

Numerical Study of Heat Transfer Enhancement in Contour Corrugated Channel Using Water and Engine Oil


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ABSTRACT

Improving the design of geometrical parameters of heat exchanger leads to enhance heat transfer and makes it further compacted which in turn increases the efficiency of the thermal process, leading to save operating costs. In the present investigation, thermal and hydraulic performance of laminar flow of the trapezoidal, sinusoidal, and straight counter heat exchanger with water and engine oil was carried out numerically over Reynolds number ranges of 1100-2300 for water and 250 for engine oil. The effect of wave height and wavelength of both trapezoidal and sinusoidal on the thermal properties and hydraulic performance are studied. The numerical study showed that the effect of wave height on the Nusselt number was greater than that of wavelength in both trapezoidal and sinusoidal channels. The study also showed that the trapezoidal channel's influence on Nusselt number was higher than that of the sinusoidal channel and straight channel respectively. Thermal and flow characteristics are explored with the help of the streamwise velocity and isotherms contours for trapezoidal and sinusoidal-corrugated channels. In addition, the success of the heat exchanger design was evaluated by the results of the thermal performance criteria. The results of the thermal performance criteria at all wave heights and wavelength of the corrugated channel were greater than 1, which is indicating that the heat transfer rate is higher than the friction losses. Consequently, the use of corrugated surfaces in Contour heat exchangers can improve heat transfer in many applications.

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1. Introduction

In recent years, research on the methods for heat transfer enhancement in heat exchangers has received great attention in order to cater to the growing needs of higher efficiencies in these devices. There are diverse ways to improve heat transfer methods. One of the traditional procedures to decrease thermal resistance is using a heat exchanger with a larger surface area or reduce the thickness of the thermal boundary layer on the surface of a heat exchanger. The most reliable method to improve heat exchangers has used corrugated surface geometry. The idea behind the

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enhancement of heat transfer in this system is disrupting the fluid flow when it runs through the corrugated channel and rising recirculation regions close to the corrugated wall resulting in enhances the mixing of fluid and heat transfer. There are many numerical and experimental studies on the use of corrugated surface geometry as a passive technique to improve the heat transfer rate. Mohammed *et al.*, [1] carried out a numerical study on the plate heat exchanger to investigate heat exchange and forced turbulent convective flow in a model of corrugated channel. This investigation was including measurement of performance evaluation criterion in the corrugated surface using water as a working fluid in the channel and wavy heights and the effect on the thermal and flow fields. The results illustrate the significant effect of the wavy channel on the enhancement of heat transfer. Heidary *et al.*, [2] Performed a parametric study to display the influence of corrugated flow channel on the improvement of heat exchange between the cold bottom wall and the core hot flow in the anode electrode of direct methanol fuel cells. They are observed that corrugated bottom wall with triangular, wavy, and trapezoidal shapes can significantly increase the efficiency of the heat exchange between the wall and the core flow. Tokgoz *et al.*, [3] numerically and experimentally investigated the flow features and thermal efficacy in various ducts geometries. The entire studies were done for Reynolds numbers (Re) in the range of [3000-6000]. They found that improvement in heat transfer was significant at a larger amplitude wavelength ratio, especially at higher Re. Ghule *et al.*, [4] have analysed numerically heat transfer of different cross-sections of corrugated microchannels by different Re and the amplitude of waviness. The study has considered four different cross-sections, circular, namely rectangular, notched circular and notched rectangular in this study. The results showed that enhancement in fluid mixing resulting in an increase in the amplitude of waviness and yield an increase in the heat transfer coefficient Nfawa *et al.*, [5] studied numerically the heat transfer rate and the behaviour of the fluid flow in a corrugated channel with new configuration. The study showed that as the surface wave increases, the heat transfer increases, accompanied by increased pressure drop. In addition, the study verified the performance evaluation criteria, which showed the difference between the rate of heat transfer and the pressure drop, where the values of this parameter were higher than one, which means that the heat transfer is higher than the pressure drop. Harikrishnan *et al.*, [6] presented numerical investigations of the effect of corrugated channels with skewness on heat transfer and characteristics of flow. The results showed that the Nusselt number was elevated with the rise in skewness angle up to 35° and friction factor up to 30°. This is attributed to increasing secondary flow strength generated inside the channel resulting from spanwise velocity which lowers the strength of vortices trapped inside the grooves Zhang *et al.*, [7] investigated numerically the influence of corrugation profile for cross-corrugated plates on thermal-hydraulic performance. Different corrugations profiles such as isosceles triangular sinusoidal, elliptic corrugations and trapezoidal were considered in this study. It was observed that the corrugation profile had a clear effect on the performance of the corrugated channel. The channel with sharp corrugations has a higher average Nu and friction factor compared to the channel with the smooth corrugations. Numerically, the findings of Ajeel *et al.*, [8-13] uncovered that the average Nu was significantly enhanced by the corrugation profile as opposed to the smooth channels. Aneesh *et al.*, [14] performed a numerical investigation on two high-pressure circuit heat exchangers. This work was expanded by reviewing the outcome of 3 wavy channel configurations viz. triangular, trapezoidal, and sinusoidal. In order to test working conditions, the trapezoidal wavy channel provides an increase in the expected heat transfer rate of about [41%] compared to the straight channel, Whereas, the corresponding heat transfer is expected to be [33%] and [28%] for the PCHE wavy channel formation and sinusoidal configurations, respectively. Ajeel *et al.*, [15-17] considered the influence of geometrical parameters on thermal performance factor in various corrugated channels by using nanofluids. The findings of PEC explained that the ratio of height-to-width was more efficient than

the pitch-to-length ratio. In addition, it was detected that by increasing the volume fraction, the Nusselt number was increased, but the Δp was also increased. Ahmed *et al.*, [18] studied numerically laminar flow in corrugated and straight channels of Re [100-800]. Different shapes of corrugated channels including triangular, sinusoidal, and trapezoidal are tested. the lower Nusselt number was found in the straight channel and triangular were trapezoidal channel was the highest.

From the observation of previous studies, there is no study has been done to investigate the laminar convective heat transfer between water and engine oil in Contour heat exchanger with Corrugated surfaces according to the author's knowledge, as this study aimed to design a heat exchanger that cools the engine oil. Moreover, this study also aimed to improve the effectiveness of heat transfer of the counter corrugated channel with a moderate increase in the pressure drop penalty by passive methods; corrugated walls (surface extensions).

2. Mathematical Model

2.1 Problem Description

The basic geometry of the corrugated contour channel is shown in Figure 1. It consists of one corrugated aluminum wall. there are ten corrugations (itches) along the corrugated wall. To create proper boundary conditions for both outlet and inlet of the corrugated channel of water and engine oil, four adiabatic smooth sections are considered.

The form has an axial length of $L_d = 200$ mm and the later has an axial length of $L_e = 60$ mm. The average height (H_{av}) of all these sections was 10mm. The test section $L_c = 200$ mm However, the following geometric parameters are considered in the current study; the amplitudes of the corrugated channel (a) are 0,1,2,3,4 and 5 mm and the wavelengths of the corrugated wall (L_w) are 20,30 and 40mm.

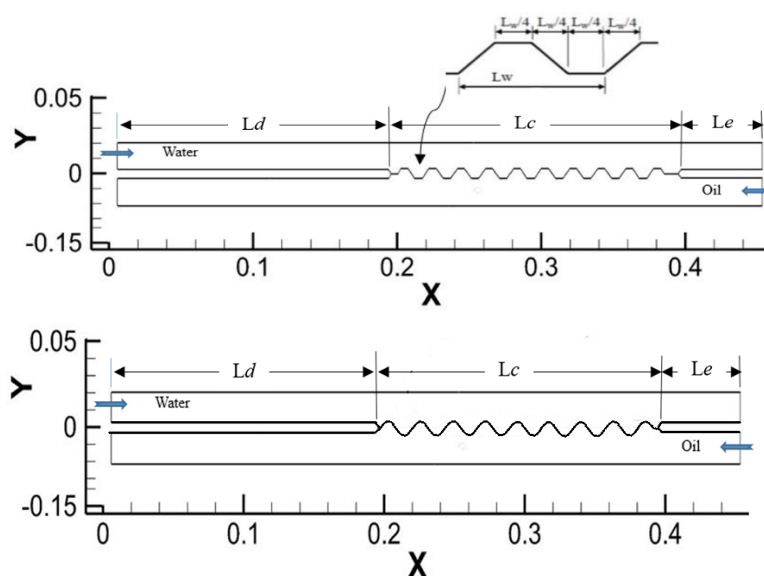


Fig. 1. The physical domain of the present study

2.2 Inlet Boundary Conditions

A uniform velocity and temperature distributions are commonly assumed at the inlet of water and engine oil channel.

