# Numerical Study of Thermal Performance on Fin and Tube Heat Exchanger with Flat Rectangular and Sinusoidal Winglet Vortex Generators

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## Abstract

Generation of vortices in the fin and tube heat exchanger is one of the common methods to reduce the air-side thermal resistance. This study deals with the enhancement of heat transfer in the air side using conventional rectangular and sinusoidal sine wave vortex generators. The vortex generators are placed in the downstream location of the tube in the common flow-down configurations and the range of Reynolds number is maintained about 400 to 1100. The results of the above vortex generators are compared with baseline configuration based on thermos-hydraulic criterion parameters like variation in the flow structure, variation in the temperature distribution, variation in the pressure distribution, variation in the friction factor, and overall thermal enhancement factor. Based on the comparative numerical analysis, sinusoidal and conventional rectangular winglet shows good heat transfer enhancement in that they have a large pressure loss penalty.

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## 1. Introduction

The present work aims to compute the heat enhancement levels achievable in a fin and tube heat exchanger with rectangular and sinusoidal vortex generators. The heat transfer performance between the plates and with built-in vortex generators mounted on these fins in the form of different winglets is studied. The fin and tube heat exchanger was numerically studied with a punched rectangle winglet having a hole on its fin surface and it was compared with a non-punched rectangular winglet. The results revealed that it has 34 % thermal-hydraulic performance when compared to a non-punched rectangular winglet [1]. In another study numerical analysis was done on punched rectangular winglets with 1,2,4 and 6 holes, and the results were compared with regular rectangular winglets. The results showed that the 6-hole winglet exhibited a lower Nusselt number and less friction factor (13.8%) compared to all other holes [2]. Experimental investigation made both punched triangular and rectangular winglets, the results showed that punched rectangular type winglet provides a 47.23% augment in overall thermal enhancement factor [3]. A numerical investigation was made on rectangular winglets as vortex generators by providing the different numbers of 1,2,3 and 4 holes on the winglets for Reynolds number ranging from 400 to 1100 and the results revealed that the friction factor was reduced [4]. In the experimental investigation for different types of vortex generators, with and without hole revealed that the flow resistance was reduced up to 47.34% and thereby the hydraulic performance was increased [5].

The cross-section vortex generators had been changed to circular and elliptical and it was compared with flat cross-section. The numerical study revealed the results that the circular cross-section gives the optimum performance and the non-conventional configuration gives a 14% high thermal performance when compared to the normal configuration [6]. The study of experimental and numerical analysis on two different circular rectangular configurations (P and V type) and the results showed that the for the P type heat transfer rate increased up to 54-118% and flow resistance increased up to152-568% compared to the smooth tube. For V type the heat transfer rate and flow resistance increased up to 60-118% and 141-641% when compared to the smooth tube [7].

The vortex generator of the heat exchanger on wavy fins was analyzed numerically and the attack angle was 60º. In the crest region, the longitudinal vortices strengthened and in the trough region, the longitudinal vortices are weakened in the bottom wall respectively. The results revealed that 31.5 % increase in the Nusselt number and a 23.4 % increase in friction factor observed [8]. The performance of rectangular winglet vortex generators was studied numerically for different attack angles and the results revealed that the optimum angle 50º gives the best thermos-hydraulic value when compared to the other angles via MOORA optimization methods [9]. Another study was made for different attack angles of 30º, 45º, 60º and 90º on elliptical tube heat exchanger and was observed that the angle rectangular winglet exhibits good performance while increasing the Reynolds number [10].

The delta-type winglet was studied in an experimental investigation on solar air heater absorber plate as the vortex generator and the results revealed that due to rough surfaces created by the delta vortex generator the thermal enhancement factor of solar air heater is increased [11]. The longitudinal crescent-type vortex generators located downstream were studied under the range of Reynolds number about 2800, Prandtl number 0.7 and for different attack angles [12]. The punched rectangular winglet was investigated numerically and it was placed upstream and downstream, the results showed that the thermal enhancement factor was 34 % compared to the downstream cases [13]. In another numerical study slit fins with delta vortex generators. The delta vortex generators mounted on slit fins were numerically studied and the results revealed that the combination of slit fins and vortex generator provides an increase in thermal performance and pressure drop by 9.57% and 17.39% [14].

The Performance of the vortex generator on the microchannel was studied numerically. The result indicated that the combination of Vortex generators and spherical dimples could augment the heat transfer rate by 23.4-59.8 % with an increased friction factor by 22.1-54.4% compared with a smooth surface [15]. Numerical and experimental analysis was conducted for fouling factor and its characteristics. The results showed that the smooth channel and rectangular winglet without a hole the rectangular winglet with a hole have high fouling resistance [16].

The delta winglet vortex generator mounted on the receiver of a solar collector was numerically studied and the results revealed that the heat transfer rate and friction factor is increased up to 75.78 % and 166.67 % while the turbulent kinetic energy was enhanced up to 5.2 times [17]. The trapezoidal winglet as a vortex generator was experimentally studied using the Latin hypercube sampling space method from the Reynolds number ranging from 1500 to 4500 and it was concluded that increasing the trapezoidal winglet size the flow is often redirected in the wake zone and the overall thermal performance factor is widely increased [18].

