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Augmentation of Fluid Flow and Heat Transfer Characteristics in corrugated Channel: A Review Study

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ABSTRACT

The corrugation configuration played an important role in heat transfer enhancement in many engineering applications such as heat exchangers, microchannel heat sink, solar collectors, etc. The significance of the corrugation configuration was manifested in its ability to offer a larger heat transfer area more than a straight channel. Besides, the periodic interruption and redeveloping of the thermal boundary layer which was an important feature offered by corrugation was remarkably enhanced the heat transfer. The researchers were keen to take advantage of these features and develop them by manipulating geometrical parameters to obtain the optimal results. The current work aims to collect available research data, which focused on improving heat transfer in corrugated channels and identifying the most important factors affecting the performance of corrugated channels. Several corrugated channel shapes were demonstrated including sinusoidal, trapezoidal, house-type, and V-type. Among the studied shapes of the various operating conditions of the corrugated channels, the researchers unanimously agreed that the trapezoidal shape of the corrugations gives the best thermal improvement with a reasonable pressure drop inside the channels.

1. Introduction

Corrugation was one of the most critical passive heat transfer techniques which proved its effectiveness through many studies in recent decades. The mechanism of heat transfer enhancement in corrugated channels was based on several features available in corrugation geometry. The corrugation induces the eddies to emerge which enhances the flow mixing [1]. Besides, the corrugation prompts the boundary layer to be periodically interrupted and redeveloping which significantly enhances heat transfer [2]. Moreover, the corrugation provides more heat transfer area than the straight channel due to the longer path. Several experimental and numerical studies were performed to examine the impact of various configurational parameters of the corrugated channels on fluid flow and heat transfer. In general, the configurational parameters used in these studies comprise; the shape of the corrugations, the height of the corrugations, and the arrangement of the corrugations. A schematic diagram of a corrugated channel was depicted in Figure 1. The corrugated channel generally consists of two identical corrugated sheets. The channel surface comprises a flat wall and a corrugated wall where the smooth flat sections were located before and after the corrugated section [3].

2. Experimental studies

Islamoglu [4] studied experimentally and numerically the hydrothermal characteristics of the corrugated channels.

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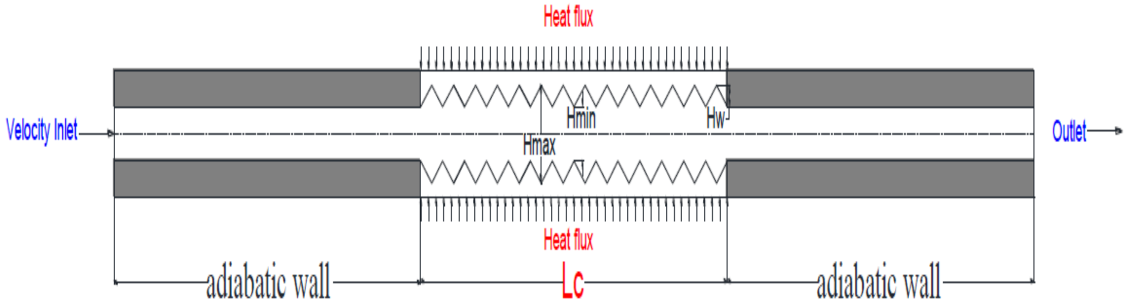

Figure 1. Schematic of the most important components of corrugated channel [3]

The tests were performed on the corrugated channel for air Reynolds number 1200-4000 for corrugated ngle 20° with a channel height equal to the corrugated height under uniform heat flux. It was found that the lower part of the convex has a lowest local heat transfer coefficient due to flow seperation, while the highest local heat transfer coefficient was found at the concave part due to the reattachment of boundary layer.

Islamoglu and Kurt [5] conducted an experimental study of the thermal hydraulic characteristics of the corrugated channel of air for Reynolds number range 1200-4000 with four corrugating angles ranged from 20 to 50°. The corrugated channel was shown in Figure 2 manufactured with a thickness of 10 mm from copper sheets 278 mm long and 50 mm wide. Then the study focused on the applicability of the artificial neural networks method to predict the thermal performance of the corrugated channels to be utilized in the design of plate heat exchangers. The results indicated the Nusselt number was directly proportional to both the Reynolds number and the corrugating angle.

