokes equations are applied to the following boundary conditions:

- At the entrance to the channel

$$T_{in} = 298K, \qquad u_{in} = u = \frac{Re\mu}{\rho D_h}, \qquad 10000 < Re < 30000.$$

- Near smooth and corrugated walls

  - smooth channel $\frac{\partial T}{\partial y} = 0.$
  - corrugated channel $\frac{\partial T}{\partial y} = q_w.$

- To the output

$$\frac{\partial u}{\partial x} = 0; \ \frac{\partial v}{\partial x} = 0; \ \frac{\partial T}{\partial x} = 0; \ \mathrm{p} = \mathrm{p}_{atm}.$$

2.3. Numerical Modeling

Figure 1 presents the physical model, which is composed of an entry channel (L1) of 200 mm, a test section (L2) of 200 mm, and an exit channel (L3) of 100 mm. The maximum height (H) is 10 mm, while the minimum height (h) is 5 mm. The wavelength (P) is 10 mm, and the diameter of the half circle (W) is 5 mm. The VGs extrude from the middle of the half circle with a distance (A) of 2 mm, have a length (L) of 4 mm, a thickness (E) of 0.5 mm, and different distances between two VGs (D) of 2, 4, and 6 mm. The working fluid in the simulations is water, with a density of 998.2 kg/m³, a thermal conductivity of 0.6 W/m·K, and a dynamic viscosity of 0.001 Pa·s.

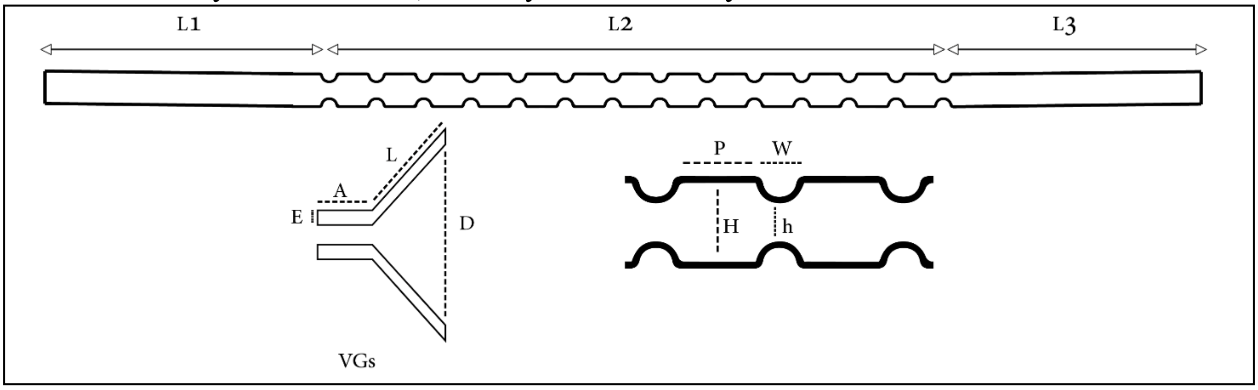


Figure 1 Geometry and vortex generations definition the wavey channel

3. Mesh Independence

The mesh can have significant effect on the result. To avoid it, we studied five different meshes with node counts ranging from 98037 to 557168. Inflation layers were applied near the walls and vortex generators (VGs). The relative error measured based on the average Nusselt number. We can notice between mesh 4 and 5 where the error almost stable about 0.5%. We choose mesh 4 with 392205 nodes to continue my study.

MESH	Number of noeds	Error (%)
1	98037	_
2	148639	0.8591
3	226732	0.6446

4	392205	0.5194
5	557168	0.5160

4. Validation

Our results are compared with Ajeel et al. [2]. The average Nusselt number was calculated with Reynolds numbers varying in the range 10000–30000. As presented in Figure 2, the results show good agreement with the Nusselt number. In this comparison, we specifically considered the water case from Ajeel et al. [2], as it provides a consistent reference for validating the simulation methodology.