The new type of vortex generator design called combined rectangular winglet and concluded that the enhancement of heat transfer up to 24.22% as compared to the baseline case [19]. Different type of conventional vortex generators was mounted on the wave plate of the demister and a numerical study was conducted. The results revealed that the rectangular-type vortex generator exhibits better separation efficiency up to 0.72 when compared to other different types of vortex generators [20]. A new configuration type of vortex generator called an inclined projected winglet vortex generator which gives augmented heat transfer performance than the delta winglet vortex generator [21]. Three different types of rectangular vortex generators (conventional, up-wavy, down-wavy and curved). They found that the reduction in the wake zone is high in the conventional type rectangular vortex generator [22]. A numerical investigation was performed and found that instead of using the circular tubes, the new oval tube used in the fin and tube heat exchanger provided a better thermo-hydraulic performance compared to circular tubes [23].

From the literature, it is concluded that the vortex regulators are used for enhancing heat transfer performance in the different heat transfer equipment. In this paper, the Reynolds number range is selected from about 400 to 1100 and the attack angle is 25º. The fin and tube heat exchanger without vortex generator and the rectangular and sinusoidal vortex generators are selected for this numerical analysis and the results are compared in detail.

## 2. Model Description

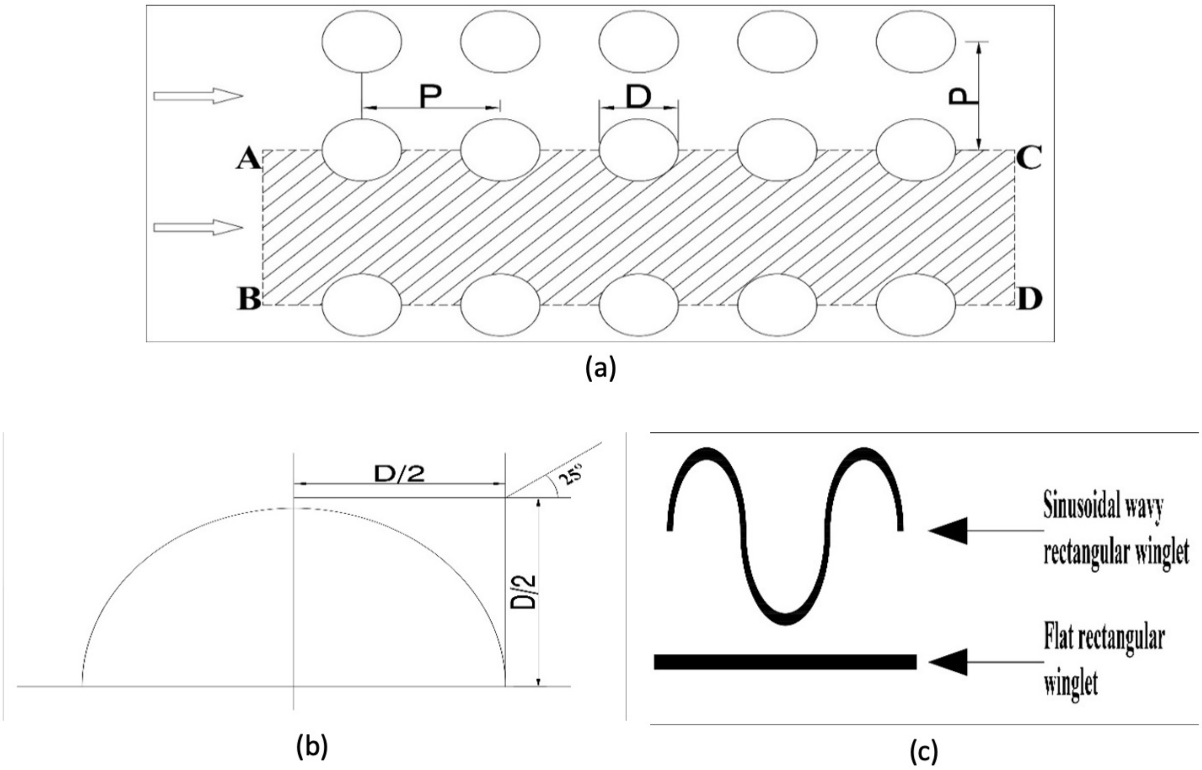


**Figure 1.** (a), (b) and (c) Geometry and configuration of computational domain

Figure 1 (a), (b) and (c) shows the geometry and configuration of computational domain. The fin and tube heat exchanger consists of seven rows of circular tube patterns arranged in an in-lined manner. In this present work, two types of vortex generator namely flat rectangular and sinusoidal vortex generators are considered for the numerical study. the angle of attack and aspect ratio of the vortex generator are considered as 25º and 0.5 respectively and are kept constant for all the Reynolds values as literature survey. The model and position of rectangular and sinusoidal vortex generator are shown in Figure 2.

