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Journal homepage: www.akademiabaru.com/cfdl.html
ISSN: 2180-1363

Heat Transfer Enhancement in A Corrugated-Trapezoidal Channel Using Winglet Vortex Generators

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ARTICLE INFO

Article history:
Received 27 August 2019
Received in revised form 20 October 2019
Accepted 24 October 2019
Available online 30 October 2019

ABSTRACT

In this study, heat transfer rates and flow behavior of water inside corrugated channel with a new configuration of winglet longitudinal vortex-generators have been numerically carried out. In general, the main objective of using the winglet longitudinal vortex-generators with the corrugated surfaces is to obtain an increase in the rate of heat exchange by generating vortex and reverse flow which in turn increases the efficiency of the thermal process, leading to save operating costs. To achieve this purpose, four amplitude heights are introduced: *a* = 1, 2, 3 and 4 mm. Furthermore, the arrangement of winglet longitudinal vortex-generator is placed at the entrance of each wave existing with the same as the slant angle of the waves in the trapezoidal channel. A constant heat flux is adopted to be the thermal condition for the lower and upper corrugated walls while the Reynolds numbers (*Re*) rate is in the range of 5,000 to 17,500. The effects of the trapezoidal amplitude heights with winglets longitudinal vortex-generator are studied and compared using the non-dimensional parameter performance evaluation criteria (PEC). Thermal and flow characteristics are explored with the help of the stream wise velocity and isotherms contours for trapezoidal-corrugated channels with winglet inserts and different amplitudes. Nusselt number (*Nu*), skin friction coefficient and PEC are substantial factors that studied at turbulent flow. According to the results obtained, the winglet longitudinal in corrugated duct has showed a significant improvement of the *Nu* but accompanied by increased of skin friction coefficient over those of a plane duct. Consequently, winglet longitudinal vortex-generator with corrugated channel might be favorable in several heat transfer applications.

Keywords:
heat transfer enhancement; turbulent flow; trapezoidal corrugated channel; winglet longitudinal vortex generator; performance evaluation criteria

1. Introduction

Over the last few decades, many industries have a strong used of compact heat exchangers for a

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high performance in various engineering applications such as, power systems, chemical engineering, automobile industries, air conditioning, electronic devices and aerospace, etc. A high thermal performance has received great attention to reduce the size of the heat exchanger, low cost, light weight. Many appropriate techniques have been used to improve conventional heat exchangers such as insertion of swirl devices in the flow field, surface modification and high thermal conductivity working fluids. The corrugated wall channel was successfully applied to promote heat transfer as a passageway in a heat exchanger. In particular, amplitude height and the wave length-to- amplitude height ratio in the corrugated channel are the criterions that influence on thermal performance and heat transfer rate.

Many attempts have been studied the effect of these parameters of corrugated geometry numerically and experimentally in both laminar and turbulent regimes on heat transfer and friction factor. Pehlivan *et al.,* [1] experimentally investigated the effect of corrugation angle (θ) and Reynolds number (*Re*) on the Nusselt number (*Nu*) and local convection heat transfer coefficient. The obtained results showed that corrugation angle as well as the *Re* has direct effect on the *Nu*. There was a considerable augmentation in the *Nu* by increasing the θ and *Re*. Rao *et al.,* [2] investigated experimentally the effect of waving angle (30, 40 and 50 degrees) of the sinusoidal plate on the friction factor and pressure drop. The study showed that the friction factor has decreased with increased the wave angles while the pressure drops increased with an increase of amplitude-wave angles. A corrugated bottom wall of facing step channel was simulated using CFD to investigate the performance of triangular amplitude height on the heat transfer performance by Selimefendigil *et al.,* [3]. Their results showed that amplitude height had a significant effect on *Nu*.

Akbarzadeh *et al.,* [4] conducted numerically the effect of sinusoidal configurations on heat transfer enhancement and pressure loss using the finite volume method. The computational results observed that there has been a marked increase in heat transfer and pressure loss due to sinusoidal configurations. The effect of rectangular cross section of wavy channel on water flow and heat transfer was performed by Sui *et al.,* [5]. The study presented that the heat transfer has been improved by wavy channel comparing with the straight channel but this improvement in heat transfer has increased pressure drop. A numerical study has been done by Zhang and Che [6] to examine the heat transfer and flow field in corrugated plates heat exchanger. The effect of cross-corrugated plates with multi configurations on thermal fields and velocity were studied and analyzed. It was found that the corrugation profile was much better than that of elliptic channel. The investigation demonstrated that heat transfer and pressure drop for laminar as well as turbulent flow enormously improved compared to those of parallel plate channel.