$u = u_{in}, v = 0, T_{in} = 298 \text{ K}$ for water

$u = u_{in}, v = 0, T_{in} = 350 \text{ K}$ for engine oil

2.3 Governing Equations and Assumptions

To complete the numerical solution and obtain the final form of governing equations for the current study, some assumptions should be considered. The flow is adopted to be steady-state conditions, fully developed and two-dimensional. Sidewalls 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 Moraveji *et al.*, [19]

Continuity equation

$$\nabla \cdot (\rho v) = 0 \quad (1)$$

Momentum equation

$$\nabla \cdot (\rho v v) = -\nabla P + \nabla \cdot (\mu \nabla v) \quad (2)$$

Energy equation

$$\nabla \cdot (\rho C v T) = \nabla \cdot (k \nabla T) \quad (3)$$

3. Code Validation and Grid Testing

3.1 Grid Independence Test

Generally, grid resolution plays an essential role in the accuracy of the numerical results. In order to evaluate the required element size of the current study, five different element sizes, which are 0.4, 0.3, 0.2 and 0.15 have been chosen (Table 1).

Table 1
Different element's size with elements number

Grid size	Elements number
0.4	158690
0.3	264044
0.2	539280
0.15	920766

The local Nusselt number and pressure distribution along the distance $X=0.25$ to 0.3m for the trapezoidal wall of water at $Re=1200$ and oil at $Re=250$ have been investigated over these elements Size. It was found that the grid size of the 0.2 uniform grid appears to be suitable to certify the independence of numerical results from the grid system (Figure 2).

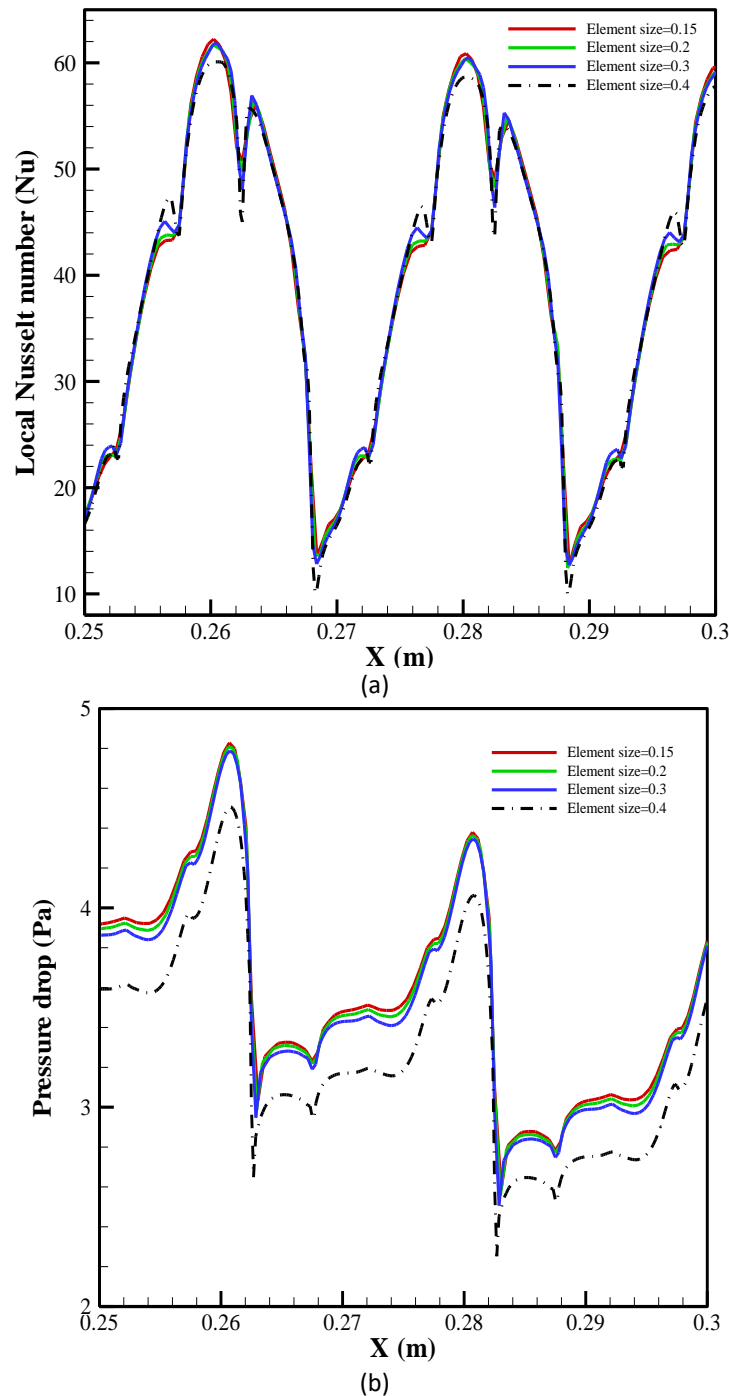


Fig. 2. (a) local Nusselt number and (b) Pressure drop a long-distance $X=0.25$ to 0.3 m for water at $Re = 1200$

3.2 Numerical Validation

To test the validity of the proposed numerical model, experimental and numerical investigation of the turbulent forced convection of SiO_2 -water nanofluid flow in a corrugated channel has been studied by Ahmed *et al.*, [20]. Figure 3 observe the compression of average Nusselt number and pressure drop versus Reynolds number which were calculated in this investigation with those in numerical and experimental results Ahmed *et al.*, [20].

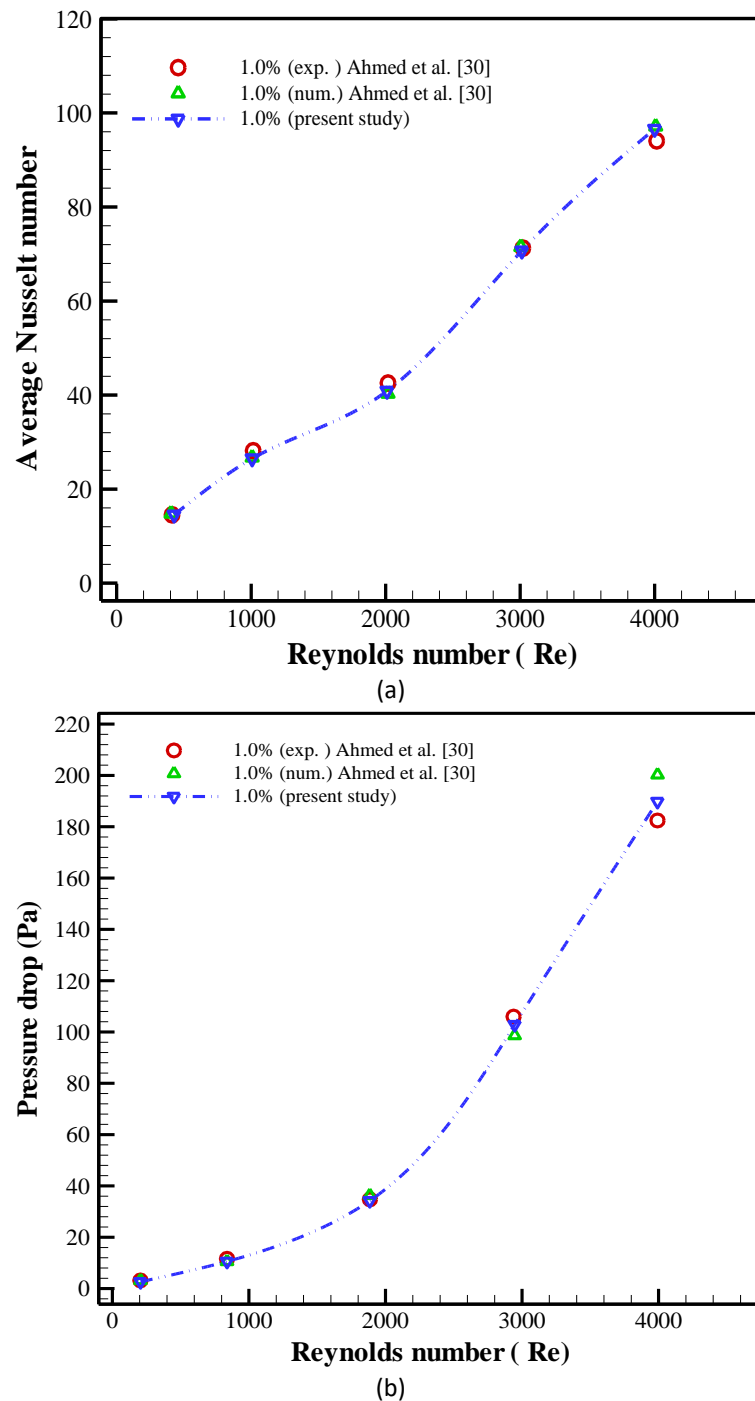


Fig. 3. Comparison results of turbulent convection in a corrugated channel with [18]. (a) average Nusselt number versus Reynolds number. (b) pressure drop versus Reynolds number

It is observed from the figure that there was a good agreement in the results between these studies. The error deviation of the Nusselt number in Figure 3(a) is 0.0102% and 0.0208% with numerical and experimental work and the error deviation of the pressure drop in Figure 3(b) is 0.0512% and 0.0325% with numerical and experimental work over Reynolds number=4000.