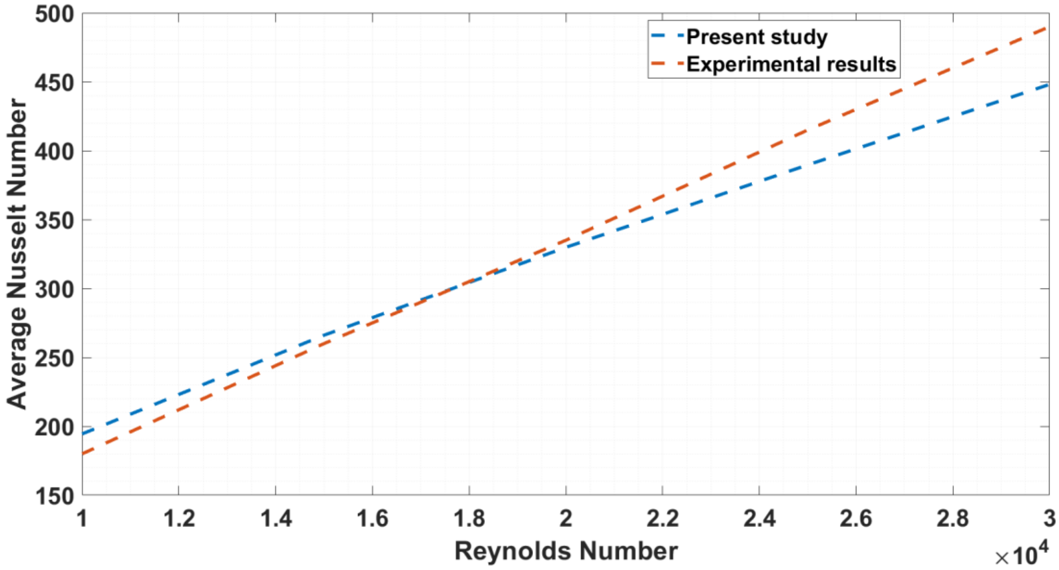


Figure 2 Comparing averaged Nusselt numbers with experimental results [2]

5. Results

Figure 3 shows the velocity contours. The velocity is concentrated in the middle of the channel while there is a dead zone because of the pitch of the corrugations. The use of vortex generators changes the flow direction toward the wall where the velocity increases. The increase of the distance between the VGs leads to velocity increase around the walls, where we can see at distance D = 6 mm it is higher, which makes better contact between the fluid and the wall.

Figure 4 presents the velocity streamlines. The dead zones are recirculation of the fluid, which decreases the efficiency of the heat transfer. The VGs decrease the recirculation zone around the wall but increase it in the middle, which causes a pressure drop. The distance of VGs affects the recirculation zone, where a higher distance reduces the recirculation zone near the wall while producing a larger one in the middle.

Figure 5a and 5b represent the x-velocity and temperature along a line at the middle of the corrugated section, varying with Y. The x-velocity exhibits a parabolic distribution at the center and reverses direction. The distances D = 4 mm and D = 2 mm increase the velocity closer to the center, while D = 6 mm shows higher velocity near the wall, which indicates better contact. The temperature shows variation around the walls while remaining constant in the fluid domain, indicating uniformity. The channel without VGs shows a higher temperature difference near the walls. Increasing the distance between VGs reduces this difference, meaning the thermal boundary layer becomes thinner, which improves heat transfer.