In several applications, further improvement in heat transfer rate is appropriate to meet industry requirements for superior performance. Some efforts have already been done to enhance the heat transfer rate by using insertion of swirl devices or vortex generator techniques. Habchi *et al.,* [7] and, Lu and Zhou [8] studied different configurations of vortex generators to check their effect on heat transfer enhancement in varied flow field. The study has shown that the use of plane and curved longitudinal vortex generators has significantly improved heat transfer, with moderate pressure drop. Althaher *et al.,* [9] have examined the effect of the inclination angle of a perforated delta-wing on the Nusselt number (*Nu*) and friction factor in triangular channel. The study observed that with increased Reynold number (*Re*) the *Nu* has increased obviously and friction factor decreased.

Heat transfer rates and fluid flow characteristics were carried out numerically and experimentally by Al-khishali and Ebaid [10] to investigate the effect of the locations and configurations of vortex generators (VGs) in rectangular channel. The study used two configurations of VGs (square and circular) and clarified that the use of circular type of vortex generators had a greater effect on heat transfer rate compared with square type. Turbulent and laminar convective heat transfer was conducted to study the performance of smooth and curved trapezoidal winglet type vortex generators numerically by Kamboj *et al.,* [11]. During this study, it was found that the curved trapezoidal winglet type was significantly improved heat transfer compared to plain winglet type. Various shapes (rectangular, triangular and trapezoidal) have been studied to verify their effect on the thermal performance and pressure loss of the water flow in a plate-fin heat exchanger by Khoshvaght-Aliabadi *et al.,* [12]. Their outcomes revealed enhancements in thermal performance by utilizing the rectangular wings compared to using triangular and trapezoidal wings respectively.

To summarize what has been presented from the previous studies above for both corrugated surfaces and vortex generator techniques, it can be noted that both techniques have a significant effect on improving heat transfer accompanied by an increase in pressure drop (Depending on the above). This study attempts to combine these two techniques to demonstrate their effect on heat transfer enhancement as well as friction factor. The present study considers turbulent forced convective flow in two-dimensional trapezoidal-corrugated channels with winglet pair inserts vortex generator over Reynolds number in the range of 5,000 ≤ Re ≤ 17,500 under constant heat flux condition.

2. Physical Model

The basic geometries of channel, which is trapezoidal channel with winglet inserts, are shown in Figure 1. It consists three sections: developing section L_d (upstream = 200 mm), exit section L_e (downstream = 100 mm) and test section L_c = 200 mm. Two corrugated walls with amplitude a =1, 2, 3 and 4 mm, wavelength L_w = 20 mm, minimum channel height H_{min} = 6 mm and maximum channel height H_{max} = 14 mm are shown in Figure 1. Furthermore, the total (axial) length of corrugated wall is (10 × L_w). There are ten corrugations (pitches) along the corrugated wall. Moreover, the length and thickness of the winglet inserts are 4 mm and 0.5 mm respectively. The distance h = 2 mm. In addition, both top and bottom of the corrugated walls are exposed to uniform wall heat flux. To create appropriate boundary conditions for both the inlet and outlet of the corrugated channel, they are considered adiabatic.

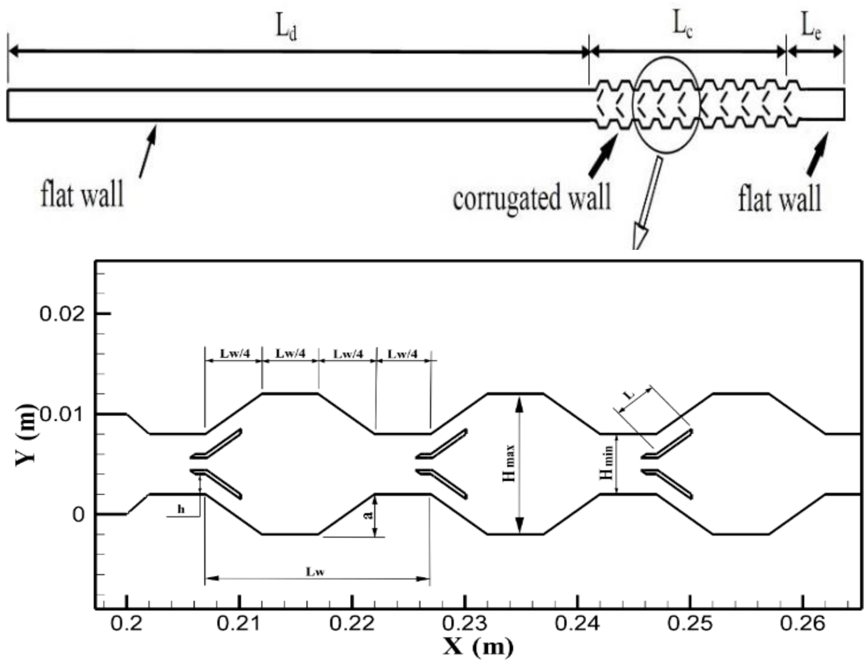

Fig. 1. Schematic diagram of numerical domain

3. Governing Equations and Assumptions

To complete the numerical solution and obtain the final form of governing equations for current study, some assumptions should be considered. The flow is adopted to be steady-state conditions, fully developed and two-dimensional. Side walls and all the upstream walls are considered to be adiabatic surfaces. The base fluid is assumed to have a thermal equilibrium and no slip condition occurs. The fluid flow is considered to be Newtonian and incompressible. In this model, the governing equations were discretized using the finite volume approach. Continuity equation, momentum equation and energy equation can be written as [13]:

Continuity equation:

$$\nabla.\left(\rho_w \vec{V}\right) = 0 \tag{1}$$

Momentum equation:

$$\nabla.\left(\rho_w \vec{V}\vec{V}\right) = -\nabla P + \nabla.\left(\mu_w \nabla\vec{V}\right) \tag{2}$$

Energy equation:

$$\nabla.\left(\vec{V} C_{p,w} T\right) = \nabla(k_w.\nabla T) \tag{3}$$

4. Grid Independence Tests

In general, the accuracy of the numerical results depends on the grid resolution. In order to estimate the required element size of the current study, six different elements size which includes 0.7, 0.6, 0.4, 0.3, 0.2 and 0.15 mm have been chosen. The average Nusselt number (*Nu*) along the trapezoidal walls for water at *Re* = 17,500 have been investigated over these elements size. It is found from the Table 1 and Figure 2 that the relative percentage error between grid size 0.2 mm and 0.15 mm is 0.00021 which is very small and this grid size 0.2 mm appears to be suitable to certify the independency of numerical results.

Table 1
Grid independence test for turbulent flow regime

Grid size(mm)	Nu_{avr}	Relative error
0.70	464.3334	--------
0.60	469.1402	0.01030
0.50	477.7441	0.01800
0.40	484.5302	0.01400
0.30	488.0045	0.00710
0.20	490.7320	0.00550
0.15	490.8320	0.00021

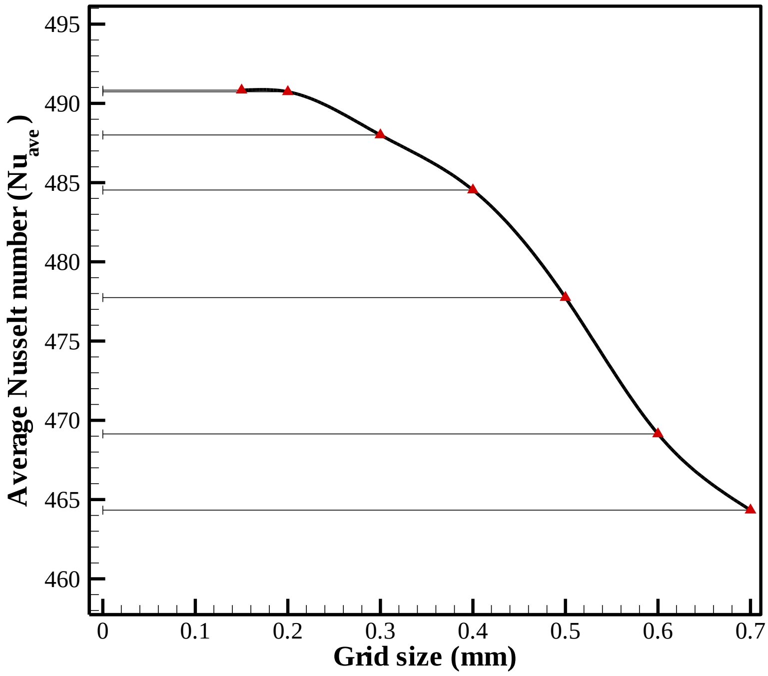

Fig.2. Grid independence test for turbulent flow regime

5. Numerical Validation

The results of the CFD should be validated with the experiment or numerical study of other researchers in order to obtain more accurate results. The validation of the heat transfer coefficient versus Reynolds number (*Re*) of CFD was compared with study of Khoshvaght-Aliabadi *et al.,* [12]. It can be clearly seen from the Figure 3 that the CFD results of present work are in a good agreement with experimental work of Khoshvaght-Aliabadi *et al.,* [12].

