European Society of Computational Methods in Sciences and Engineering (ESCMSE)

Journal of Numerical Analysis, Industrial and Applied Mathematics (JNAIAM)
vol. 19, no. 1-2, 2026, pp. 69-76
ISSN 1790–8140

CFD Analysis of Vortex Generator Placement in Wavy Corrugated Heat Transfer Channels

A. Tanougast and **K. Hriczó** [1]

Institute of Mathematics,
Faculty of Mechanical Engineering and Informatics,
University of Miskolc,
Miskolc-Egyetemváros, H–3515, Hungary

Received 7 August, 2025; accepted in revised form 31 October, 2025

Abstract: The corrugated channels are common passive heat transfer enhancement methods in many applications. For better heat transfer, this channel could be improved further with another passive heat transfer enhancement method, which is vortex generators. This work focuses on the numerical investigation of wavy corrugated channels with inserted vortex generators, and we investigated the placement effect of the VGs. This model is simulated using ANSYS Fluent, which is commercial software based on the finite volume method, a suitable method for such CFD problems.

© 2025 European Society of Computational Methods in Sciences and Engineering

Keywords: CFD analysis, corrugated channel, heat transfer, vortex generator.

Mathematics Subject Classification: 76-XX (76-10), 80-XX (80-10)

PACS: 47.60.+i, 47.55.pb

1 Introduction

Heat transfer plays an important role in many engineering applications, such as HVAC systems, heat exchangers, and cooling devices. Methods for enhancing heat transfer performance are generally divided into three categories: active, passive, and compound techniques. Passive methods include the use of vortex generators (VGs), extended surfaces, surface modifications, irregular boundaries, and different corrugated channel geometries. These techniques are cost-effective and operate without the need for external power sources, but they typically provide lower heat transfer coefficients [1], [2].

Many experimental and numerical studies have looked at heat transfer in corrugated channels. Compared to straight channels, the corrugated ones generally improve heat transfer. This is mainly because the corrugations help mix the fluid more and increase the surface area in contact with the flow. However, they also tend to cause a higher pressure drop. In some cases, the corrugations create recirculation zones, which can reduce flow efficiency and limit the overall heat

[1] Corresponding author. E-mail: krisztian.hriczo@uni-miskolc.hu

transfer performance [3], [4], [5].
To improve both heat transfer and flow characteristics, vortex generators (VGs) have been widely studied as devices that actively influence fluid motion. By creating swirling flows, these devices enhance mixing, disturb boundary layers, and increase thermal performance. When placed correctly inside channels, vortex generators can raise local flow velocity and turbulence, leading to better convective heat transfer [6], [7], [8], [9]. The shape of the vortex generator plays a major role in its effectiveness—it influences the strength and direction of the vortices formed, helping to steer the flow into specific regions where heat transfer can be intensified.
In this study, we examined the thermal and hydraulic performance of a wavy corrugated channel with full-circle vortex generators and investigated the effect of VG placement at different Reynolds numbers.

2 Numerical model

Figure 1 shows the geometry of the channel, which includes an inlet and outlet section (L1 = 200 mm and L2 = 100 mm, respectively) designed to prevent backflow. The test section (L3 = 200 mm) consists of waves with a maximum height (H) of 15 mm and a minimum height (h) of 5 mm. The wavelength (P) is 20 mm. Full-circle vortex generators with a diameter (D) of 6 mm are placed at varying distances (d = 4, 6, and 8 mm) from the start of the wave to the center of the vortex generator. In this model, water is selected as the working fluid.

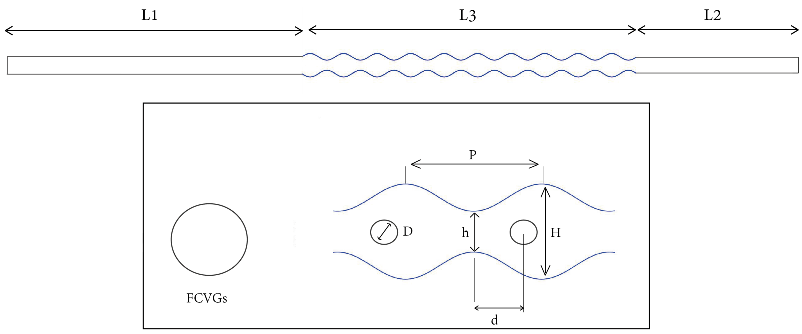


Figure 1: Geometry and vortex generations definition the wavey channel

The governing equations, which include the conservation of mass, momentum, and energy, can be expressed in the following mathematical forms [10].