4. Results and Discussion

4.1 Effect of Channel Shape on (Nu)

In this section, the effect of channel shape on the average Nusselt number (Nu), pressure drop, wall temperature, and Nusselt number enhancement ratio have been presented and analyzed over Reynolds number (Re) range of 1200-2300 of water and for oil Reynolds number (Re)=250. Two different corrugated channels including sinusoidal and trapezoidal with a wavelength of 20 mm and amplitudes of 4 mm to the straight channel have been considered. Figure 4 offers the variation of the average Nu with Re for different channel shapes. As seen from this figure, the average Nusselt number (Nu_a) for all shapes of channels significantly increases with Re because the wall temperature gradient increases, as expected, and hence increase the heat exchange between the wall and the fluid. It is also observed that the straight channel has the lowest Nu compared with the corrugated channel due to poor fluid mixing, therefore, the thermal boundary layer thickens, thereby reducing the heat transfer rate. The trapezoidal- corrugated channel provides the highest average Nu_a over Re range with amplitudes of 4mm.

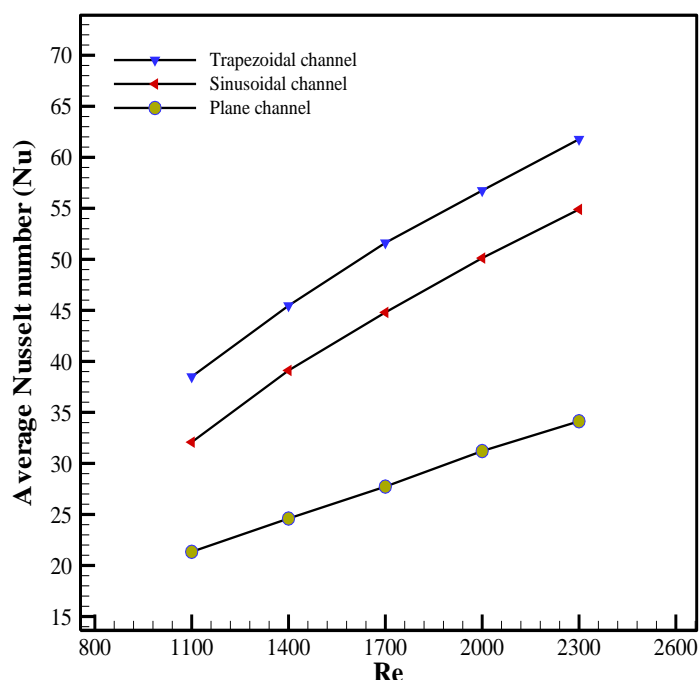


Fig. 4. Average Nusselt number vs. Reynolds number for different shapes at $L_w=20$ mm, and $a=4$ mm

4.2 Effect of Channel Shape on (ΔP)

The pressure drop versus Re with different channel shapes is shown in Figure 5. As expected, for all channel shapes the pressure drop increased when Re increase. Besides, the highest-pressure drop was in trapezoidal-corrugated channel at any amplitude because of the intensity of the re-circulation region. Besides, the throat of the trapezoidal-corrugated channel is larger wall surface area than that for the other channel shapes and because the velocity gradient in this section is very high and thereby, the pressure drop will be higher. At $Re=500$ of water, the channel shape effect on the pressure drop is not clear and quite close to each other because the flow is less disturbance at low Re . The straight channel, as expected, has the lowest pressure drop due to the regular flow and absence of re-circulation regions, as pointed out earlier.

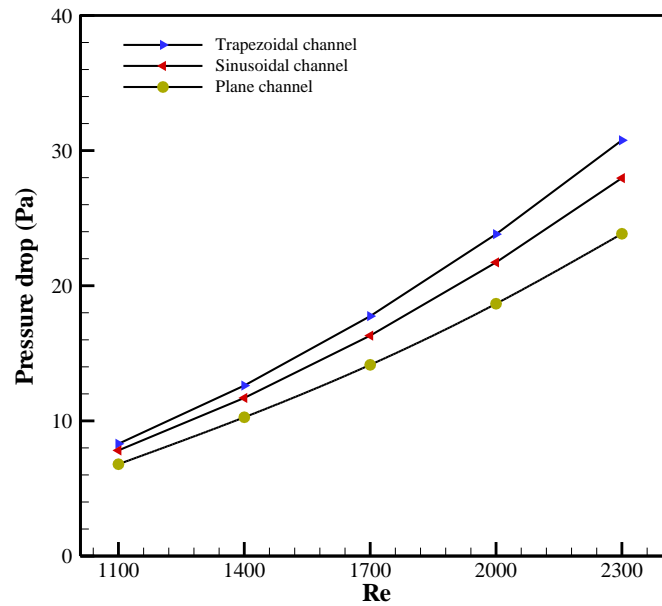


Fig. 5. Pressure drop vs. Reynolds number for different shapes at $L_w=20$ mm and $a=4.0$ mm

4.3 The Effect of Wall Shapes on the Average Wall Temperature

The variation of the average wall temperature with Re for different channel shapes is shown in Figure 6. It can be observed that the average wall temperature decreases as the Reynolds number increase in the corrugated channel, as mentioned previously.

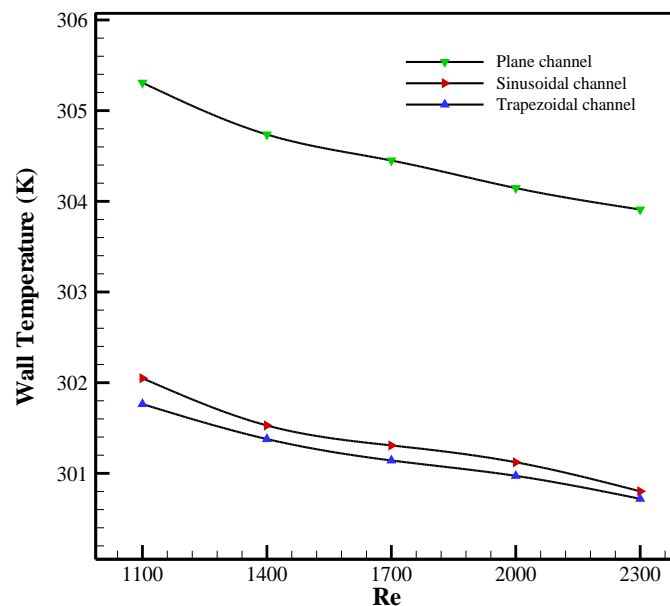


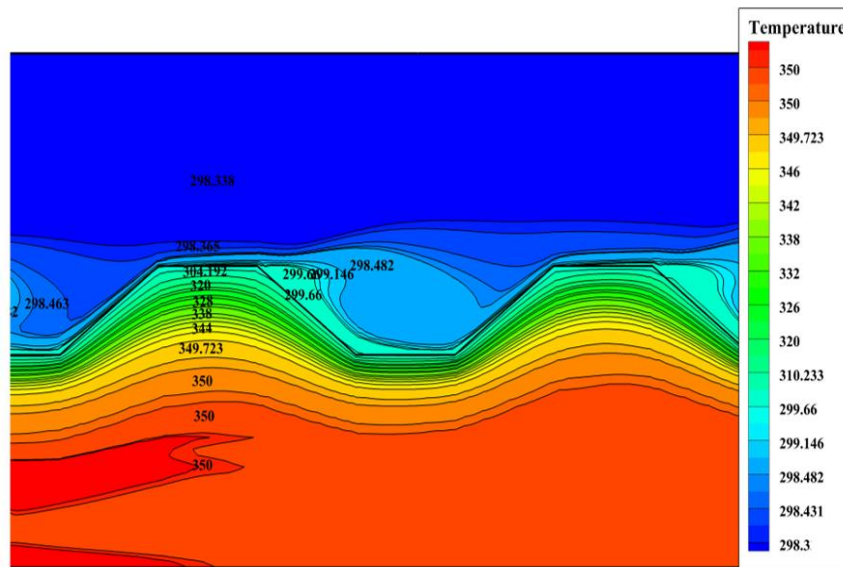
Fig. 6. Average wall temperature vs. Reynolds number for different channel shapes