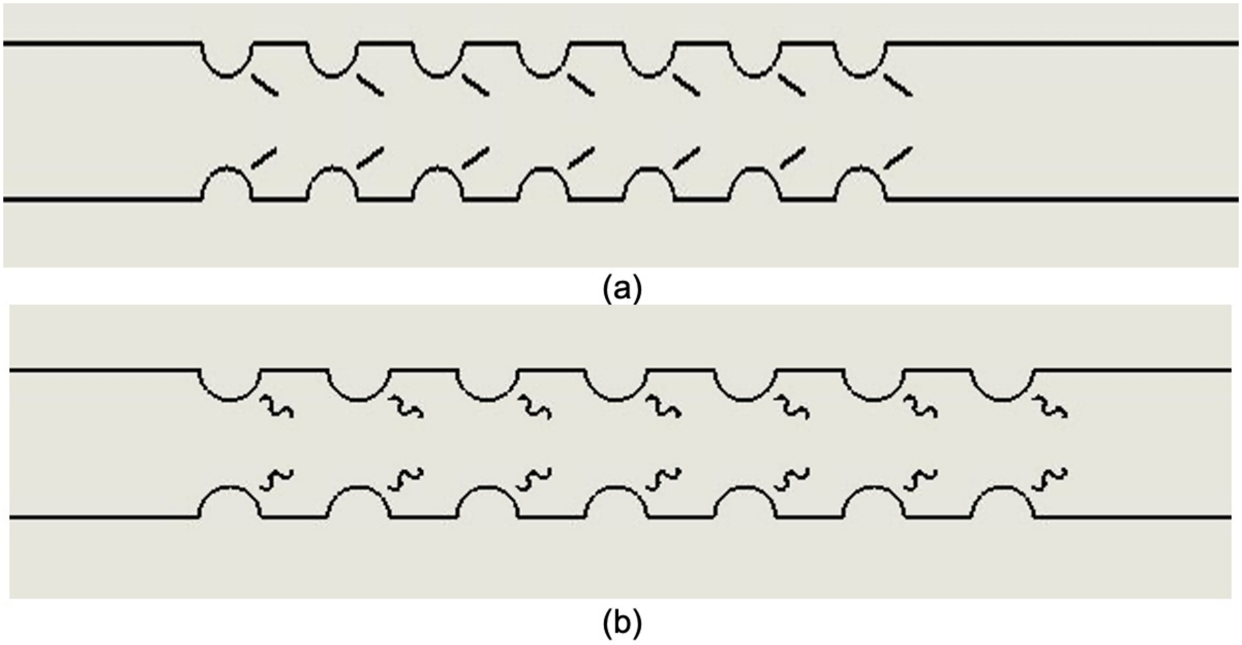

**Figure 2** (a) and (b) Position of rectangular and sinusoidal vortex generators

## 2.1. Governing Equations

The compressible fluid (air) is chosen as working medium for this work. The inlet velocity considered becomes very small. The various transport equations such as continuity, momentum, energy equations are implemented to solve the complex flow structure near the wall boundary. The dimensionless Navier-Stokes equations for momentum, continuity (Reynolds averaged Navier–Stokes's equations) and energy may be demonstrated in tensor form as follows,

$$\text{Continuity equation} \quad \frac{\partial U_i}{\partial X_j} = 0$$

$$\text{Momentum Equation} \quad \frac{\partial}{\partial Xj}(UiUj) = -\frac{1}{\rho}\frac{\partial p}{\partial Xj} + \frac{\mu}{\rho}\nabla^2 U_i \frac{\partial}{\partial Xj}\left(\vec{u}_i \vec{u}_j\right) = 0$$

$$\text{Energy Equation} \quad \frac{\partial}{\partial X_j}\left(TU_i\right) = \propto \nabla^2 T - \frac{\partial}{\partial X_i}\vec{U}\vec{T}$$

Where, U - average velocity and u - fluctuation velocity. Turbulence viscous model K-ϵ (RNG model) is selected because it has the capabilities of capturing the flow separation near the wall boundary. The values of derived constants are k- ϵ RNG theory, derived values of other constants i.e., $\alpha_k$, $\alpha_e$, $C_{1\epsilon}$ and $C_{2\epsilon}$ are 0.0845, 0.85, 1.42 and 1.68, respectively.

In this current study, the air is assumed as the working medium and its properties are listed in Table 1. The wall is made up of aluminum and its properties are also listed. The inlet of the computational domain is extended up to 5 times the height (5 H) to become a flow to be a fully developed flow and the outlet domain is extended up to (30 H) to avoid the reverse flow effect. The inlet velocity is considered to be very low, the temperature at the inlet is maintained as 303 K and also the turbulent intensity is set to be 5%. The tube wall is maintained at the temperature of 350 K. At the outlet

Neumann boundary conditions are to be set and all the variables are assigned as zero. There is no viscous and slip condition applied at the top and side of the tube.

**Table 1.** Properties of air and aluminum

| Properties | Unit | Material | |
|---|---|---|---|
| | | Air | Aluminium |
| **Density, $\rho$** | $Kg/m^3$ | 1.225 | 2719 |
| **Specific heat, $C_P$** | J/kgK | 1006.43 | 871 |
| **Thermal conductivity, $k$** | W/mK | 0.0242 | 202.4 |
| **Kinematic viscosity, γ** | $Ns/m^2$ | $1.568 \times 10^{-5}$ | - |
| **Diffusivity, α** | $m^2/s$ | $22.07 \times 10^{-6}$ | – |

The meshing is done using unstructured tetrahedral elements with Ansys 19.0. The circular tubes are meshed with refinement mesh. The vortex generator also meshed with unstructured mesh. The values of nodes are 562707, 858963, 0.95 million obtained for the Re in the range from 400 to 1100. To save the computational resources without compromising the results the 0.8 million nodes are selected. The grid independence test results are shown in Figure 3.