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

$$\nabla.(\rho \mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot \left[\mu \left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right)\right], \tag{2}$$

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

© 2025 European Society of Computational Methods in Sciences and Engineering (ESCMSE)

where ρ denotes the fluid density, $\mathbf{u}$ is the velocity vector, p is the pressure, μ is the dynamic viscosity, c_p is the specific heat capacity, k is the thermal conductivity, and T is the temperature. The governing equations are solved under the assumptions of steady, incompressible, and turbulent flow.

Computational stability and solution convergence become more difficult for higher Reynolds values [11]. Therefore, the SST k–ω turbulence model was employed to overcome these difficulties. This model improves the prediction accuracy near the wall region of governing equations, this model adds two more transport equations, one for the particular dissipation rate (ω) and another for the turbulent kinetic energy (k).[12].

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

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

where G_k represents the kinetic energy production rates obtained from the mean velocity gradient and G_ω refers to the production rates of ω which are determined from the mean flow. Y_k and Y_ω are the dissipation k and ω due to turbulence.

To describe the increase in pressure drop in a wavy channel with VGs relative to an equivalent wavy channel without VGs, we introduce parameters: the pressure drop ratio (PR) [13]:

$$PR = \frac{\Delta p_{VGs}}{\Delta p_{WVGs}}, \tag{6}$$

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

The percentage increase in heat transfer for a wavy channel with VGs, relative to a wavy channel without VGs, is represented by the percentage enhancement (PE) [13]:

$$PE = \left(\frac{Nu_{VGs} - Nu_{WVGs}}{Nu_{WVGs}}\right) 100, \tag{7}$$

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

The inlet velocity is determined from the Reynolds number as

$$Re = \frac{\rho u D_h}{\mu}, \tag{8}$$

with the inlet thermal condition given by

$$T_{in} = 298\ K. \tag{9}$$

At the heated wavy walls, a constant heat flux boundary condition is imposed as

$$-k\frac{\partial T}{\partial n} = q''. \tag{10}$$

The straight channel walls and vortex generators are assumed adiabatic, satisfying

$$\frac{\partial T}{\partial n} = 0. \tag{11}$$

In addition, the no-slip condition is applied at all solid walls as

© 2025 European Society of Computational Methods in Sciences and Engineering (ESCMSE)

$$\mathbf{u} = 0. \tag{12}$$

At the outlet, fully developed flow conditions are imposed by assuming zero gradients for velocity and temperature:

$$\frac{\partial \mathbf{u}}{\partial n} = 0, \tag{13}$$

$$\frac{\partial T}{\partial n} = 0. \tag{14}$$

Table 1: Mesh independence

Mesh	Number of nods	Nusselt number	Relative erorr (%)
1	23198	198.41	-
2	28777	196.72	0.85
3	36804	195.46	0.64
4	80738	194.45	0.51
5	105568	193.54	0.46

To further verify the spatial convergence of the finite volume discretization, a Grid Convergence Index (GCI) analysis was performed using the three finest meshes (Meshes 3, 4, and 5) following the method proposed by Roache [15] and Celik et al. [16]. The grid refinement ratio between Mesh 5 and Mesh 4 was calculated as

$$r_{21} = \left(\frac{105568}{80738}\right)^{1/2} = 1.143. \tag{15}$$

The relative error between the fine and medium meshes was determined using the average Nusselt number as

$$e_{21} = \left|\frac{193.54 - 194.45}{193.54}\right| = 0.0047. \tag{16}$$

The fine-grid convergence index was then computed as

$$GCI_{21} = \frac{1.25 \times 0.0047}{1.143^2 - 1} \times 100 = 1.91\%. \tag{17}$$

Table 1 presents the grid independence study for five different mesh sizes. A GCI analysis was additionally performed using Meshes 3, 4, and 5 following the method of Roache [15] and Celik et al. [16]. The calculated fine-grid convergence index was $GCI_{21} = 1.91\%$, indicating low numerical uncertainty due to mesh refinement. Moreover, the relative error between Mesh 4 and Mesh 5 was only 0.46%. Therefore, Mesh 4 was selected for the subsequent simulations as it provides sufficiently grid-independent results with acceptable computational accuracy.