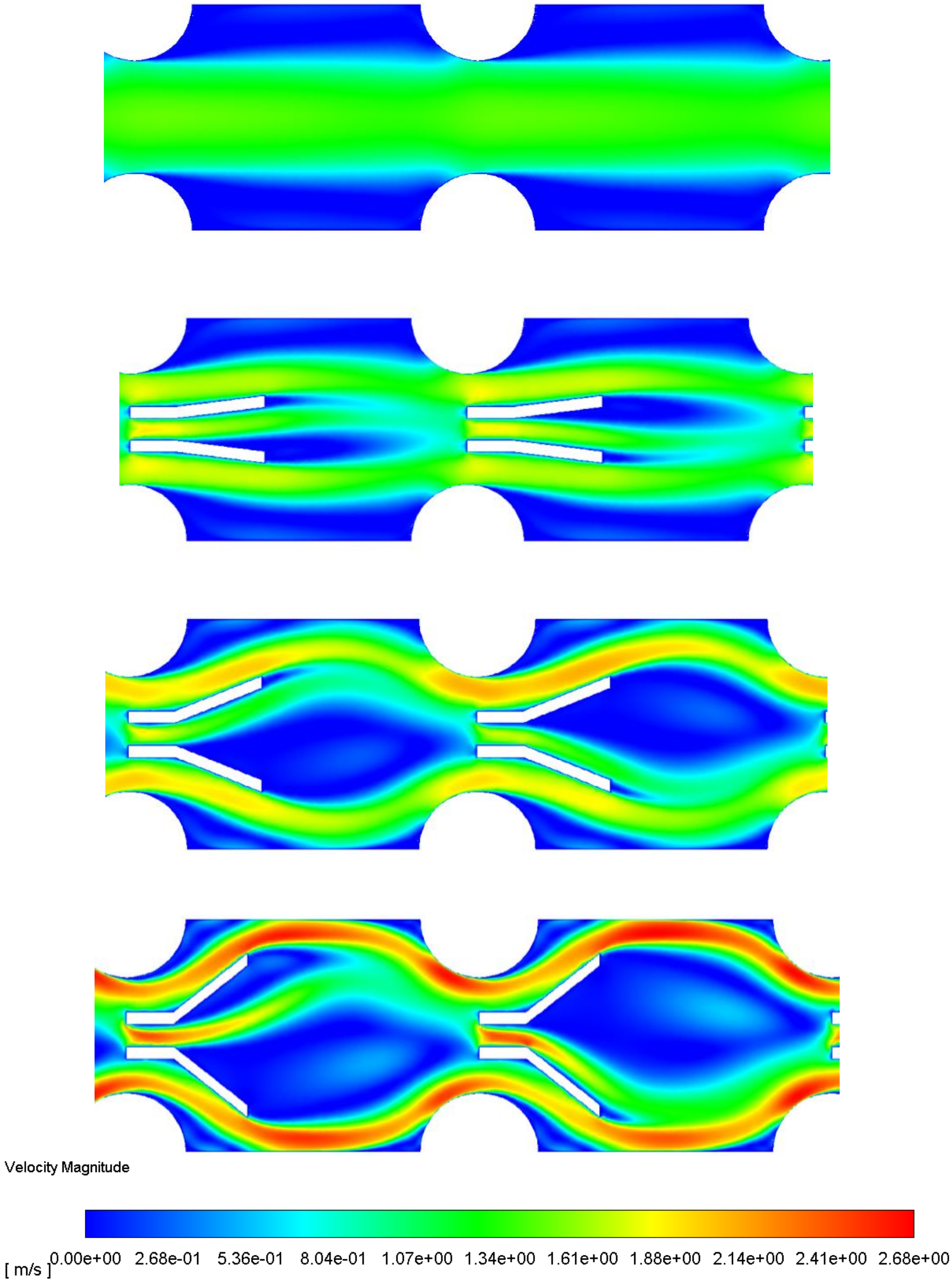


Figure 3 The velocity contours of the geometry with and without VGs