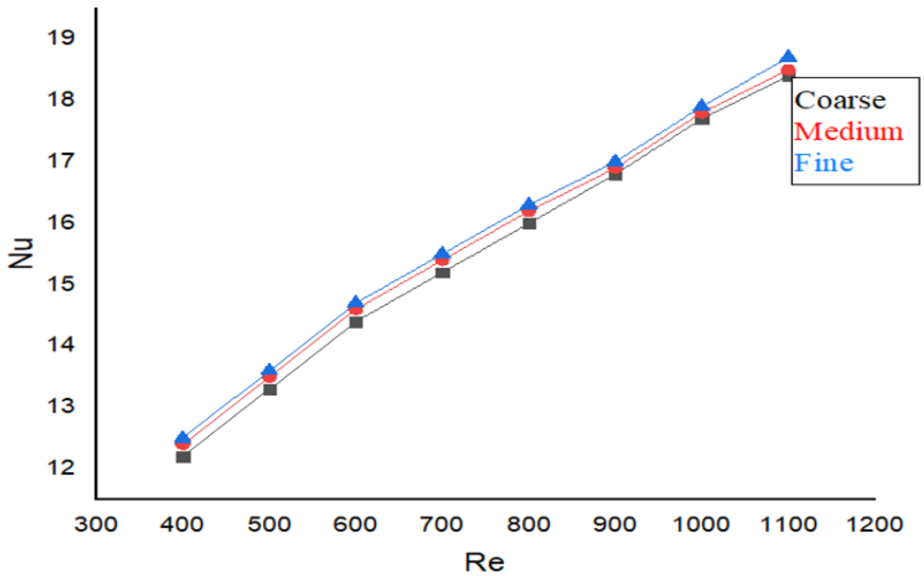


**Figure 3.** Grid independence test

## 3. Results and Discussion

In this study, the K-epsilon viscous model was selected because of its ability to capture the separation of the boundary layer near the wall when compared to other viscous models stated in the literature survey. The angle of attack was chosen as 25°, the common flow down configuration was preferred for the two cases and vortex generators were located in the downstream location. The Reynolds number taken for this study from 400 to 1100. Based on the simulation results achieved, the type of vortex generator that gives the optimum performance is discussed below.