© 2025 European Society of Computational Methods in Sciences and Engineering (ESCMSE)

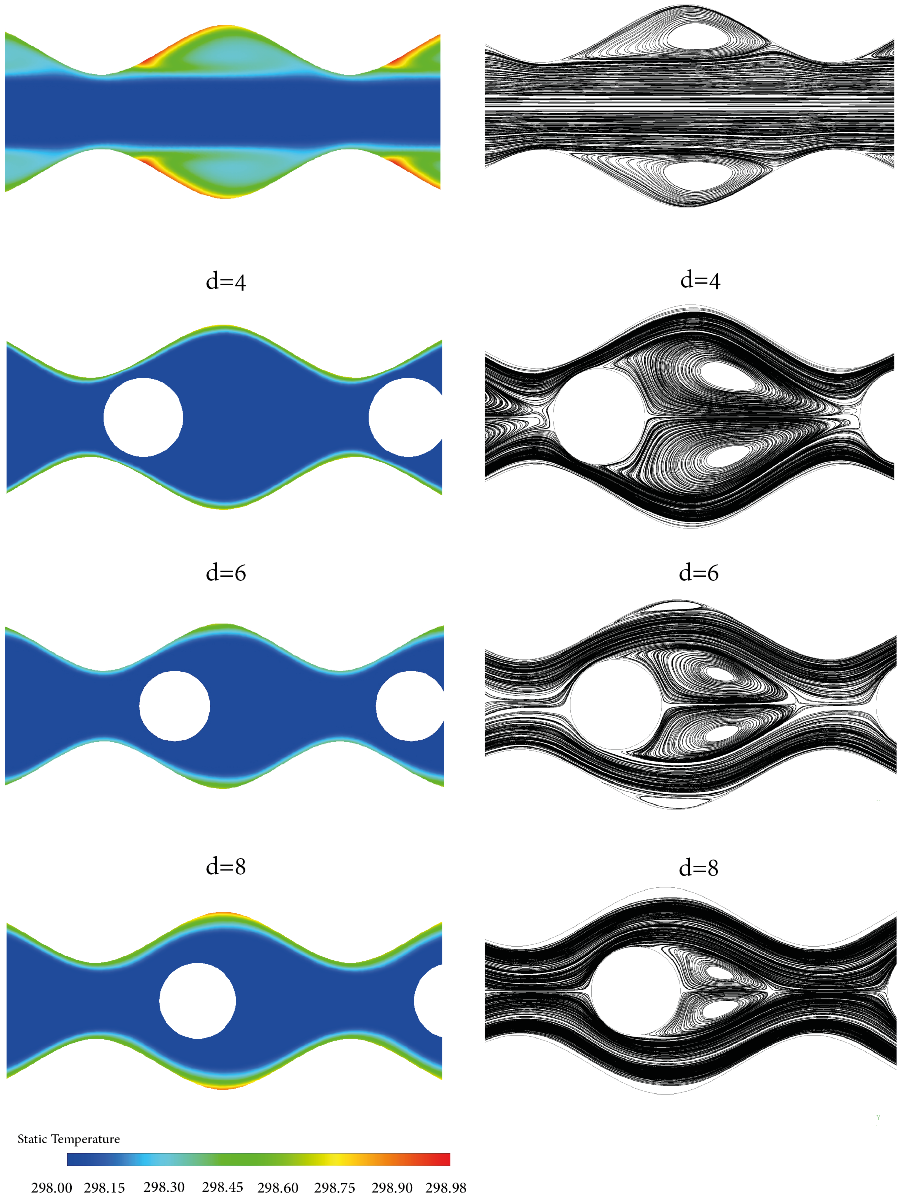


Figure 2: The isotherm contour and the velocity streamlines

3 Results and discussion

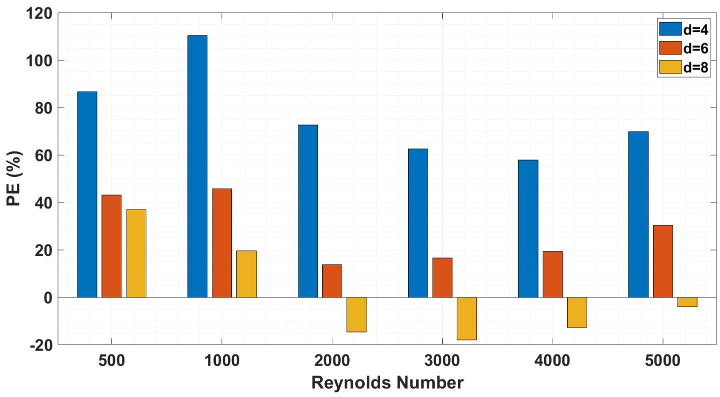
From a numerical analysis perspective, the present study involves the solution of a strongly coupled system of nonlinear partial differential equations governing mass, momentum, energy, and turbulence transport. The finite volume method is employed to discretize the governing equations over complex corrugated geometries containing vortex generators, which introduces additional chal-

© 2025 *European Society of Computational Methods in Sciences and Engineering (ESCMSE)*

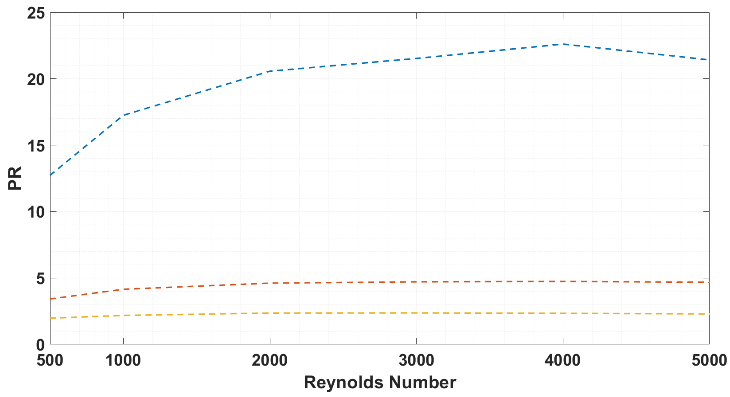
lenges related to mesh quality, numerical diffusion, and spatial convergence. The implementation of the SST k–ω turbulence model further increases the mathematical complexity of the numerical formulation due to the coupling between the turbulence transport equations and the mean flow equations.

Moreover, numerical stability and convergence become increasingly challenging at higher Reynolds numbers because of the strong interaction between flow separation, vortex formation, and thermal boundary layer development inside the corrugated channel. Therefore, careful attention was devoted to the selection of discretization schemes, mesh refinement, and convergence monitoring. The performed Grid Convergence Index (GCI) analysis provides a quantitative assessment of the discretization uncertainty and demonstrates the reliability of the finite volume approximation adopted in the present work. Consequently, the study contributes not only to thermal engineering applications but also to the computational and numerical analysis aspects associated with complex turbulent transport phenomena.