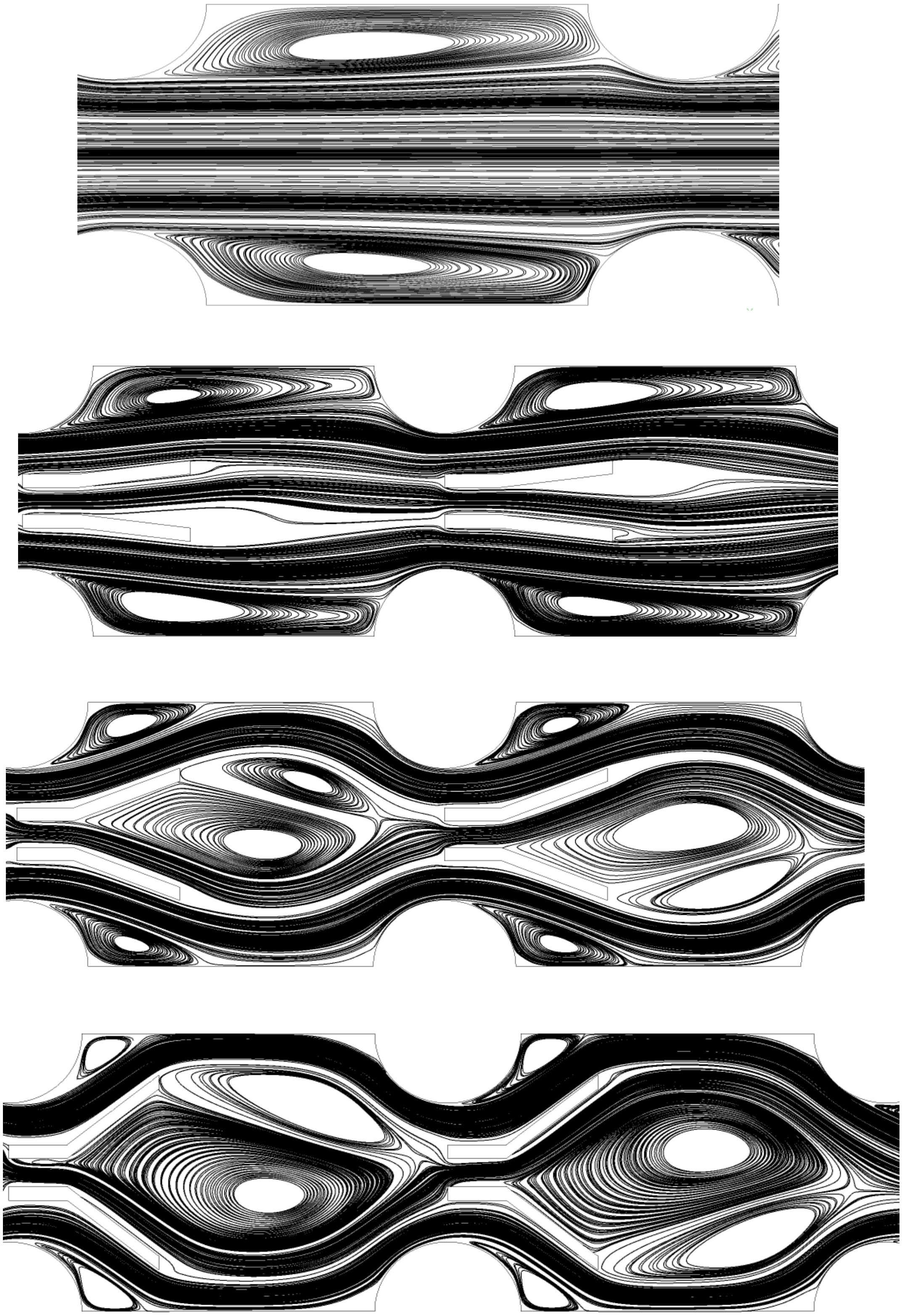
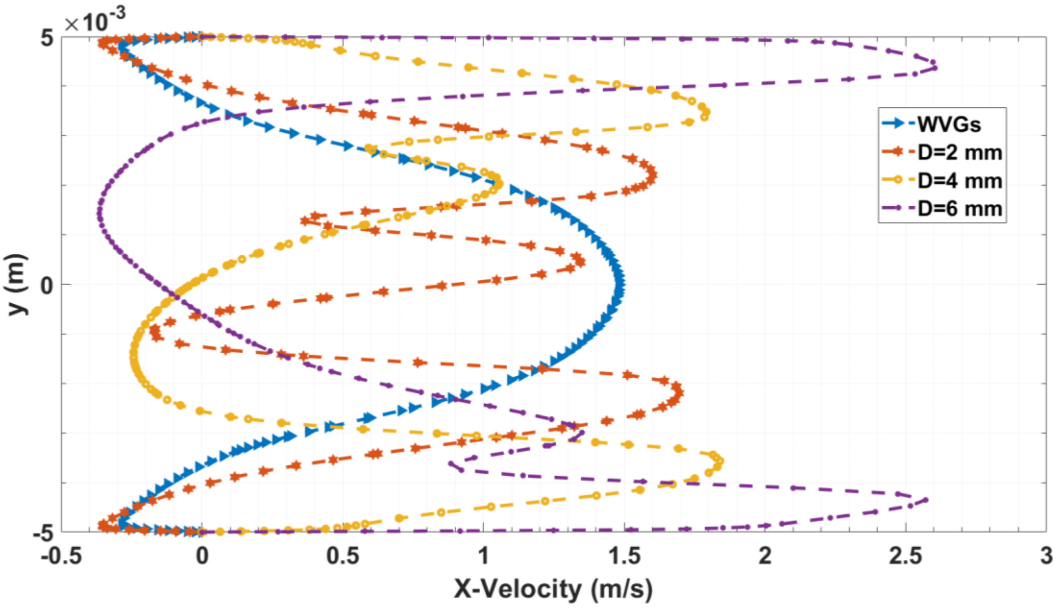