### 3.1. Velocity Distribution

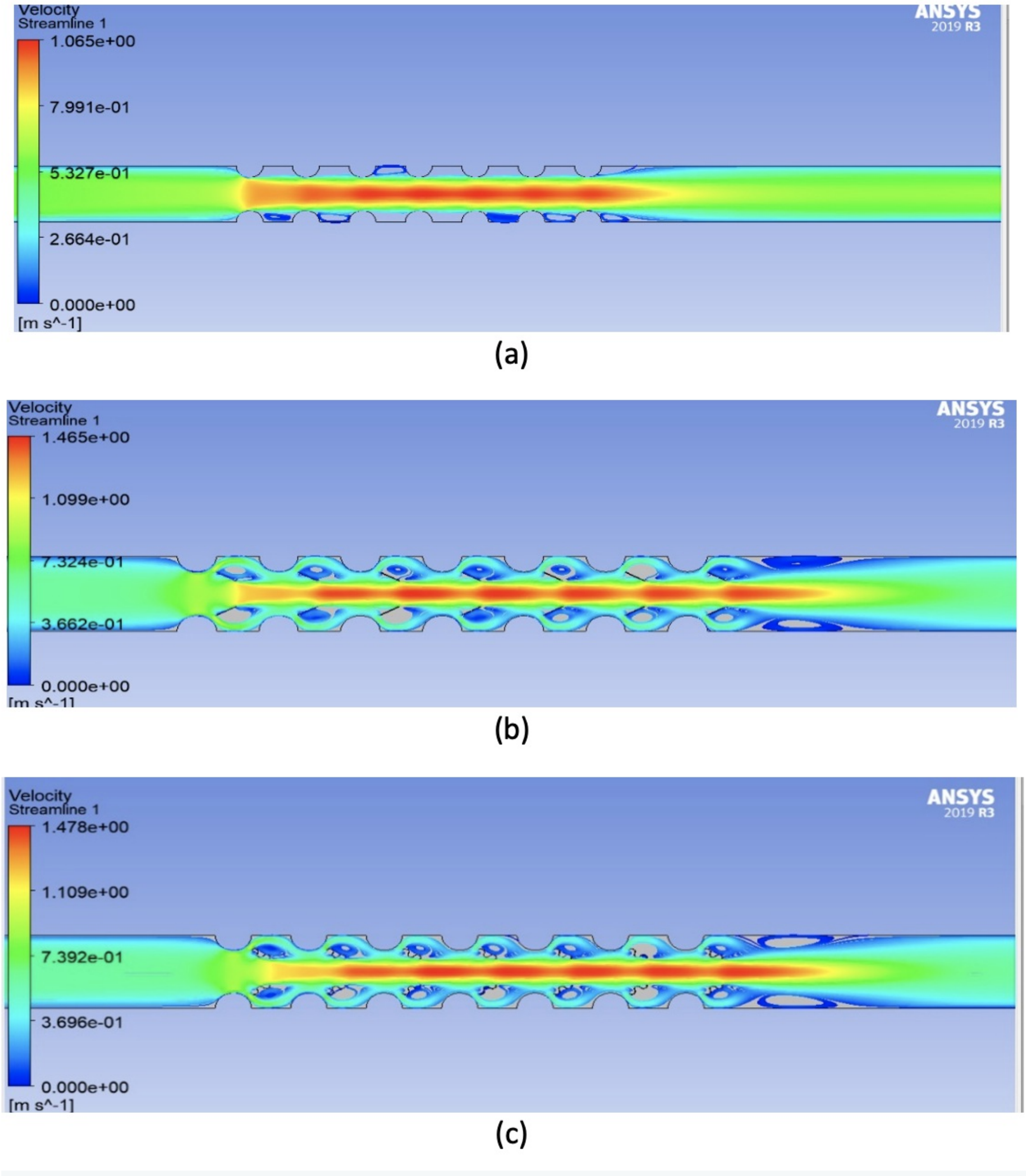


**Figure 4.** Velocity distribution of baseline, rectangular and sinusoidal vortex regulators

Generally, streamline flow indicates that the tangent drawn at any point will be in the direction of the velocity of the fluid at that point. Figure 4 shows the streamlined view of the baseline case. The enhancement in the heat transfer mainly depends upon the flow pattern of the fluid passing over the fin plate surface. From the streamline diagram, it is understood that the boundary layer formation or the separation of flow takes place behind the tube and the flow recirculation zone forms in the front side of the circular tube. Due to boundary layer formation, a wake zone is created at the rear side of the tube. It can be seen that the other side of the tube receives very little velocity because of boundary layer formation. Also, it is noticed that the incoming air is diverted from the first row of the tube and directly goes to the second row of the tube passing the wake zones. Due to the non-contact of incoming air with the back side and front side of the circular tubes poor rate of heat transfer had been obtained in the fin plate.