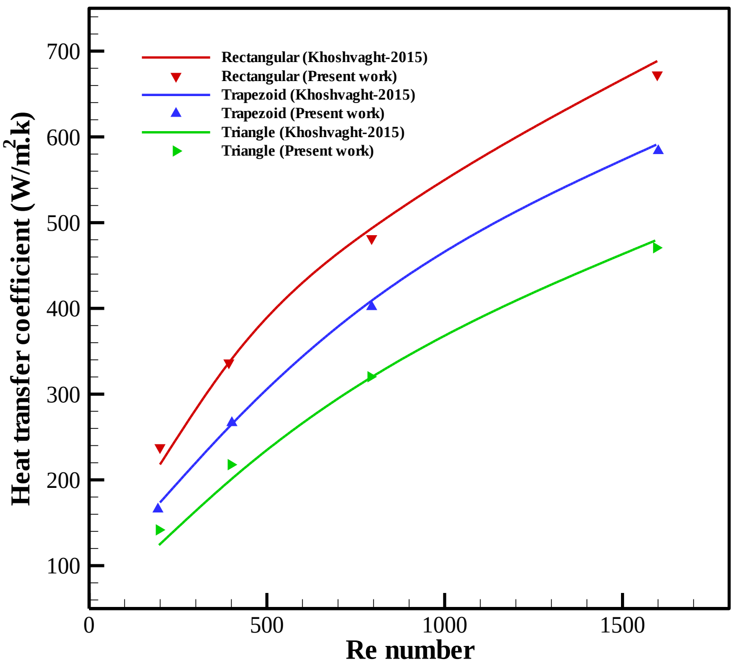

Fig. 3. Comparison between the current work and the outcomes of Khoshvaght-Aliabadi *et al.,* [12]

6. Results and Discussion

6.1 Comparison Between A Corrugated Channel, Corrugated Channels with Winglet Inserts, Smooth Channel with Winglet Inserts and Smooth Channel

In this section, comparison between a corrugated channel with winglet inserts, corrugated channel, smooth channel with winglet inserts and smooth channel has been done to indicate their effect on the local Nusselt number (*Nu*) value as illustrated in Figure 4. It can be seen from this comparison at the section between 0.225 m and 0.3 m of the test section of each channel with Reynolds number (*Re*) = 5,000 that the combination of insertion of swirl devices technique and surface modification technique has given a better improvement in local *Nu* comparing with other techniques which will be explained more later. This study has proved that the combination of two techniques has improved heat transfer rate.

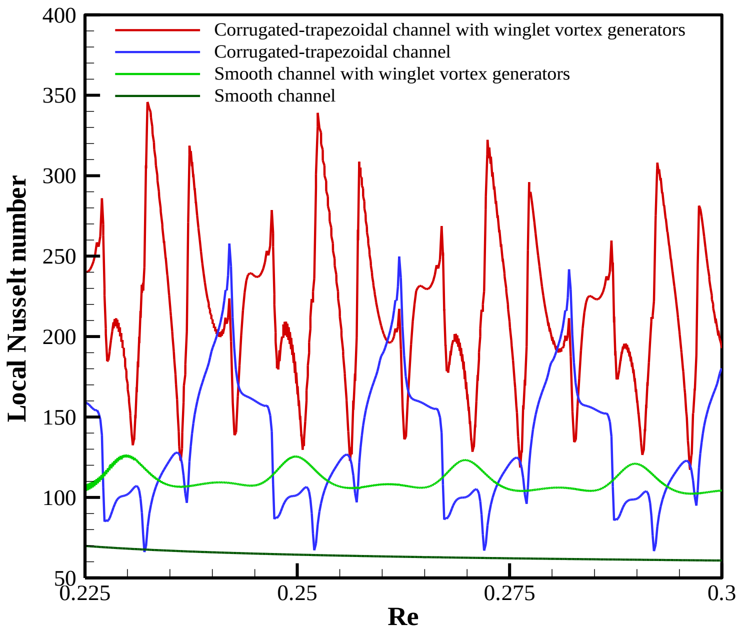

Fig. 4. Comparison between a corrugated channel, corrugated channels with winglet inserts, smooth channel with winglet inserts and smooth channel

6.2 Effect of Amplitude of Corrugated Channel and Winglet Inserts

The effect of winglet inserts and the amplitude of trapezoidal corrugated walls on thermal and flow fields using water has been considered over Reynolds number (*Re*) range of 5,000 – 17,500 at L_w = 20. Figure 5 shows the stream wise velocity contours at *Re* = 5,000 with different amplitude (1, 2, 3 and 4 mm) and winglet inserts. Generally, it can be observed that the stream wise contours are symmetric about (*x*-coordinates) for all amplitudes of corrugated wall. Moreover, the Figure 5 indicates that the reverse flow in trough (crest) of the lower and (upper) walls of all amplitude of corrugated channels generated due to the corrugated walls and winglet inserts. Figure 5 also shows that the core fluid velocity at the converging (throat) section increases as the amplitude increases. This because channel height at the converging (throat) section decreases as the amplitude increase and since the fluid flow rate is constant at any cross section along the channel, therefore, the velocity of the fluid at this section will increase.