Figure 4 The velocity streamlines with and without VGs



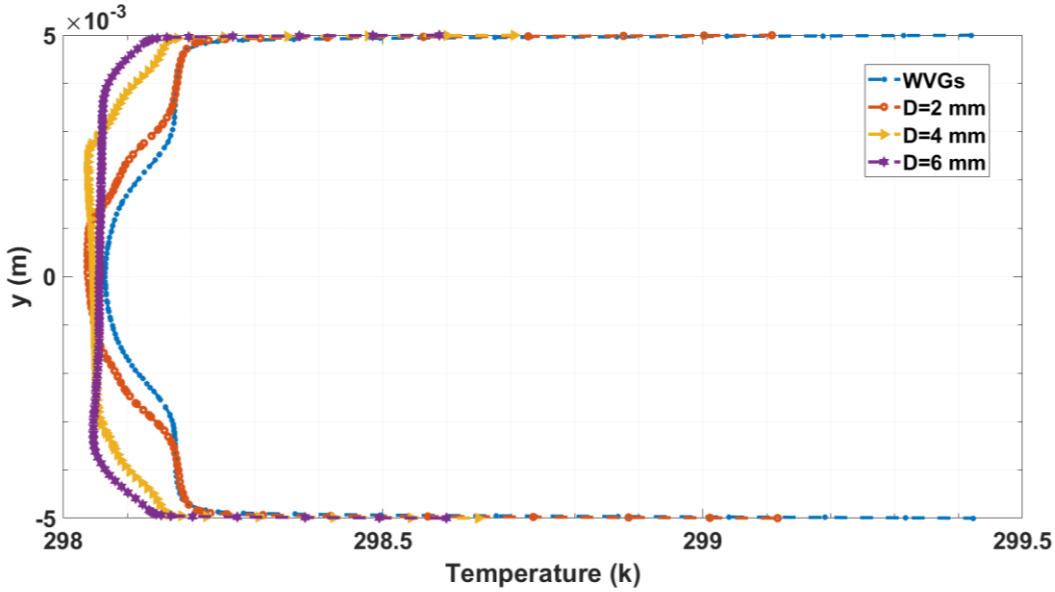


Figure 5 The variation of a) x-velocity and b) temperature along the y-axis

Figure 6a and 6b present the percentage heat transfer enhancement and pressure drop ratio varying with Reynolds number. The VGs show a good effect on heat transfer enhancement, which increases respectively with the increase of the distance. The highest value is for D = 6 mm, about 86%, while the lowest is for D = 2 mm, about 22%. D = 4 mm shows average performance. The pressure drop increases more than 9 times at the largest distance, while it is about 5 times and 4 times for D = 4 mm and D = 2 mm, respectively.