### 3.2. Pressure Distribution

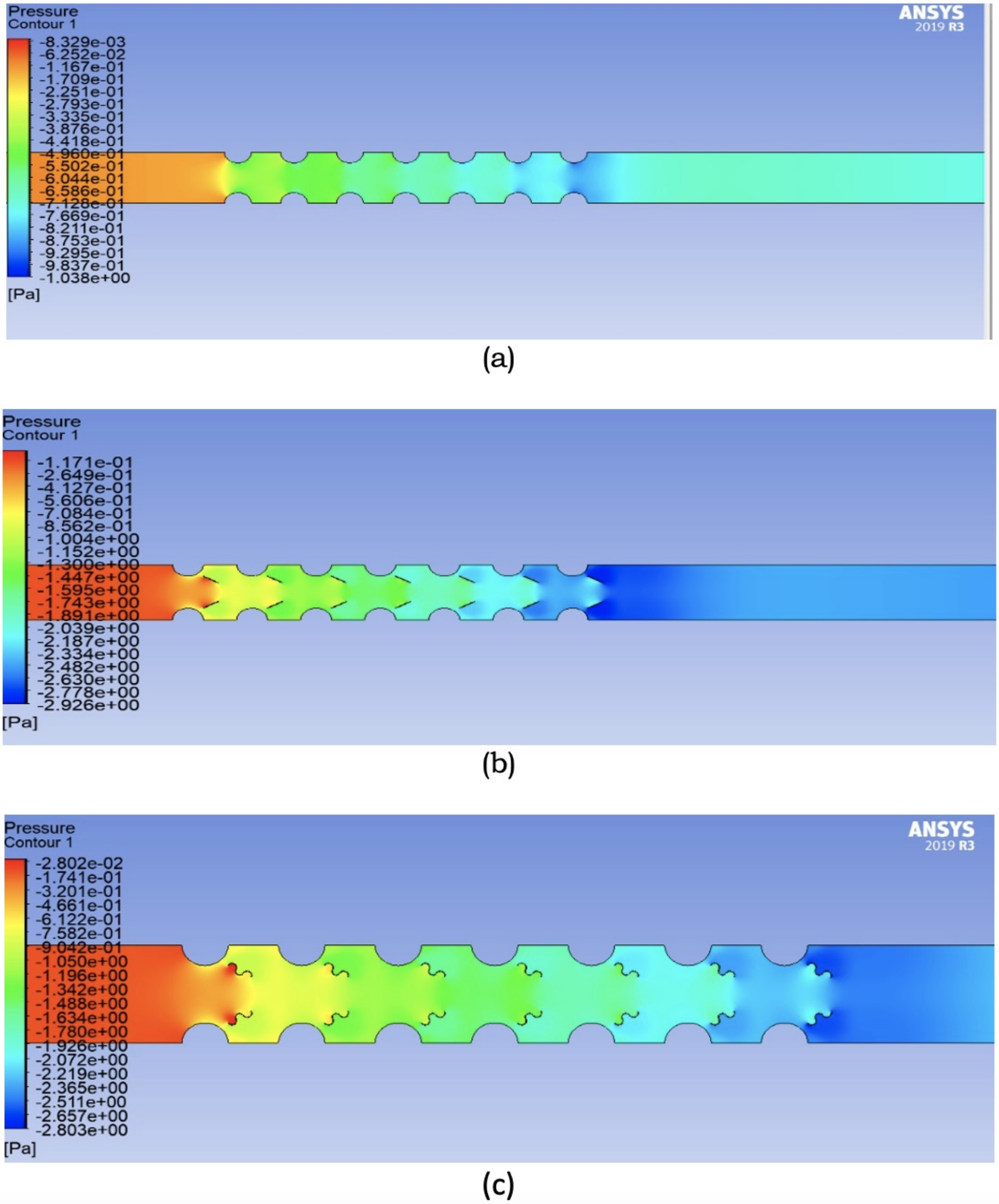


**Figure 5.** Pressure distribution of baseline, rectangular and sinusoidal vortex regulators

The pressure contours of all the cases are demonstrated in Figure 5. The baseline cases have the least pressure drop compared to all other cases. At the entrance region, here the pressure energy is highly developed due to a decrease in kinetic energy. As the flow progress, further decrease in pressure energy is observed. It indicates that by the application of vortex generator, there is an increase in kinetic energy. Moreover, a simultaneous reduction in the pressure energy is noted. When the fluid flows through the domain, there are two different types of drag forces are generated, namely pressure drags and friction drags. The friction between the wall and the air (fluid) induces the friction drag.

## 3.3. Heat Transfer Performance

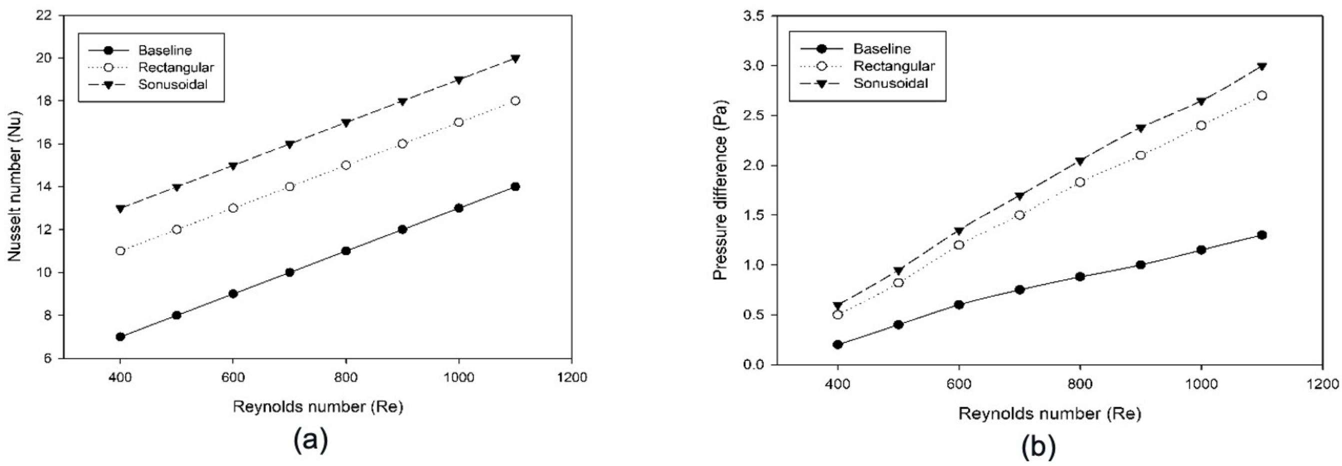


**Figure 6.** (a) and (b)Variation of Nusselt number and pressure difference with Reynolds number

Figure 6 (a) constitutes the variation in Nusselt number (Nu) considering the Reynolds number (Re) ranging from 400 to 1100. The results are in concurrence with the temperature distribution. As the results, the increase in the Re, the increase in Nu is observed. When compared to the baseline cases all other cases have an increment in Nusselt number. The sinusoidal vortex generator shows the highest Nusselt number followed the rectangular vortex generator. At Reynolds number 1100, the increment in Nu for the comparison with baseline case is 16.32% in conventional rectangular winglet, and 18.44% in solenoidal winglet.

The loss in pressure energy is seen in the pressure contour diagram (Figure 6 b) for various stages. The increase in the Reynolds number the increase in pressure loss penalty observed. The curved type winglet exhibits the less pressure difference compared to the rectangular. The pressure difference is compared with baseline and it is maximum of 107.69% and 130.76% for rectangular and sinusoidal winglet respectively.

The friction factor also was analyzed for different Reynolds number. It was observed that the increase in Re with the decrease in friction factor. For the Re 400 the increase in friction factor in comparison with the baseline configuration are 67.24% higher in rectangular, and 54.407% higher in sinusoidal. For the Re 1100 the raise in friction factor when compared to baseline configuration are 64.73% higher in rectangular, 51.06% higher in sinusoidal winglet.

## 3.4. Overall Thermal Hydraulic Performance

Generally, the overall thermal hydraulic performance factor or London area goodness factor (j / f factor) provides the relationship between the Colburn factor to the friction factor. From the above discussion, it is clear that sinusoidal vortex generator provides augment heat transfer rate with less pressure penalty when compared to the rectangular vortex generator. Figure 7 shows the variation of London area goodness factor with Reynolds number

From the overall thermal performance factor graph, the larger value of j/f indicates the higher heat transfer rate with less pressure drop penalty. From Figure 7, it is clear that the sinusoidal vortex generator provides the augment heat transfer rate with lass pressure difference penalty.