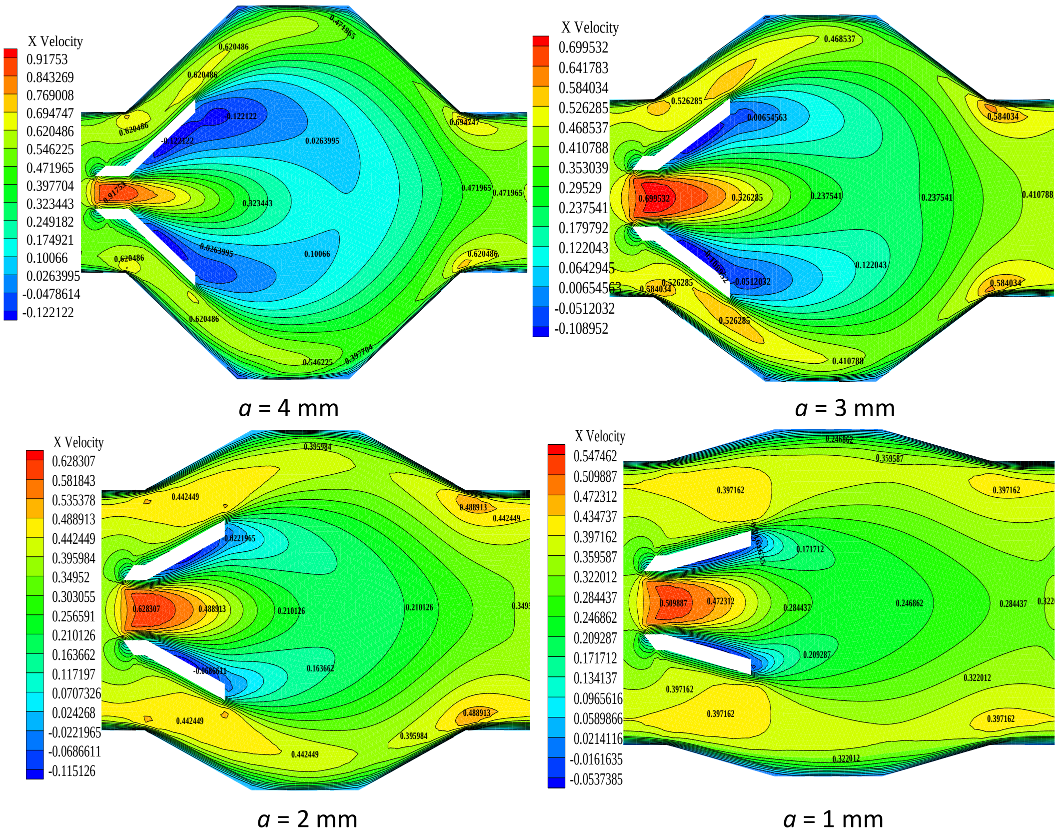

Fig. 5. Streamwise velocity contours for water in corrugated channels with different amplitude winglet inserts and at *Re* = 5,000

Figure 6 displays the isotherms contours for trapezoidal-corrugated channels with winglet inserts and different amplitudes. According to these figures, it can be clearly observed that the winglet inserts and amplitude of channel have strong influence on the wall's temperature gradient. The temperature gradient increases and the thickens of the thermal boundary layer decreases due to the inclusion of the winglet inserts as well as the amplitude of the wall of corrugated channels, which increases the velocity and the flow becomes more turbulent on the walls. Moreover, it can also be seen that the temperature gradient at the throat of corrugated channel has significant increased due to accelerate the fluid velocity at this section. Therefore, it is expected to highly enhance the heat transfer rate at this section. Non-dimensional streamwise velocity and non-dimensional temperature distribution of different amplitude heights and winglet inserts of turbulent fully developed flow have been presented in this part.

Figure 7 shows the non-dimensional streamwise velocity distribution at trough of the fifth wave of different amplitude of corrugated channels with winglet inserts at Reynolds number *Re* = 5,000. As mentioned before, the velocity near the walls increases in magnitude due to winglet inserts as well as the amplitude of the wall of corrugated channels when the flow enters the corrugated channel, the winglet inserts will change the direction of the flow towards the walls causing an increase in velocity and disturbance.

Figure 8 displays the non-dimensional temperature distribution at trough of the fifth wave of corrugated channels with different amplitude of corrugated wall and winglet inserts. Figure 8 indicates that Temperature gradients on walls augmented significantly with higher amplitude, as expected. Because the velocity of the flow increases in the diverging section due to the wigs inserts which promote the fluid mixing and hence reduces the thickness of thermal boundary layer and increase the heat transfer augmentation.