In addition, the average temperature at the wall of the straight channel is the highest as compared to the corrugated channels due to the low heat transfer rate between the channel walls and the working fluid, as expected. In corrugated channels, the average wall temperature highly

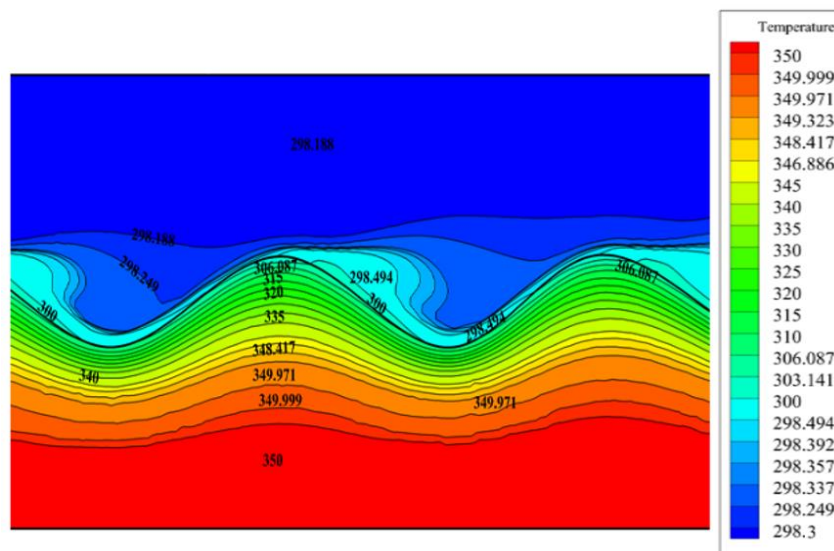
reduces due to improving heat transfer augmentation. However, the lowest wall temperature due to the highest heat transfer augmentation and this led to the lowest thermal resistance at the walls of the channel.

4.4 Effect of the Wall Shape on the Temperature Gradient

Figure 7 exhibits the isotherms contours for trapezoidal(a) and sinusoidal(b)-corrugated channels with amplitudes 4mm. According to these figures, it can be observed that the amplitude of the channel extremely affects the gradient of walls temperature.



(a)



(b)

Fig. 7. Isotherms contours for trapezoidal and sinusoidal - corrugated channel at $Re=1000$, with $L_w=20$ mm and $a=4$ mm

It can also be seen that the temperature gradient at the throat of the corrugated channel is significantly increased due to accelerating the fluid velocity in this section. Therefore, it is expected to highly enhance the heat transfer rate in this section. Moreover, it can be clearly seen that the

temperatures gradient in the trapezoidal channel is higher than the sinusoidal channel because the improving mixing of the cold fluid in core with hot fluid near the walls due to growing the lower walls re-circulation regions, trough (crest), is more in the trapezoidal channel than the sinusoidal channel.

4.5 Effect of the Wall Shape on the Average (Nu) Enhancement Ratio

The ratio of the (Nu_a) in different shapes of channels to that for the straight channel is depicted in Figure 8. It is noted that the enhancement ratio strongly depends on channel shapes, amplitude and (Re). The highest enhancement ratio is found in the case of the trapezoidal-corrugated channel with amplitudes of 4 mm for the entire range of Re . Furthermore, the peak value of the enhancement ratios is (85.5%) that found in the case of the trapezoidal-corrugated channel at $a=4$, when $Re=1600$ of water. While at $a=4$ mm, the sinusoidal-corrugated channel provided the highest enhancement ratio with a peak value of 63% at $Re=1600$.

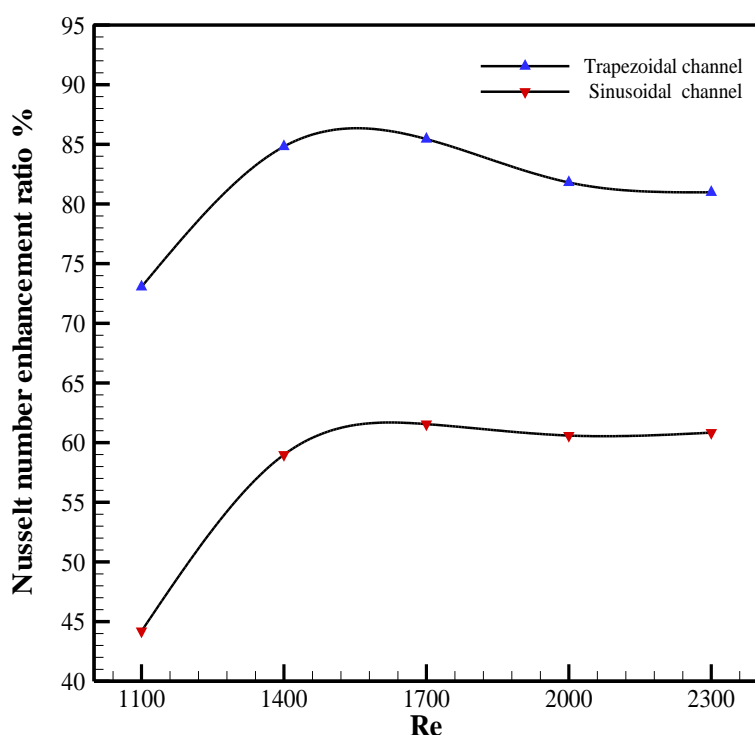


Fig. 8. enhancement ratio of Nusselt Number vs. Re for different shapes at $L_w=20$ mm and $a=4$ mm

4.6 Effect of the Amplitude on the Flow Field

The effect of amplitude of trapezoidal-corrugated channels on the flow and thermal fields using water and oil has been considered over the Re range of (1100-2300) of water and $Re=250$ of oil at $L_w=20$ mm. Figure 9 display the streamwise velocity contours at $Re=2300$ with a different amplitude of (1, 2, 3, 4 and 5) mm. Generally, at $a=1$ mm, it is noticed the absence of reversal (recirculation) flow in the trough (crest) of the lower walls of corrugated channels. At $a=2$ mm, the re-circulation regions begin to grow laterally along the wall of the diverging section. As noted from streamwise contours that the velocity in the diverging section near the walls, which is in the opposite direction to the main flow, increases in magnitude at larger amplitude. Therefore, there was an increase in the size of re-circulation regions, as shown in the velocity contours, and hence the flow becomes disturbed. At $a=5$ mm, the intensity of the re-circulation regions to the main flow increase and the

size of these regions become larger, and as a result, the flow becomes more disturbed. On the other hand, 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.