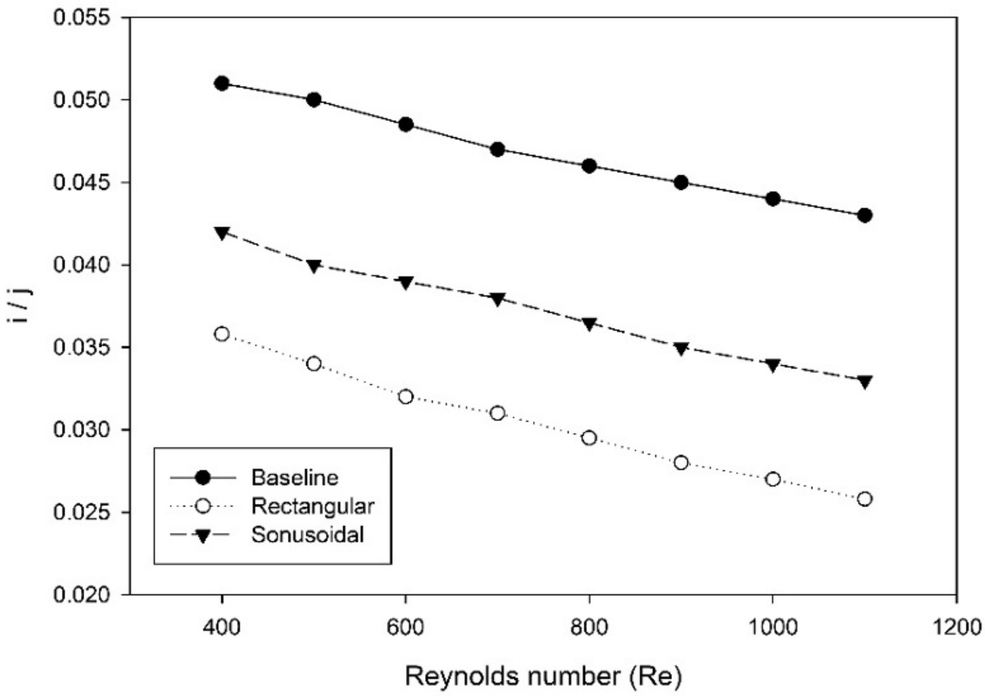


**Figure 7.** Variation of London area goodness factor with Reynolds number

## 4. Conclusions

In the present study, the numerical models of rectangular and sinusoidal vortex generators are constructed to establish the performance on flow structure, pressure distribution, temperature distribution, friction factor(f), overall thermal performance factor (j/f). Major outcomes from the numerical analysis are as follows,

- It is noted that vortex regulators are capable of decrease in the wake zones behind the circular tubes when compared to the baseline case.
- The heat transfer enhancement of the fin and tube heat exchanger is largely improved in the rectangular and sinusoidal vortex generator.
- Nusselt number (Nu) raises with a raise of Reynolds number (Re), the sinusoidal type has the higher of Nusselt number when compared to the rectangular. At Reynolds number 1100, the increment in Nu for the comparison with baseline case is 16.32% in conventional rectangular winglet, and 18.44% in solenoidal winglet.
- The curved type winglet exhibits the less pressure difference compared to the rectangular. The pressure difference is compared with baseline and it is maximum of 107.69% and 130.76% for rectangular and sinusoidal winglet

respectively.

- The sinusoidal and conventional rectangular winglet shows the good heat transfer enhancement that they have large pressure loss penalty.

## References


1. ^*S. Tiggelbeck and M. Fiebig, "Flow Structure and Heat Transfer in a Channel With Multiple Longitudinal Vortex Generators iL liquid," pp. 425–436, 1992.*
2. ^*A. Gupta, A. Roy, S. Gupta, and M. Gupta, "International Journal of Heat and Mass Transfer Numerical investigation towards implementation of punched winglet as vortex generator for performance improvement of a fin-and-tube heat exchanger," Int. J. Heat Mass Transf., vol. 149, p. 119171, 2020, doi: 10.1016/j.ijheatmasstransfer.2019.119171.*
3. ^*S. Caliskan, "International Journal of Heat and Mass Transfer Experimental investigation of heat transfer in a channel with new winglet-type vortex generators," HEAT MASS Transf., vol. 78, pp. 604–614, 2014, doi: 10.1016/j.ijheatmasstransfer.2014.07.043.*
4. ^*A. J. Modi and M. K. Rathod, "International Journal of Heat and Mass Transfer 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., vol. 141, pp. 310–326, 2019, doi: 10.1016/j.ijheatmasstransfer.2019.06.088.*
5. ^*T. Yu, J. Zhao, J. Zhou, and B. Lei, "Experimental investigation of thermal performance of a heating system combining solar air collector with hollow ventilated interior wall," Renew. Energy, vol. 147, pp. 1825–1835, 2020, doi: 10.1016/j.renene.2019.09.116.*
6. ^*M. Tian, S. Khorasani, H. Moria, S. Pourhedayat, and H. Sadighi, "International Journal of Heat and Mass Transfer Profit and efficiency boost of triangular vortex-generators by novel techniques," Int. J. Heat Mass Transf., vol. 156, p. 119842, 2020, doi: 10.1016/j.ijheatmasstransfer.2020.119842.*
7. ^*K. Zhang, Z. Sun, N. Zheng, and Q. Chen, "International Journal of Heat and Mass Transfer Effects of the configuration of winglet vortex generators on turbulent heat transfer enhancement in circular tubes," vol. 157, 2020, doi: 10.1016/j.ijheatmasstransfer.2020.119928.*
8. ^*C. Luo, K. Song, T. Tagawa, X. Wu, and L. Wang, "International Journal of Thermal Sciences Thermal performance of a zig-zag channel formed by two wavy fins mounted with vortex generators," Int. J. Therm. Sci., vol. 153, no. August 2019, p. 106361, 2020, doi: 10.1016/j.ijthermalsci.2020.106361.*
9. ^*M. Zeeshan, S. Nath, and D. Bhanja, "Determination of optimum winglet height of longitudinal vortex generators for the best thermo-hydraulic performance of compact heat exchangers †," vol. 33, no. 9, pp. 1–6, 2019, doi: 10.1007/s12206-019-0849-1.*
10. ^*Q. Wang, B. Lot, M. Zeng, and B. Sund, "3D numerical investigation of fl ow and heat transfer characteristics in smooth wavy fi n-and-elliptical tube heat exchangers using new type vortex generators," vol. 73, 2014, doi: 10.1016/j.energy.2014.06.016.*
11. ^*M. T. Baissi, A. Brima, K. Aoues, R. Khanniche, and N. Moummi, "Thermal behavior in a solar air heater channel*