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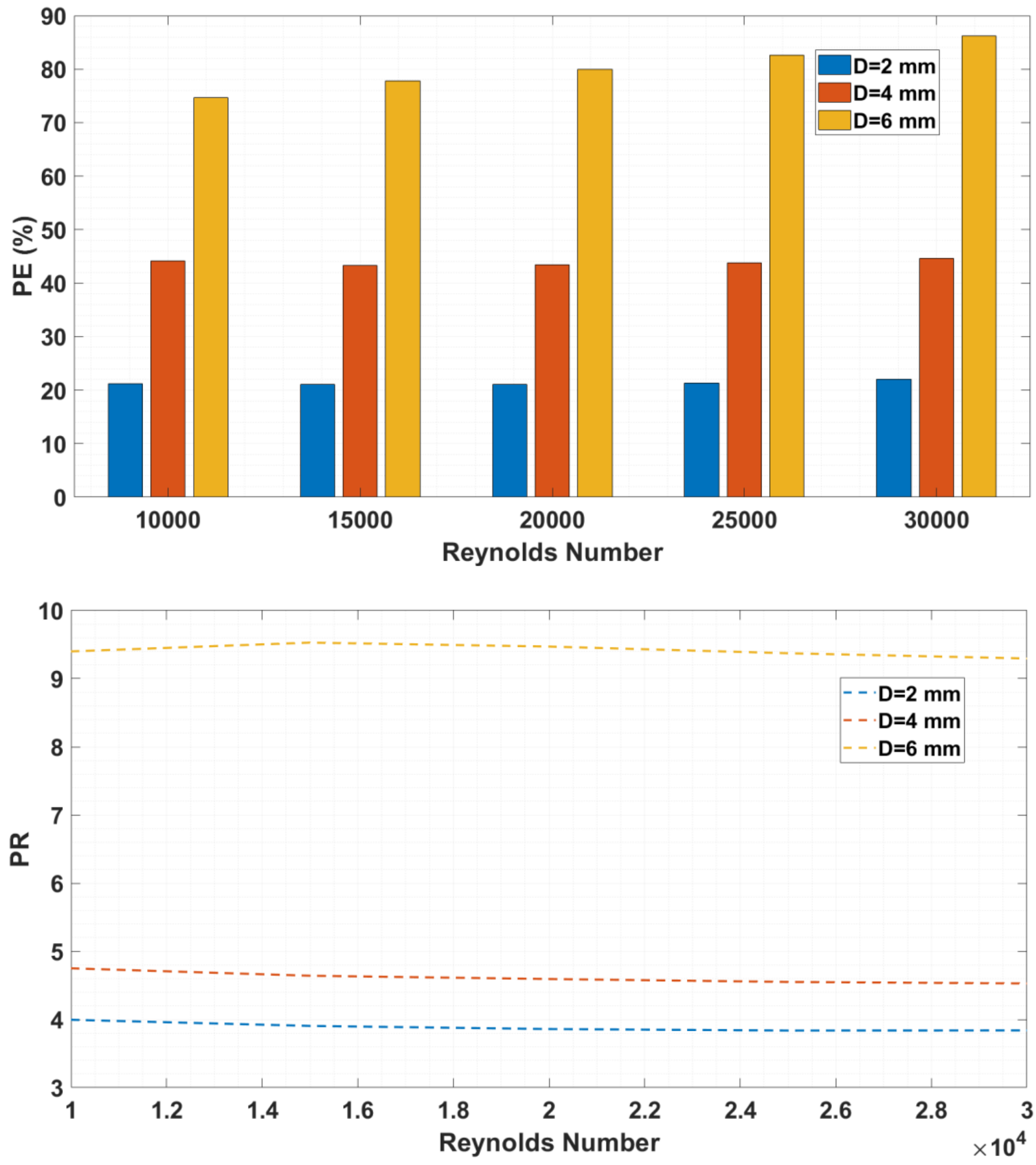

Figure 6 a) The percentage enhancement and b) the pressure drop ratio function of Reynolds number

To balance between heat transfer enhancement and pressure drop, the thermal hydraulic performance coefficient was measured, as shown in Figure 7. The smallest distance has a lower PEC compared to the other two distances. The cases D = 4 mm and D = 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. D = 4 mm shows higher values for Reynolds numbers between 10,000 and 26,000, while D = 6 mm performs better above 26,000.