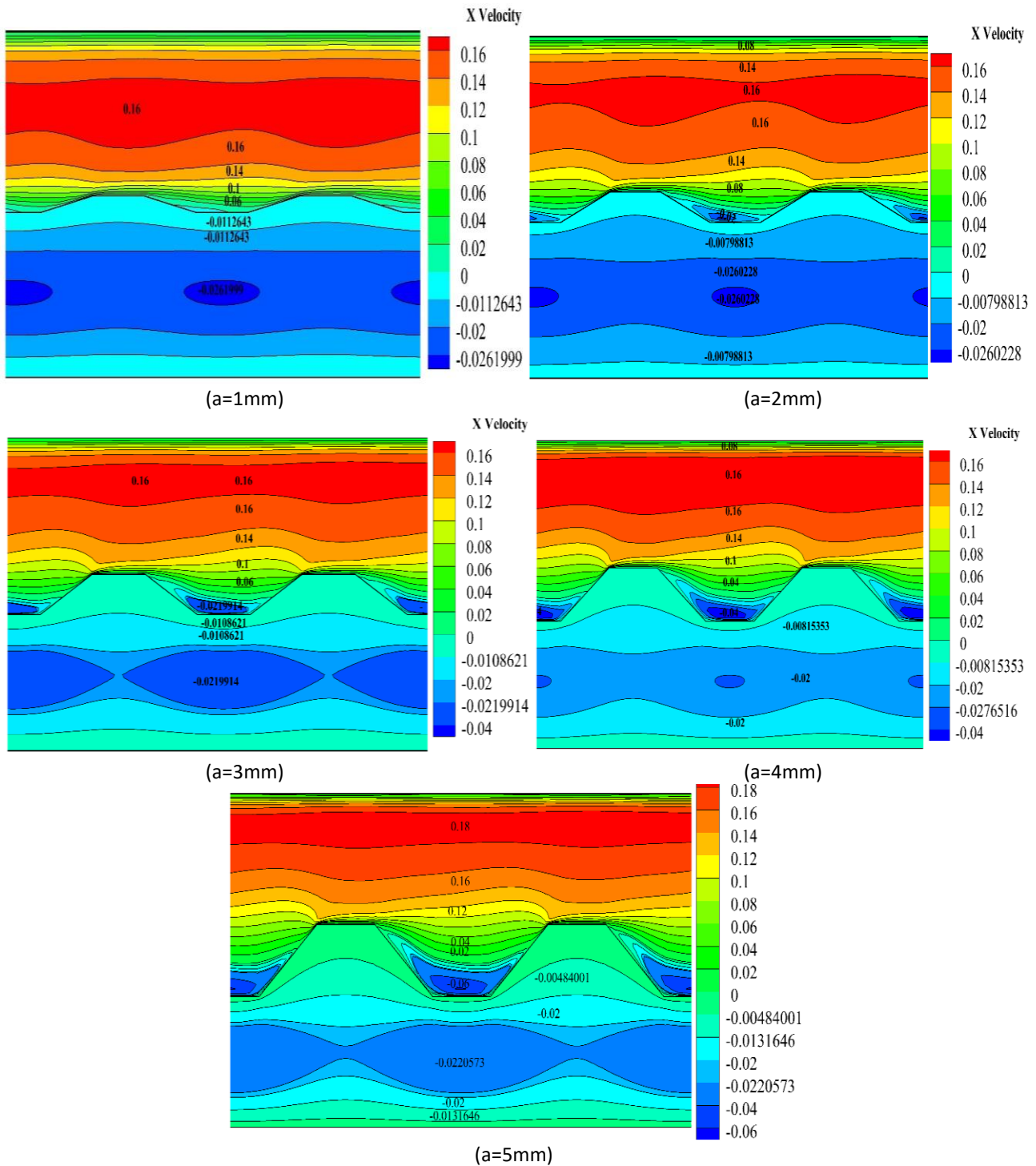
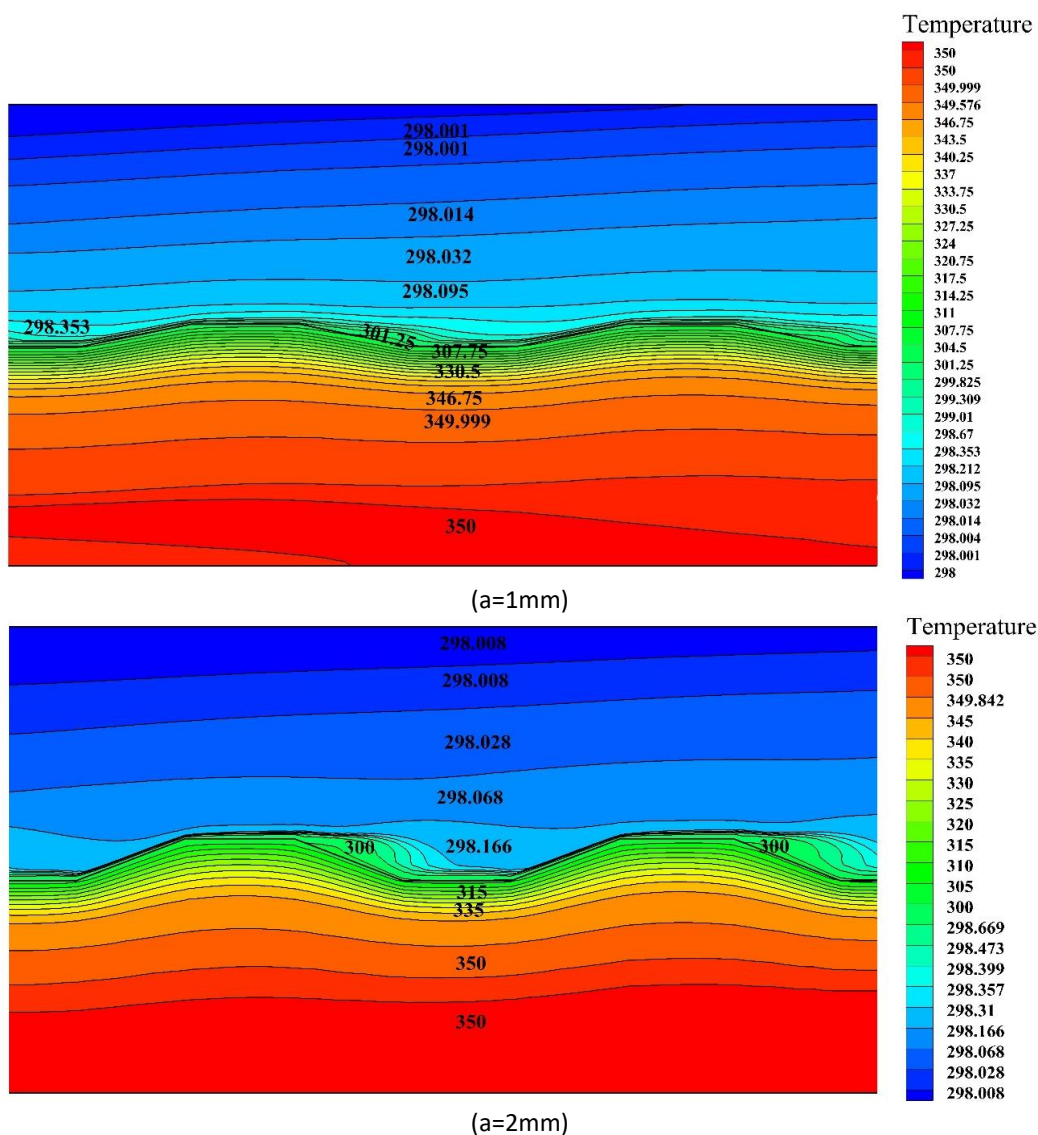


Fig. 9. Velocity contours for water in the trapezoidal channel with different amplitude at $Re=2300$

4.7 Effect of the Amplitude on the Temperature Gradient

Figure 10 exhibit the isotherms contours for trapezoidal-corrugated channels with different amplitudes. According to these figures, it can be clearly observed that the amplitude of the channel strongly affects the temperature gradient at the walls. At $a=1\text{mm}$ the temperature gradient at the walls has a small amount. This is due to the non-generation of eddies on the corrugated surface, this surface is almost similar to the flat surface. As the amplitude increases, the gradient of temperature also increases near the walls of corrugated channels. This is resulting from improvement in the mixing of the cold fluid in hot fluid core near the walls due to the re-circulation regions grow in the trough (crest) of the lower walls. Therefore, the thermal boundary layer thickness decreases as the amplitude increased. It can also be seen that the temperature gradient at the throat of the corrugated channel is significantly increased due to accelerating the fluid velocity in this section. Therefore, it is expected to highly enhance the heat transfer rate in this section.