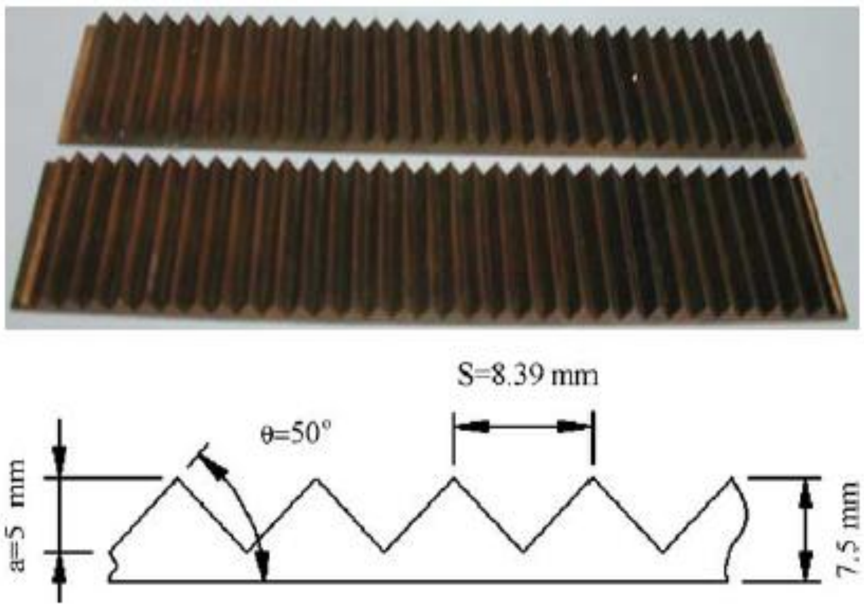

Figure 2. Manufactured corrugated channel [5]

Islamoglu and Parmaksizoglu [6] and Ali and Ramadhyani [7] experimentally studied the hydro-thermal of air flow in the corrugated channel. The effects of two different channel heights on the fluid flow and heat transfer were studied for a corrugation angle of 20°. Figure3a shows the corrugated channel shape, dimensions locations of pressure tap, and thermocouples in the test cross-section. The impact of the channel height on the pressure drop was shown in Figure 3b.

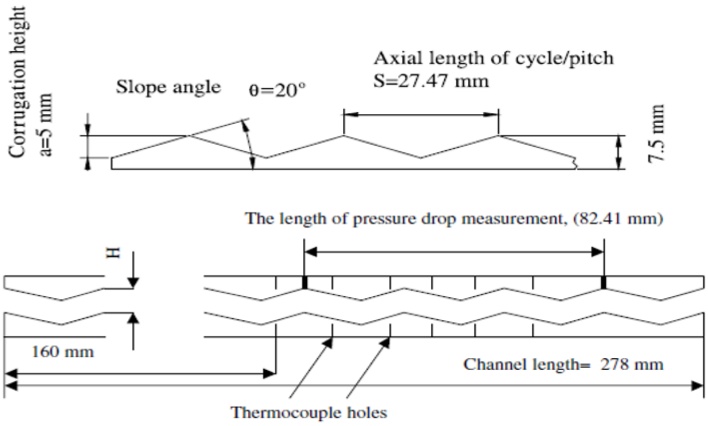

Figure 3a. Corrugated channels arrangement and temperatures measurement.

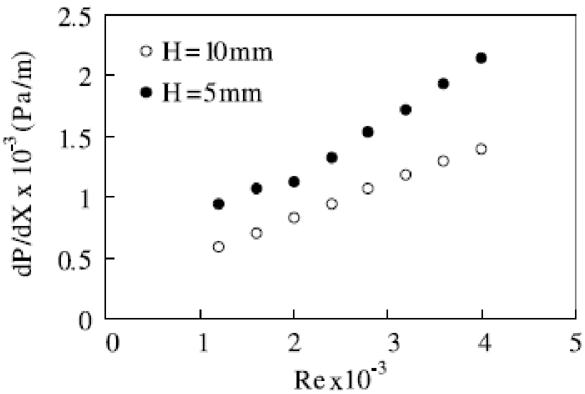

Figure 3b. Influence of height of the channel on pressure drop [6]

Naphon [8] experimentally studied the thermal hydraulic performance of the duct using the upper and lower V-corrugated walls. The test section consists of two inverse corrugated plates in which all formation peaks were in a zigzag arrangement. Under constant heat flux, the corrugated channel was tested with various angles of the corrugated tiles and various channels height of 20-60° and 20-25 mm, respectively. Experiments were performed for Reynolds number range of (2000-9000) and the heat flux range of (0.5-1.2 kW/m2). It was observed that the corrugated wall has a great influence on improving mixing flow which results in enhancing heat transfer. Due to the presence of vortex distribution territories, the coefficients of heat transfer get from the channel with the corrugated wall were better than that containing the smooth surface.