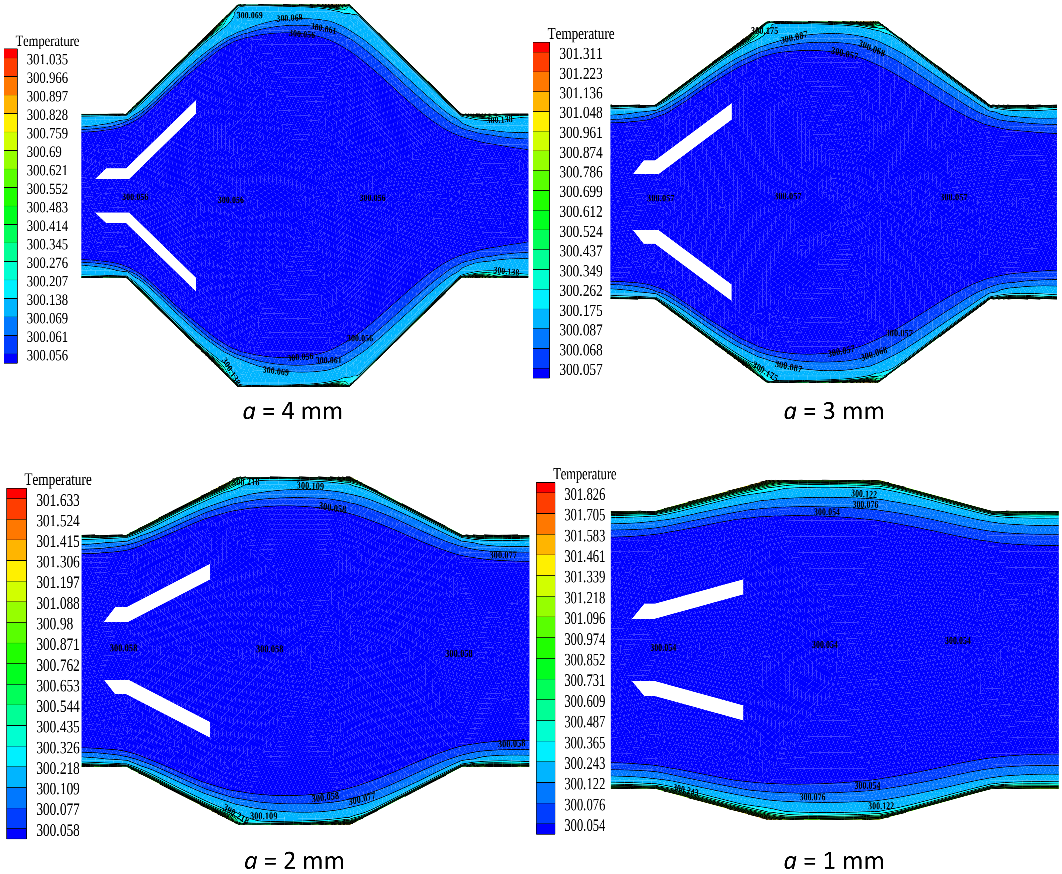

Fig. 6. Isotherms contours for water in -corrugated channel at *Re* = 5,000 with different amplitudes and winglet inserts

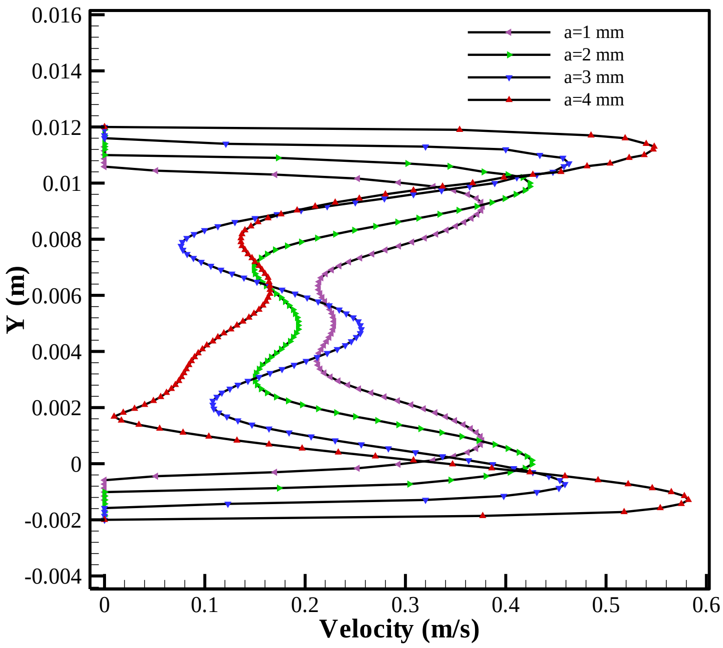

Fig. 7. Non-dimensional streamwise velocity for water with different amplitude heights and winglet insert at L_w = 20 mm, in trapezoidal corrugated channel