*roughened with delta-shaped vortex generators," Appl. Therm. Eng., 2019, doi: 10.1016/j.applthermaleng.2019.03.134.*

12. ^*M. Jeong, M. Yeong, and Y. Gap, "International Journal of Heat and Mass Transfer Numerical investigation of heat transfer enhancement in a dimpled cooling channel with different angles of the vortex generator," Int. J. Heat Mass Transf., vol. 144, p. 118644, 2019, doi: 10.1016/j.ijheatmasstransfer.2019.118644.*
13. ^*S. Gupta, A. Roy, A. Gupta, and M. Gupta, "Numerical simulations of performance of plate fin tube heat exchanger using rectangular winglet type vortex generator with punched holes," SAE Tech. Pap., vol. 2019-April, no. April, p. 4271, 2019, doi: 10.4271/2019-01-0145.*
14. ^*R. Roberto, "Numerical Optimization of a Heat Exchanger with Slit Fins and Vortex Generators using Genetic Algorithms," Int. J. Refrig., 2020, doi: 10.1016/j.ijrefrig.2020.07.023.*
15. ^*G. Lu and X. Zhai, "International Journal of Thermal Sciences Analysis on heat transfer and pressure drop of a microchannel heat sink with dimples and vortex generators," Int. J. Therm. Sci., vol. 145, no. October 2018, p. 105986, 2019, doi: 10.1016/j.ijthermalsci.2019.105986.*
16. ^*Z. Han, Z. Xu, and H. Qu, "Parametric study of the particulate fouling characteristics of vortex generators in a heat exchanger," Appl. Therm. Eng., p. 114735, 2019, doi: 10.1016/j.applthermaleng.2019.114735.*
17. ^*L. Luo, W. Du, S. Wang, L. Wang, B. Sundén, and X. Zhang, "AC SC," Energy, 2017, doi: 10.1016/j.energy.2017.07.001.*
18. ^*A. Sinha, H. Chattopadhyay, A. Kannan, and G. Biswas, "International Journal of Heat and Mass Transfer Enhancement of heat transfer in a fin-tube heat exchanger using rectangular winglet type vortex generators," Int. J. Heat Mass Transf., vol. 101, pp. 667–681, 2016, doi: 10.1016/j.ijheatmasstransfer.2016.05.032.*
19. ^*W. Wang, Y. Bao, and Y. Wang, "Numerical investigation of a fi nned-tube heat exchanger with novel longitudinal vortex generators," Appl. Therm. Eng., vol. 86, pp. 27–34, 2015, doi: 10.1016/j.applthermaleng.2015.04.041.*
20. ^*L. Yang, M. Xu, J. Wang, and L. Song, "u Pr pr oo f," Chinese J. Chem. Eng., 2020, doi: 10.1016/j.cjche.2020.07.045.*
21. ^*M. Oneissi, C. Habchi, S. Russeil, and D. Bougeard, "International Journal of Thermal Sciences Novel design of delta winglet pair vortex generator for heat transfer enhancement," Int. J. Therm. Sci., vol. 109, pp. 1–9, 2016, doi: 10.1016/j.ijthermalsci.2016.05.025.*
22. ^*M. Dlimi, O. Iken, R. Agounoun, A. Zoubir, I. Kadiri, and K. Sbai, "Energy performance and thickness optimization of hemp wool insulation and air cavity layers integrated in Moroccan building walls'," Sustain. Prod. Consum., vol. 20, pp. 273–288, 2019, doi: 10.1016/j.spc.2019.07.008.*
23. ^*S. Tiwari, D. Maurya, G. Biswas, and V. Eswaran, "Heat transfer enhancement in cross-flow heat exchangers using oval tubes and multiple delta winglets," vol. 46, pp. 2841–2856, 2003, doi: 10.1016/S0017-9310(03)00047-4.*