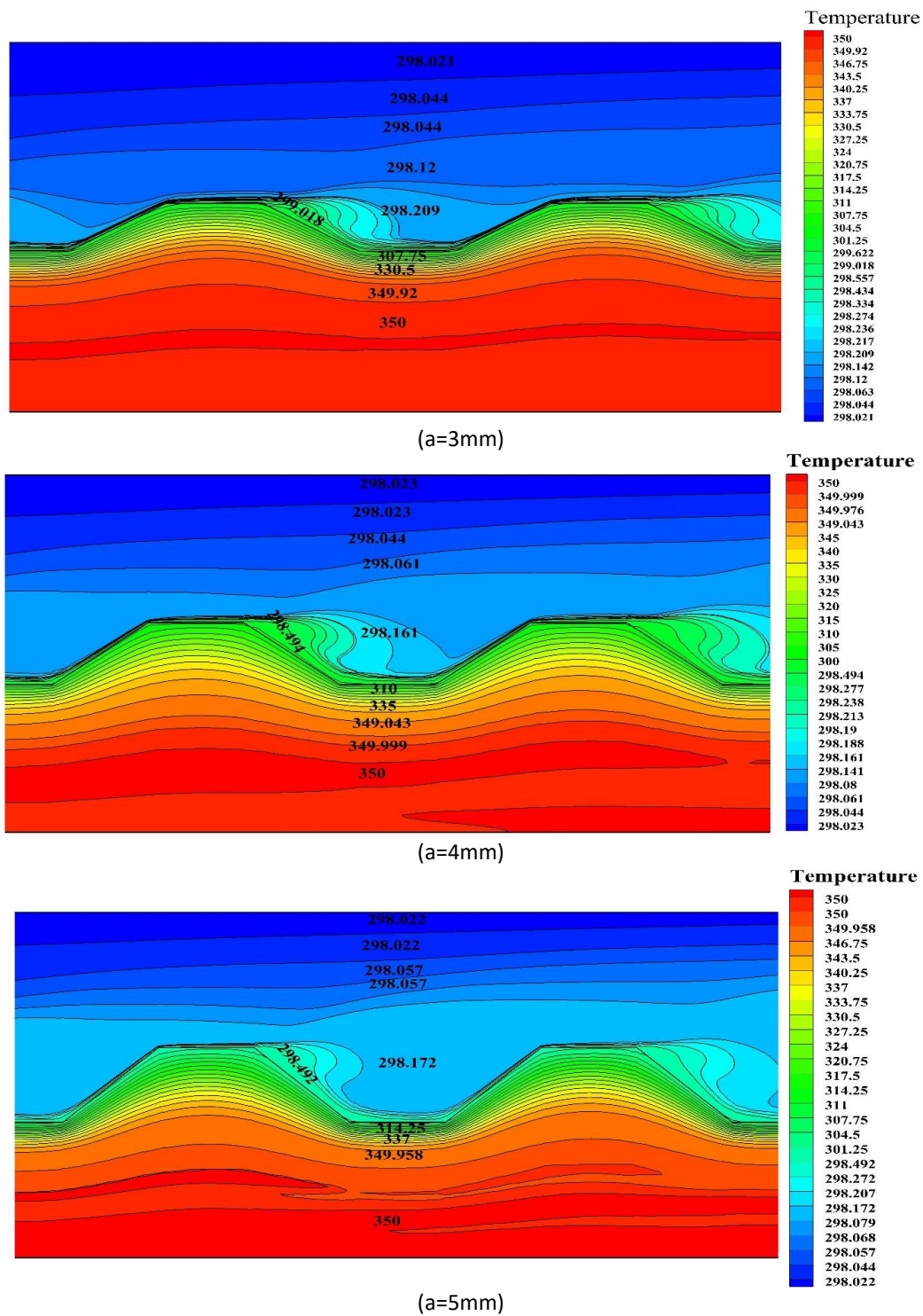


Fig. 10. water isotherms contours in the trapezoidal- corrugated channel at $Re=2300$

4.8 Effect of the Amplitude on the (Nu_a)

Figure 11 shows the Nusselt number vs. Re average with multiple amplitudes of corrugated channels. It is clearly seen that Re and amplitude of the corrugated channel have a critical effect on the average Nu . At a given amplitude, the (Nu_a) increases with Re because of temperature gradient increment at the channel walls. As expected, Nu_a has a lower value over Re at $a=0$ in straight channel resulting from poor mixing of fluid in this model and that leads to increase thermal boundary layer

thickness and decreases the temperature gradient at channel walls. At $a=1\text{mm}$ and $Re < 1400$ for water, the Nu_a is slightly higher than those for the straight channel because the re-circulation regions that promote the fluid mixing are not generated in the diverging section. However, when $Re > 1400$, the (Nu_a) is clearly increased. This due to the fact, the secondary flow regimes begin growth in the trough (crest) of the lower walls when $Re > 1400$ and lead to enhance mixing of fluid in the diverging section. With the increase of the amplitude, the size of the recirculation regions will increase leading to improve fluid mixing in the channel and lead to an increase of (Nu_a) . In general, the (Nu_a) for all shapes of corrugated channels have a similar trend.

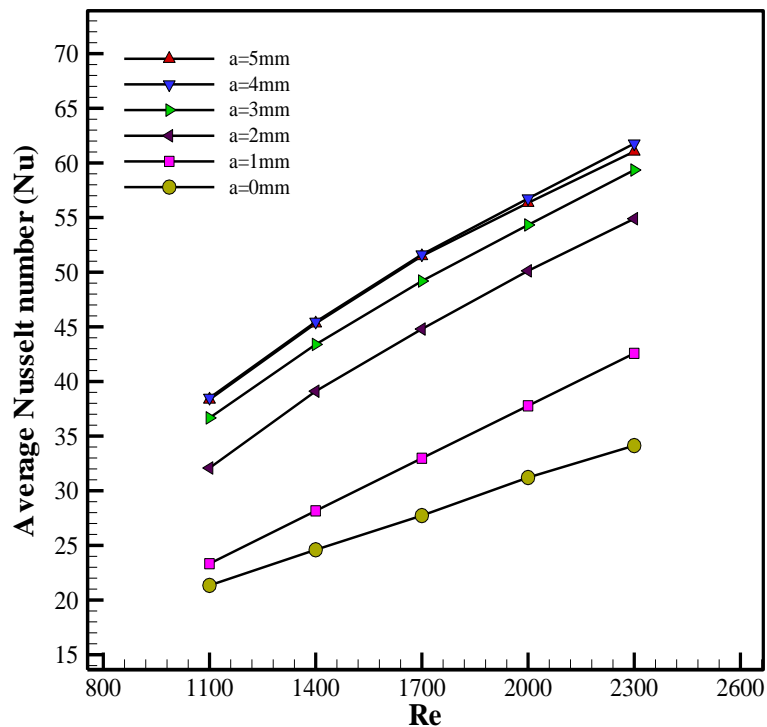


Fig. 11. Average Nu vs. Re for water with different amplitudes of the trapezoidal-corrugated channel at $L_w=20\text{ mm}$

4.9 Effect of Amplitude on the Pressure Drop

The amplitude effect on the pressure drop with a variety of Reynolds number for trapezoidal-corrugated channels is shown in Figure 12. It is found that the straight channel over the entire range of Re provides the lowest pressure drop. This decrease is due to the regular flow in the straight channel (no re-circulation regions). With increases of amplitude, the velocity of the fluid accelerates in the throat of the corrugated channel, as mentioned earlier. Therefore, the increases in gradient velocity at walls lead to increasing the pressure drop. Besides, increases the size of re-circulation regions with an amplitude of channel causes increase the intensity of these regions to the main flow, as a result, a further increase in the pressure drop. Furthermore, at $Re=500$ of water, the pressure drop is slightly increasing with the amplitude because there are no secondary flow regions in the diverging section of the corrugated channel.

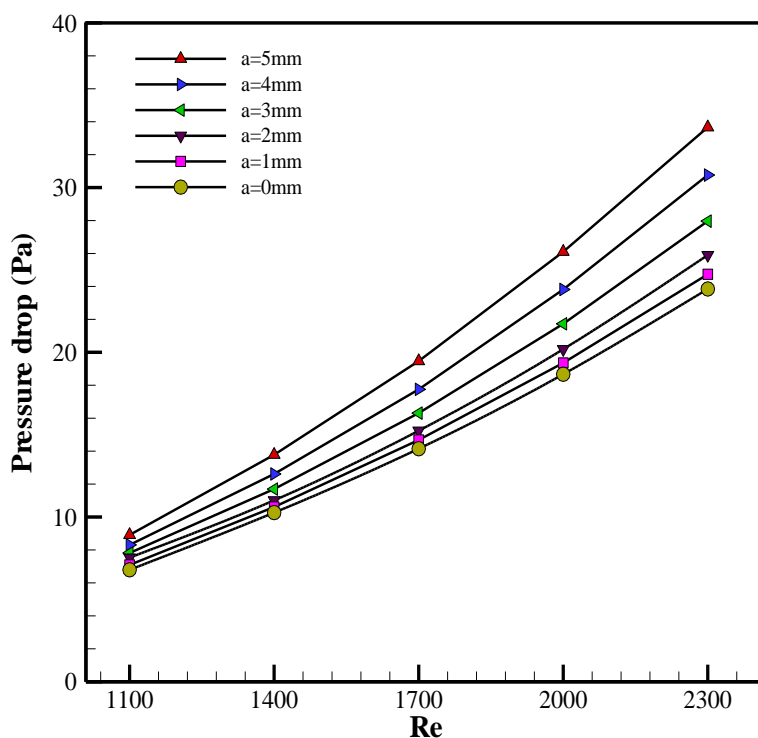


Fig. 12. Pressure drop vs. (Re) for water in a trapezoidal channel with different amplitudes at $L_w=20$ mm