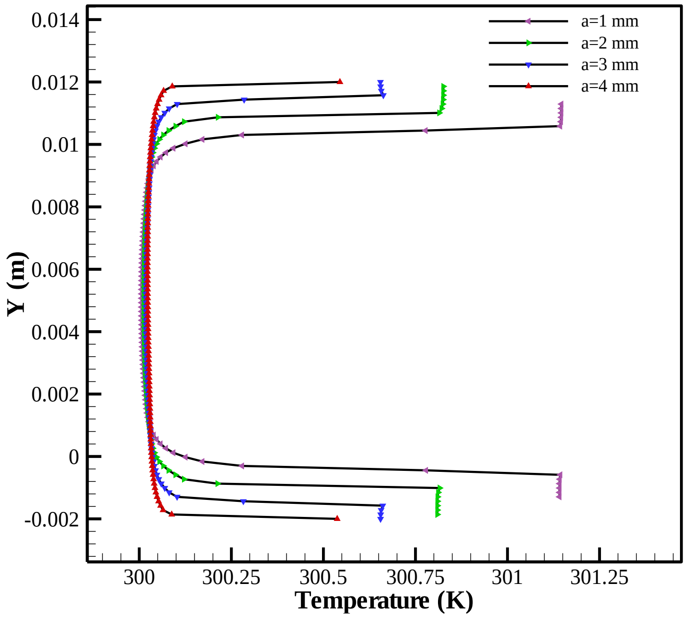

Fig. 8. Non-dimensional temperature for water with amplitude heights and winglet inserts at L_w = 20 mm in trapezoidal corrugated channel

Figure 9 shows the average Nusselt number (*Nu*) versus Reynolds number (*Re*) with different amplitudes of corrugated channels and winglet inserts. It should be noted that Reynolds number as well as the amplitude of corrugated channel and winglet inserts have a strong effect on the average *Nu*. At given amplitude and winglet inserts, when *Re* increases, a significant improvement in heat transfer can be achieved. The high flow rate reduces heat resistance and makes the boundary layer thinner and then accordingly increases in heat transfer rate. This enhancement becomes significant at highest values of the *Re* as shown in Figure 8. According to the above-mentioned explanation about the maximum temperature of the heated surface, it is expected that the *Nu* increases by *Re* and this trend is seen in this figure. In addition, secondary flow regimes are expected to begin growth in the trough (crest) of the lower (upper) walls due to the corrugated shape of the walls and vortex generators VGs then the flow becomes turbulent and thus improves fluid mixing in the divergent section, therefore, the average *Nu* will increase. In general, the average *Nu* for all the amplitude heights of corrugated channels has a similar trend.

Figure 10 depicts the skin-friction coefficient of trapezoidal-corrugated channels with different amplitudes and winglet inserts at different of Reynolds number (*Re*). Generally, the skin-friction coefficient decreases with the *Re*. Moreover, it can be seen that the friction coefficient at a = 0, is less in the case of the straight channel compared to the channel that contains the winglet inserts and different amplitude, as expected. With more increase in the amplitude, the converging section becomes narrower, the peak value of the friction coefficient increases due to increase the velocity gradient at the crest of the wall. In addition, the skin-friction coefficient augments with the winglet inserts due to the increase of velocity gradient.

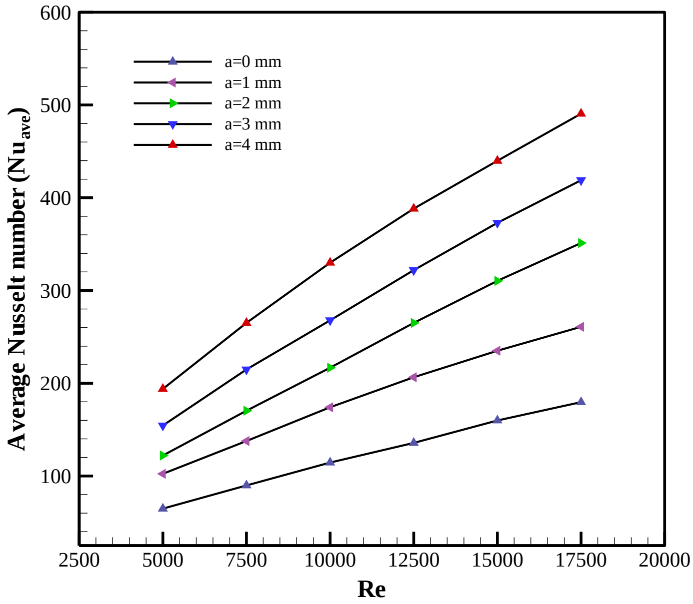

Fig. 9. Average Nusselt number vs. Reynolds number for water with different amplitudes of corrugated channel and winglet inserts at L_w = 20mm of trapezoidal corrugated channel

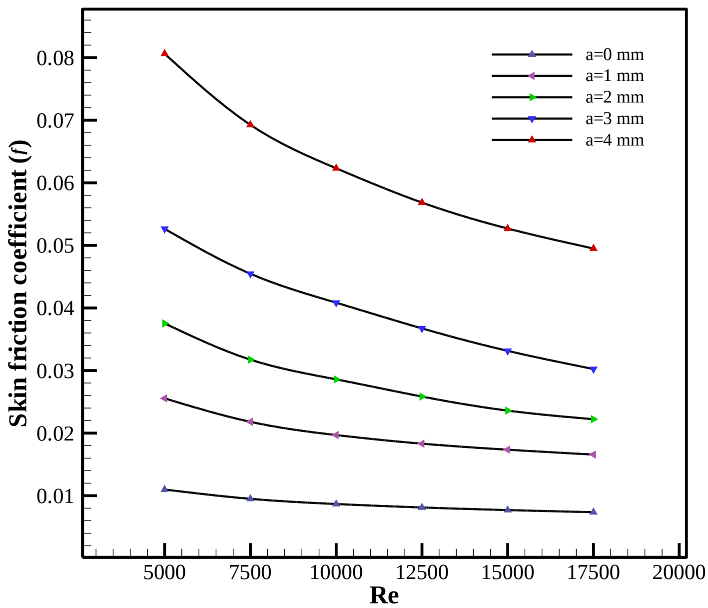

Fig. 10. Skin friction coefficient vs. Reynolds number for water with different amplitudes of trapezoidal channel and wings insert at L_w = 20mm of trapezoidal corrugated channel