The thermal hydraulic performance of the corrugated channels was experimentally tested by Elshafei et al. [9] On a band of air Reynolds range of (3220-9420), experiments were performed on channels with constant corrugation ratio (2Amplitude/waviness = 0.2) under uniform wall temperature. Three wavy channels (0 °, 90 °, and 180 °) were considered to be different distances. Compared with the traditional smooth channel, the outcomes indicated that the utilization of corrugated channels improves the thermal performance with a pressure drop penalty. The study revealed that the impact of distance spacing on pressure drop and heat transfer was more effective than the change of phase shift angle, particularly when Reynolds number increases. In the same context, Elshafei et al. [3] studied experimentally the effect of phase shift and spacing in the thermal performance of the divergent-convergent channel. The results showed that at lower spacing with a phase shift of 180° achieved the highest Nusselt number.

Meanwhile, for larger spacing, the Nusselt number accomplished a better result with a phase shift of 0°.

Elshafei et al. [10] experimentally examined the thermal hydraulic performance of the corrugated channel. For Reynolds number 3220-9420, the experiments were performed on channels with constant corrugation ratio under constant wall temperature. The influences of the phase shift changes and space between the channels were examined on heat transfer/fluid flow. The results showed a remarkable heat transfer improvement of the corrugated channels accompanied by a pressure drop penalty. Compared with the smooth channel, the maximum enhanced factor for heat transfer coefficient and pressure drop were 3.2 and 2.6 respectively, based on the phase shift and space between the channels. Also, the friction factor was found to be increased as the phase shift and distance between the channels increased. At a higher Reynolds number, the effect of distance space on the heat transfer coefficient and friction factor was more effective than the phase shift change.

Pehlivan et al. [11] tested experimentally the thermal hydraulic characteristics of convergent and divergent corrugated channels. Compared with the conventional smooth channel, under a constant heat flow of 616 W/m2 and the Reynolds number range of (1500 – 8000), three different shapes of sharp corrugated peak fins were tested. Channel height 5 and 10 mm and corrugated inclination angles (27, 50, and 22/60°) were tested. The test section front view and the top view were shown in Figure 4a. while the wall with a peak corrugated with different acute angles was shown in Figure 4b. The results indicated that the thermal performance of a convergent diagonal channel had a relatively positive effect compared to the phase arrangement. The increase in corrugated angle improved the rate of heat transfer. The reason behind this was that when increasing the corrugated angle for the same length of the channel, the number of corrugations increases, and the height of corrugated increases.

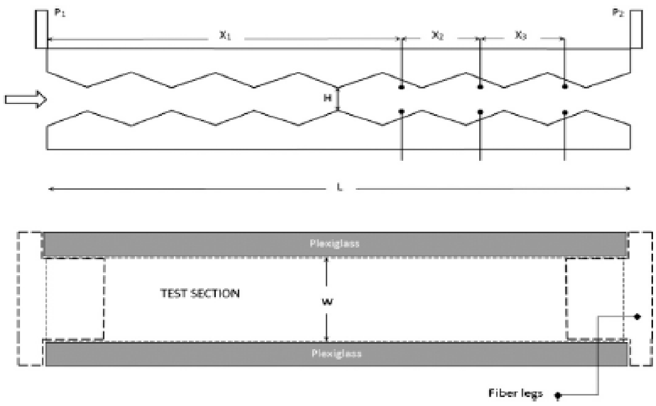

Figure 4a. The front view and the top view of the test section [11]

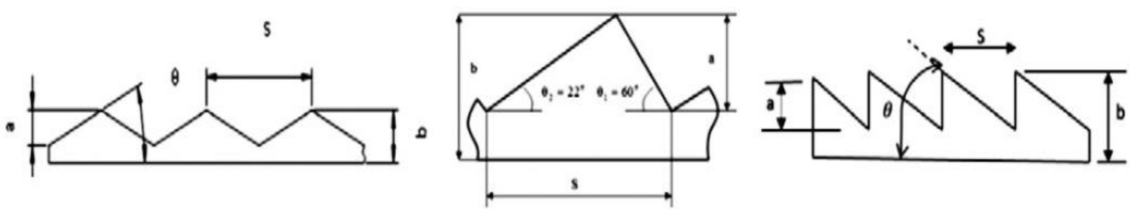

Figure 4b. wall with a peak corrugated with different acute angles is shown [11]

Ahmed et al. [12] experimentally studied the thermal hydraulic performance of flow in a corrugated channel for a range of Reynolds numbers 400-4000 in different channel shapes. As depicted in Figure 5, three different channels were fabricated and tested: flat, trapezoidal, and sinusoidal. The results showed that the best thermal performance was achieved by the trapezoidal corrugated channel. Also, it was observed the superiority of heat dissipation of the sinusoidal corrugated channel thermal hydraulic performance to that of the flat channel.