4.10 Effect of Amplitude on Performance Evaluation Criteria

The use of trapezoidal-corrugated channels leads not just to enhance Nusselt number but also increases pressure drops. In order to compare the thermal and hydraulic performance of the duct with different amplitudes, the performance evaluation criterion (PEC) is estimated. PEC represents the thermal performance comparison between the trapezoidal-corrugated channels with different amplitudes and the plane channel with distilled water to the hydraulic performance between the plane channel with distilled water. Mathematically, PEC can be written as follows

$$PEC = \frac{(Nu_t/Nu_{plane})}{(P_t/P_{plane})^{1/3}} \quad (4)$$

The variation of Performance evaluation criteria for trapezoidal-corrugated channels versus the Reynolds number with different amplitude is displayed in Figure 13. According to the figure, it can be explicitly seen that the Performance evaluation criteria for the corrugated channel at the different amplitudes and Reynolds numbers are greater than the plane channel. This means that the positive effect of heat transfer enhancement is higher than the negative effect of the pressure drop penalty. As expected, the straight channel ($a=0$) provides the lowest thermal performance over the Reynolds number among the other amplitudes. As the amplitude increases, the Performance evaluation criteria decreases with the Reynolds number. This because the pressure drops increased with the increasing of Reynolds number which leads to reducing Performance evaluation criteria. At Reynolds numbers=1100 the maximum performance for all the amplitude of corrugated channels obtained. At $Re=2300$, the best Performance evaluation criteria is found with $a=4$ mm compared to other amplitude of corrugated channels.

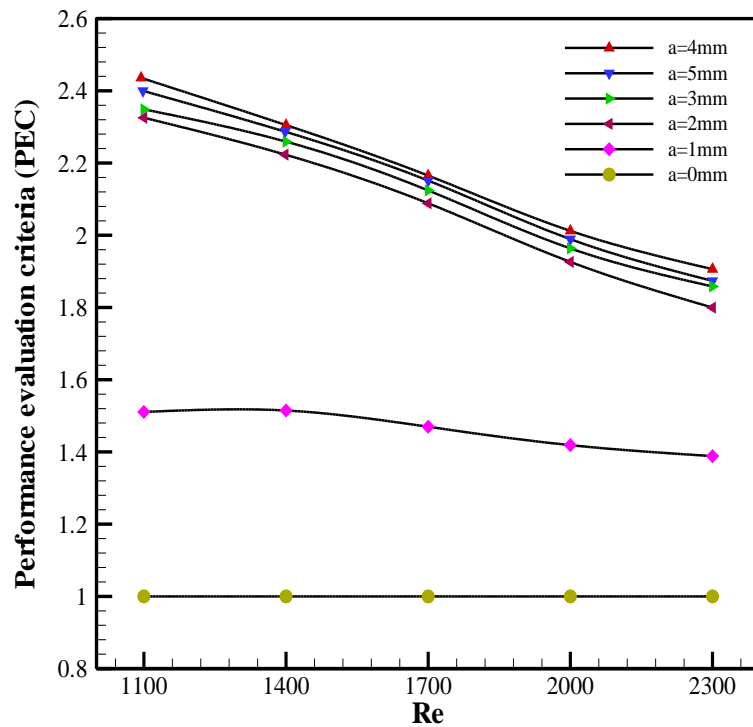


Fig. 13. Performance evaluation criteria vs. Reynolds number in the trapezoidal channel with different amplitudes and $L_w=20.0$ mm for water base fluid

4.11 Effect of Wavelength of Corrugated Channel

The effect of wavelength of trapezoidal- corrugated channels has been presented over Reynolds number range of 1100-2300 and $a=4$ mm with water. Three different wavelengths of 20, 30 and 40 mm are examined in this study. Figure 14 displays the variation of the average Nusselt number with Reynolds number for different wavelengths of trapezoidal-corrugated channels. It should be noted that at a particular wavelength, the average Nusselt number for all corrugated channels increases with Reynolds number. Furthermore, the average Nusselt number decreases as the wavelength of the corrugated channel increases. Because the flow becomes less disturbed, as mentioned before, when the wavelength increases and less mixing of fluid in core with that near the walls of corrugated channels, therefore, reduce the temperature gradient at the walls of the channel and consequently decreases the heat transfer rate between the fluid and the walls as compared with the small wavelength.

The effect of wavelength on the pressure drop in trapezoidal-corrugated channels is illustrated in Figure 15. As expected, the pressure drops for the corrugated channel increases with Reynolds number at a given different wavelength. In trapezoidal-corrugated channels, it can be noted that at particular Reynolds number, the pressure drops increase with decrease the wavelength of the corrugated-channel. This is because when the wavelength decrease, the surface area of the wall will increase which causes an increase of the friction on the wall. Moreover, the flow becomes more turbulent with decreasing the wavelength which increases the pressure drops.

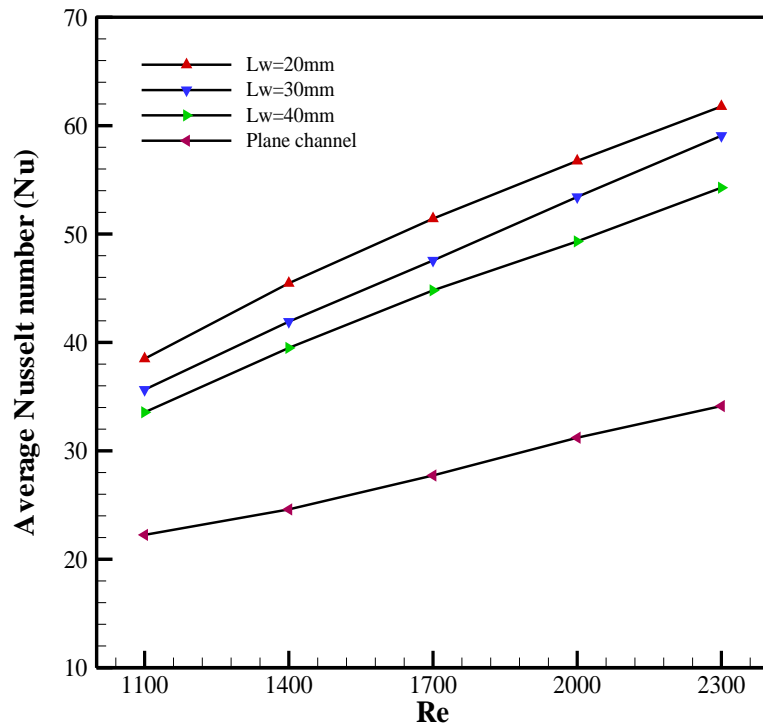


Fig. 14. Average Nusselt number vs. Reynolds number in the trapezoidal channel with different wavelengths and $a=4.0\text{mm}$ for water

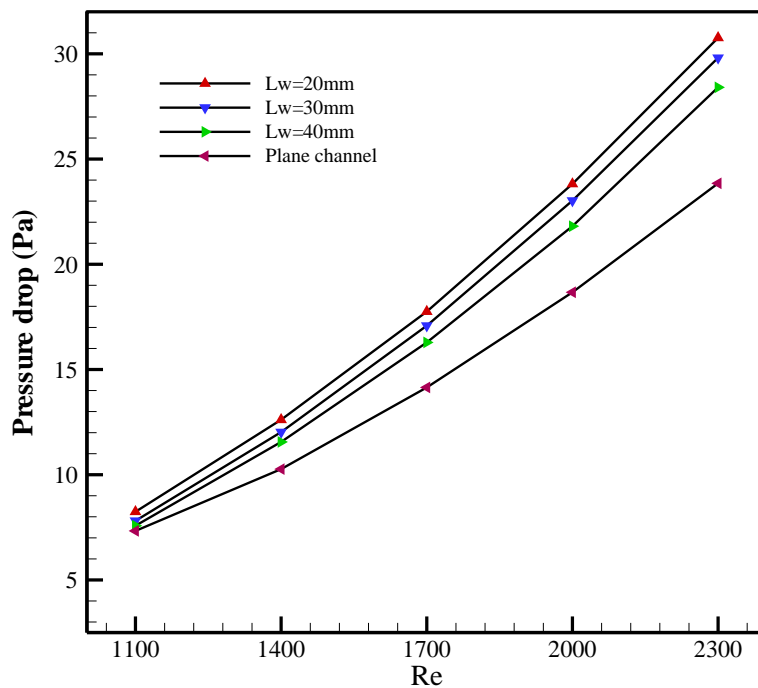


Fig. 15. Pressure drop vs. Reynolds number in the trapezoidal channel with different wavelengths and $a=4.0\text{ mm}$ for water

4.12 Effect of Wavelength on Performance Evaluation Criteria

Figure 16 depicts the effect of wavelength on Performance evaluation criteria of water in trapezoidal-corrugated channels at $a=4\text{mm}$. It may be noted that at a particular wavelength, the

performance for the all wavelength of corrugated channel decrease with increasing Reynolds number. Furthermore, it should be noted that the performance increases as the wavelength decreases for all corrugated channels. Besides, it is found that when the wavelength reduces from 40 mm to 20 mm, the performance evaluation criteria increases due to increase the heat transfer performance than hydraulic performance.