6.3 Performance Evaluation Criteria

The use of passive technique to improve heat transfer in heat exchangers is always accompanied by pressure drop. It is necessary to distinguish between the ratios of improvement in heat transfer to pressure drop to see how successful this technique is. For this purpose, many researchers have used the term thermal performance evaluation criteria (PEC). PEC can be written as follows (Webb and Kim [14], Manca *et al.,* [15]:

$$\mathrm{PEC} = \frac{(Nu_{\mathrm{VG}}/Nu_{\mathrm{plane}})}{(f_{\mathrm{VG}}/f_{\mathrm{plane}})^{1/3}} \tag{4}$$

It should be noted that the value of performance evaluation criteria PEC >1 means that the improvement in heat transfer is higher than the pressure drop penalty. The current study showed that the use of corrugated walls with winglet inserts have improved the heat transfer in the heat exchanger with less of pressure drop, which can be seen in the Figure 11. This increase of PEC is attribute to the temperature gradient in each trapezoidal wall of corrugated channel which greatly increases due to accelerate the fluid velocity at this section that result from the combination of the winglet inserts as well as the trapezoidal walls of corrugated channel, which increases the fluid velocity and the flow becomes more turbulent on the walls.

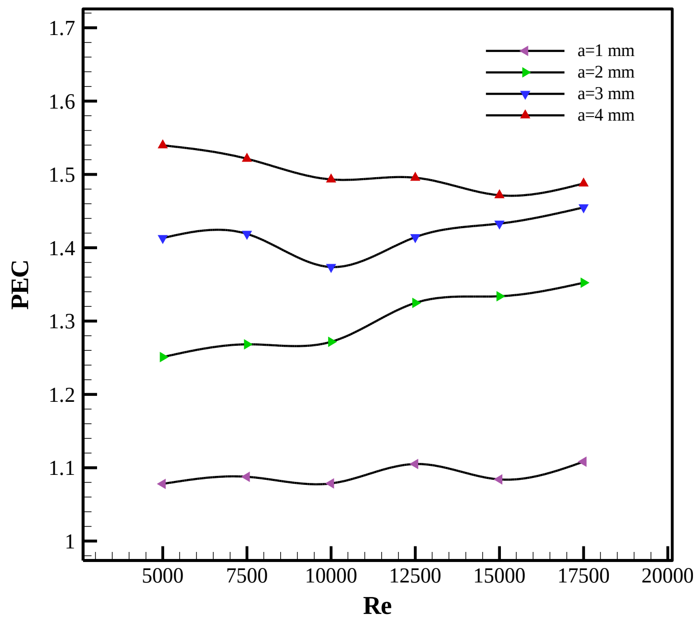

Fig. 11. Performance evaluation criteria of combined amplitudes of corrugated wall and winglet inserts for turbulent flow

In addition, Figure 11 also shows that the increases in amplitude height of the corrugated wall led to increase the average Nusselt number (*Nu*) resulting an increase of PEC as mentioned in section 6.2. It can be summarized from the above that the utilization of combination of amplitudes of corrugated wall and winglet inserts in a channel is very useful for turbulent flow.

7. Conclusion

A numerical approach has adopted the forced convection turbulent flow in a trapezoidal channel to investigate the effect of different amplitude height and vortex generators VGs on heat transfer enhancement and flow field. Nusselt number (*Nu*), skin friction coefficient and (PEC) are substantial factors that have been studied at turbulent flow, the simulation results can be summarized as:

i. The winglet inserts and the amplitude of channel have strong influence on the temperature gradient.

ii. *Nu* highly increased with increasing of Reynolds number (*Re*), while the wall temperature decreased as *Re* increased, the maximum *Nu* was found at *Re* of 17,500.
iii. A dramatic enhancement in the *Nu* obtained by using winglet inserts comparing with plane channel.
iv. The skin-friction coefficient decreases with the *Re* due to increase the velocity gradient.
v. The skin-friction coefficient augment with the winglet inserts due to the increase of the resistance to the flow.
vi. The increases in amplitude height of the corrugated with winglet inserts led to increase the performance evaluation criteria PEC.

Acknowledgement
The authors would like to thanks the Department of Aerospace Engineering for the financial support in conducting the research.

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