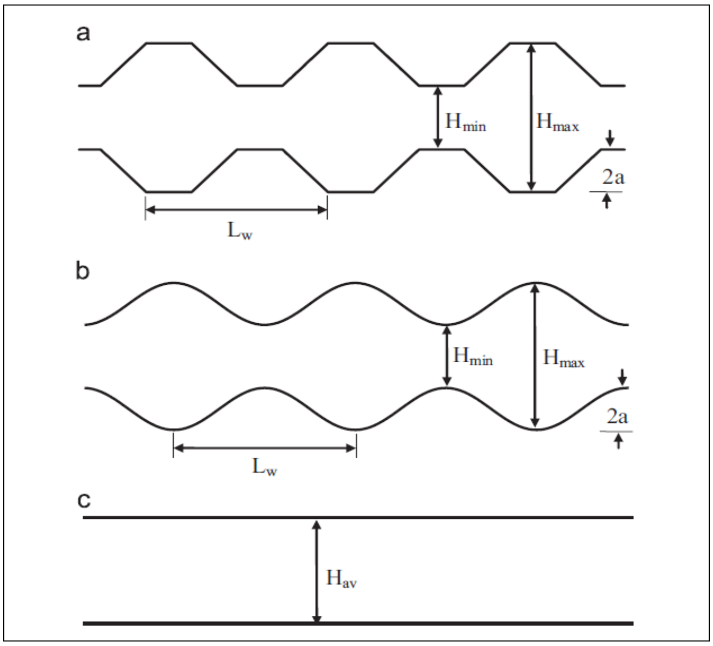

Figure 5. Corrugated channels (a) trapezoidal, (b)sinusoidal, and (c) flat channel [12]

Tokgoz et al. [13] Experimentally investigated the flow configuration of the corrugated channel having a width to height ratio such as 0.3 and a phase offset angel 180˚. Corrugated channel schematic diagram for phase shift angle 180˚ shown in Figure 6. The study was performed within a range of Reynolds numbers from 4000 to 6000. The particle image velocity measurement technique was used to examine the fluid flow characteristics. The velocity distributions were determined by mean time, simplification patterns, and corresponding turbulent statistics. The rate of convection heat transfer improves significantly due to the rapid velocity fluctuations caused by the intensity of flow turbulence which in turn enhance fluid mixing through corrugated channels.

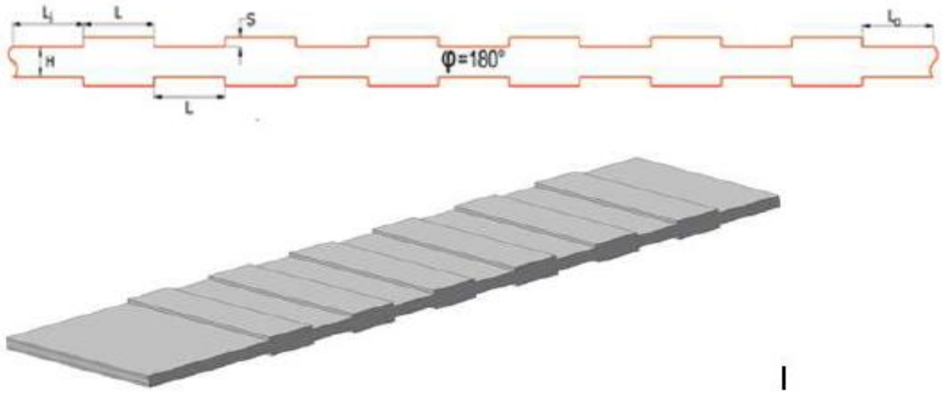

Figure 6. Corrugated channel schematic diagram for phase shift angle 180˚ [13]

Ajeel et al. [14] experimentally tested the influence of corrugation shape on the hydrothermal characteristics of flow inside a corrugated channel. In addition to the conventional smooth channel, two types of corrugated channels were tested, which were semi-circular and trapezoidal corrugated channels (see Figure 7). The tests were investigated under Reynolds numbers range of (10,000 -30,000). Compared with the traditional smooth channel, it was observed that the heat transfer improved by 63.59% due to the use of the trapezoidal corrugated channel, while the pressure drop was increased by 1.37 times and the thermal performance coefficient increased to 2.22.

a

b

c

Figure 7. Corrugated channels with various shapes (a) sem-icircle, (b) trapezoidal, and (c) straight [14]

Table 1. shows a summary of previous experimental studies conducted on corrugated channels. From the experimental studies, it be can noted that most researchers focused on the shape of the corrugations. In general, it’s found that the heat transfer improved by using corrugated channels. This improvement in heat transfer resulted from the interruption and redeveloping of thermal boundary layer. However, this enhancement was associated with higher pressure drop through the channels. Among all the studied shapes, it was noticed that the trapezoidal corrugations provide the best thermal hydraulic performance.