The numerical results are validated against previous experimental data [14], showing a percentage error between 3% and 7%, which indicates good agreement.



(a) Performance enhancement (PE)



(b) Pressure ratio (PR)

Figure 3: Comparison of (a) performance enhancement (PE) and (b) pressure ratio (PR).

Figure 2 shows the isothermal contours and velocity streamlines in the wavy channel. The thermal boundary layer can be seen forming in the corrugated section due to the wavy walls. This layer acts like insulation and reduces the efficiency of heat transfer. Using vortex generators (VGs) helps to thin the thermal boundary layer. The placement of VGs is important when they are closer to the inlet (d = 4 mm), the thermal layers become thinner. The streamlines show recirculation zones near the corrugated walls, which is the reason the thermal boundary layer forms there. Adding VGs reduces the wall recirculation, but also creates new ones in the center of the channel, which affects pressure drop. The closer the VGs are to the start of the wave, the stronger the middle recirculation becomes, which increases the pressure drop.

Figure 3 shows the thermal percentage enhancement (PE) and pressure drop ratio (PR) as a function of Reynolds number. The PE values show that VGs improve heat transfer at all Reynolds numbers for d = 4 mm and d = 6 mm. But at d = 8 mm, the improvement only appears in the laminar cases (Re = 500, 1000). This is likely because the VGs are not placed in an effective position to direct the flow to the right areas. The highest PE is around 110% for d = 4 mm. However, pressure drop also needs to be considered. The VGs placed at d = 4 mm cause a high pressure drop more than 20 times higher. The VGs at d = 6 mm give a better balance, with good enhancement (up to 46%) and less than 5 times the pressure drop.