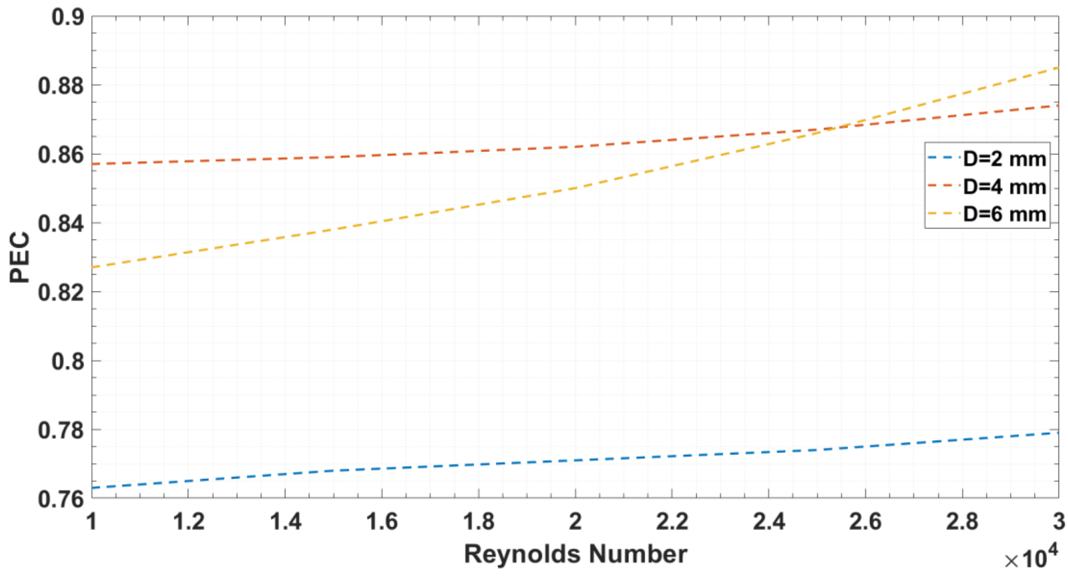

Figure 7 The thermal hydraulic performance coefficient function of Reynolds number

6. Conclusions

The effect of the distance between the two winglet VGs was examined with a focus on hydraulic and thermal performance. The main conclusions are as follows:

- Vortex generators (VGs) reduce recirculation zones near the corrugated wall, increasing local velocity and thinning the thermal boundary layer for better heat transfer.

- VGs enhance turbulence, especially near the wall, boosting heat transfer efficiency.

- Nusselt number and pressure drop increase with Reynolds number. VGs (D=6 mm) provide the highest heat transfer, followed by VGs D=4 mm. VGs with D = 2 mm provide only a modest improvement compared to a channel without VGs, due to strong flow interference between closely spaced VGs, which limits vortex formation and reduces heat transfer enhancement.

- VGs (D=6mm) enhance heat transfer by up to 86%, though with higher pressure loss.

- PEC analysis indicates that VGs with D = 6 mm provide the best overall thermal-hydraulic performance at higher Reynolds numbers, while D = 4 mm shows slightly better PEC at lower Reynolds numbers, reflecting the influence of vortex generator spacing on the thermal-hydraulic balance.

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Effect of Winglet-Designed Vortex Generators on Heat Transfer Performance in Corrugated Channels

Keywords: heat transfer, vortex generators, corrugated channel, convection, turbulent flow.

This study investigates heat transfer enhancement in semi-circular corrugated channels using winglet-shaped vortex generators (VGs) at different spacing distances (D = 2, 4, and 6 mm). Numerical simulations were performed in ANSYS Fluent with the SST k-ω turbulence model across turbulent flow regimes. Parameters including Nusselt number, pressure drop, pressure ratio, and thermal performance factor were analyzed. Results show that VGs reduce recirculation zones, increase near-wall velocity, and thin the thermal boundary layer, leading to improved heat transfer. The case with D = 6 mm achieved up to 86% enhancement but at the cost of higher pressure drop, while D = 4 mm provided the best overall thermal-hydraulic performance with a PEC close to 0.88. Comparisons with experimental data for water from Raheem et al. [2] confirm the validity of the model.