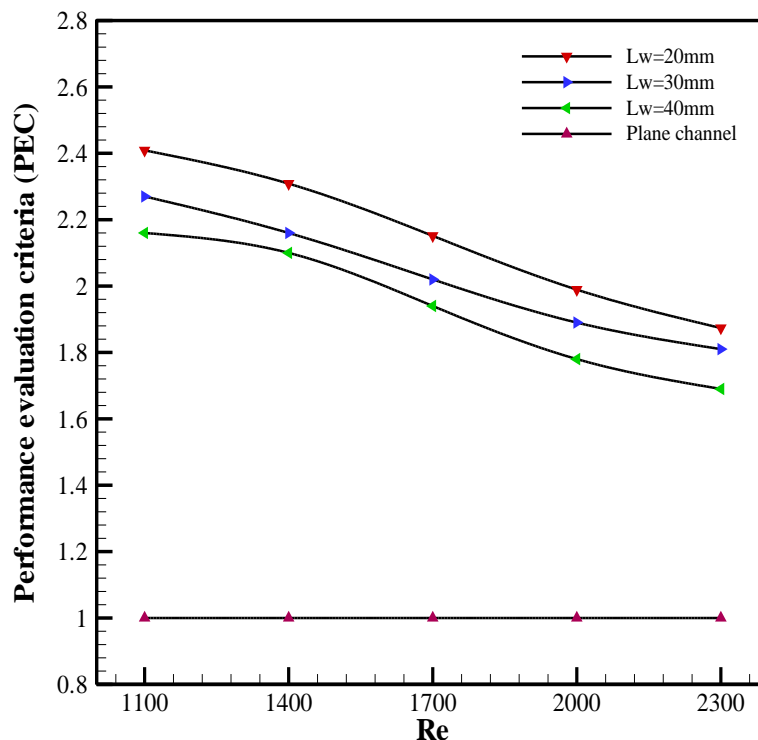


Fig. 16. Performance evaluation criteria vs. Reynolds number in the trapezoidal channel with different wavelength L_w and $a=4.0$ mm for water base fluid

4.13 Effect of Reynolds Number

The effect of Reynolds number on the temperature distribution and local Nusselt number were presented in this section. Trapezoidal-corrugated channels with $a=4$ mm and $L_w=20$ mm have been considered. The effect of Reynolds number on the variation of temperature along the lower wall of trapezoidal corrugated channels is shown in Figure 17. It can be clearly seen that at all of Reynold's numbers, the temperature of the wall in the converging section is lower than that for the diverging section because the rate of the heat exchange between the fluid and wall is higher in converging section than the diverging section and the flow is more turbulent in this section.

Figure 18 shows the variation of the local Nusselt number along the trapezoidal-corrugated wall channels with different Reynolds number. It can be seen at Re , the local Nusselt number at wall crest is higher than that at the wall trough, as pointed out earlier because the velocity and temperature gradients at the crest of the wall are higher than that for the wall trough. At a particular location on the corrugated wall, the local Nusselt number increases with increasing Reynolds number due to improve the fluid mixing as well as reduce the thickness of the thermal boundary layer.

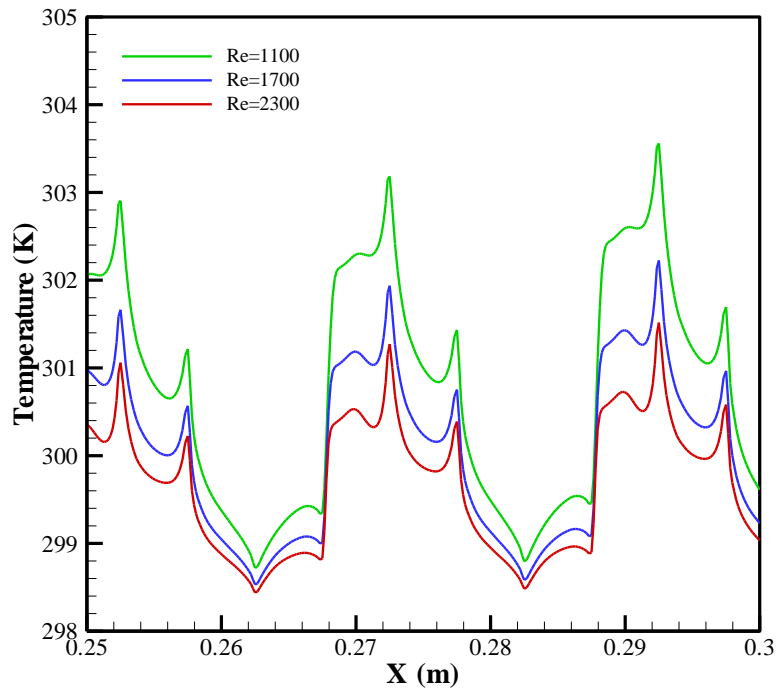


Fig. 17. Temperature distribution at the lower wall of trapezoidal channels for water with different Reynolds number at $a=4\text{ mm}$, $L_w=20.0\text{ mm}$

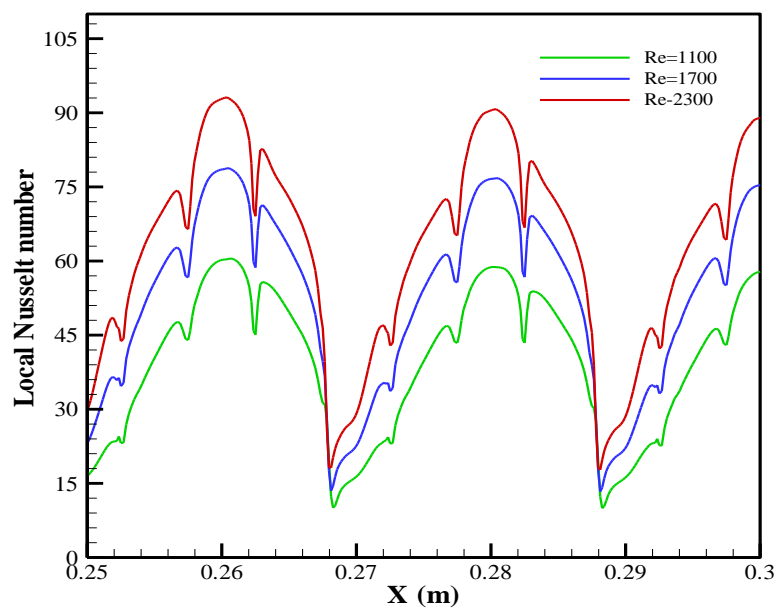


Fig. 18. Local Nusselt number distribution at the lower wall of the trapezoidal channel for water with different Reynolds number at $a=4\text{ mm}$ and $L_w=20\text{ mm}$

5. Conclusion

In the present investigation, heat transfer rate and hydraulic performance of the laminar flow of the trapezoidal, sinusoidal, and straight counter heat exchanger with water and engine oil has been investigated numerically. Moreover, the study investigated the effect of wave height and wavelength of both trapezoidal and sinusoidal on thermal properties and hydraulic performance over Reynold

number ranges of 1100–2300 for water and 250 for engine oil. The study showed that the wave height had a significant effect on Nusselt number values while the wavelength effect on Nusselt number was less. In addition, the trapezoidal -corrugated channel had a greater effect on the heat transfer rate than the sinusoidal -corrugated channel and flat channel. The streamwise velocity and isotherms contours clearly helped to understand the reasons for improving the rate of heat transfer through the channels. The thermal performance criteria helped to compare the rate of heat transfer and friction loss in order to demonstrate the validity of the new design. Consequently, the results of the thermal performance criteria showed that with increasing the wave height up to 4 mm, the heat transfer increases with fewer friction losses then it starts to decrease due to increase the friction loss compared with the heat transfer rate.

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