4 Summary

We conducted a numerical study on the effect of VG placement in a corrugated channel using ANSYS Fluent. The thermal and hydraulic parameters are presented. The placement of VGs is very sensitive each time the VGs are inserted closer to the start of the corrugation, they help direct the fluid toward the walls and make the heat transfer more uniform, which enhances performance. However, this also increases the pressure drop. On the other hand, placing the VGs in the middle does not direct the fluid to the important areas and disturbs the heat transfer.

References

[1] Alam, T., Saini, R.P., Saini, J.S.: Use of turbulators for heat transfer augmentation in an air duct—A review. Renew. Energy 62, 689–715 (2014).

[2] Samadifar, M., Toghraie, D.: Numerical simulation of heat transfer enhancement in a plate-fin heat exchanger using a new type of vortex generators. Appl. Therm. Eng. 133, 671–681 (2018).

[3] Tokgoz, N., Sahin, B.: Experimental studies of flow characteristics in corrugated ducts. Int. Commun. Heat Mass Transf. 104, 41–50 (2019).

[4] Alnak, D.E.: Thermohydraulic performance study of different square baffle angles in cross-corrugated channel. J. Energy Storage 28, 101295 (2020).

[5] Kumar, R., Goel, V., Kumar, A.: Investigation of heat transfer augmentation and friction factor in triangular duct solar air heater due to forward facing chamfered rectangular ribs: A CFD based analysis. Renew. Energy 115, 824–835 (2018).

[6] Their, K.M., Azeez, K., Mohsin, M.A., et al.: Thermohydraulic performance study of the effect of winglet inserts and a corrugated wall in a rectangular channel. Case Stud. Therm. Eng. 52, 103707 (2023).

[7] Modi, A.J., Rathod, M.K.: Comparative study of heat transfer enhancement and pressure drop for fin-and-circular tube compact heat exchangers with sinusoidal wavy and elliptical curved rectangular winglet vortex generator. Int. J. Heat Mass Transf. 141, 310–326 (2019).

© 2025 European Society of Computational Methods in Sciences and Engineering (ESCMSE)

[8] Akcay, S.: Numerical analysis of heat transfer improvement for pulsating flow in a periodic corrugated channel with discrete V-type winglets. Int. Commun. Heat Mass Transf. 134, 105991 (2022).

[9] Wu, J., Liu, P., Yu, M., Liu, Z., Liu, W.: Thermo-hydraulic performance and exergy analysis of a fin-and-tube heat exchanger with sinusoidal wavy winglet type vortex generators. Int. J. Therm. Sci. 172, 107274 (2022).

[10] Ajeel, R.K., Salim, W.S., Hasnan, K.: Design characteristics of symmetrical semicircle-corrugated channel on heat transfer enhancement with nanofluid. Int. J. Mech. Sci. 151, 236–250 (2019).

[11] Ali, Z., Bognár, G.: CFD-based analysis of ship resistance: Assessing the impact of surface roughness. AIP Conf. Proc. 3315(1), 180001 (2025). AIP Publishing LLC.

[12] Ali, Z., Bognár, G.: RANS study of surface roughness effects on ship resistance. J. Nonlinear Complex Data Sci. 25(2), 215–236 (2024). De Gruyter.

[13] Mehta, S.K., Pati, S., Baranyi, L.: Effect of amplitude of walls on thermal and hydrodynamic characteristics of laminar flow through an asymmetric wavy channel. Case Stud. Therm. Eng. 31, 101796 (2022).

[14] Ahmed, M.A., Yusoff, M.Z., Ng, K.C., Shuaib, N.H.: Numerical and experimental investigations on the heat transfer enhancement in corrugated channels using SiO–water nanofluid. Case Stud. Therm. Eng. 6, 77–92 (2015).

[15] Roache, P.J.: Perspective: A method for uniform reporting of grid refinement studies. J. Fluids Eng. 116(3), 405–413 (1994).

[16] Celik, I.B., Ghia, U., Roache, P.J., Freitas, C.J., Coleman, H., Raad, P.E.: Procedure for estimation and reporting of uncertainty due to discretization in CFD applications. J. Fluids Eng. 130(7), 078001 (2008).

© 2025 European Society of Computational Methods in Sciences and Engineering (ESCMSE)