Table 1. Summary of experimental studies

Authors	Year	Corrugation shape	Results
Islamoglu [4]	2004	V-corrugated 20°	The improvement in heat transfer of correguation channel was due to reconnecting the boundary layer.
Islamoglu and Kurt [5]	2004	V-corrugated 20° to 50°	The Nusselt number is directly proportional to both the Reynolds number and the corrugating angle.
Islamoglu and Parmaksizoglu [6]	2003	V-corrugated 20°	The pressure drop decreases with an increase in channel height.
Ali and Ramadhyani [7]	2007	V-corrugated 20°	Under the same pumping power and pressure drop,the larger spacing in the corrugated channel manifests better performance than the smaller spacing corrugated channel.
Naphon [8]	2007	V-corrugated 20° to 60°	The coefficients of heat transfer gets from the channel with the corrugated wall are better than that containing the smooth surface
Elshafei et al. [9]	2008	wavy (0 °, 90 °, and 180 °)	The impact of distance spacing on pressure drop and heat transfer is more effective than the change of phase shift angle
Elshafei et al. [3]	2014	Divergent-convergent	At lower spacing with a phase shift of 180° achieved the highest Nusselt number. Meanwhile, for larger spacing, the Nusselt number accomplished a better result with a phase shift of 0°

Elshafei et al. [10]	2010	V-corrugated 21.8°°	The friction factor is found to be increased as the phase shift and distance between the channels increased
Pehlivan et al. [11]	2013	Divergent-convergent	The increase in corrugated angle improved the rate of heat transfer
Ahmed et al. [12]	2015	Flat, trapezoidal, and sinusoidal	The best thermal performance was achieved by the trapezoidal corrugated channel
Tokgoz et al. [13]	2016	Divergent-convergent	The rate of convection heat transfer improves significantly due to the rapid velocity fluctuations caused by the intensity and turbulence of the fluid mixing through corrugated channels
Ajeel et al. [14]	2019	Smooth, semi-circular and trapezoidal	Compared with the traditional smooth channel, it was observed that the heat transfer improved by 63.59% due to the use of the trapezoidal corrugated channel, while the pressure drop was increased by 1.37 times and the thermal performance coefficient increased to 2.22

3. Numerical studies

Dutta et al. [15] Numerically investigated the 2D heat transfer through triangular wavy flow with various channel heights for a single corrugated angle. Figure 8 shows a corrugated channel diagram showing the various configuration parameters. For turbulent flow, the effects of both Reynolds number and channel height were tested on the channel thermal hydraulic performance. Compared with the traditional smooth channel, the outcomes demonstrated that the corrugated channels greatly improve the heat transfer with a higher Nusselt number. Also, an increase in the performance parameter was observed with decreasing channel height.

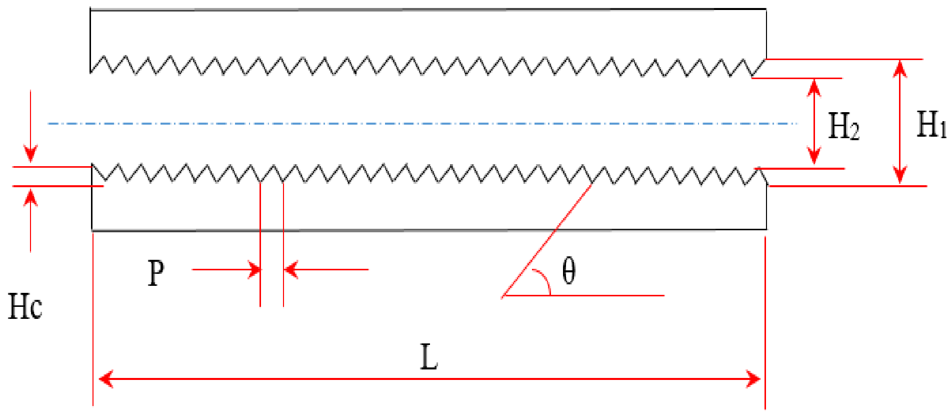

Figure 8. Corrugated channel diagram showing the various configuration parameters [15]

The effect of corrugation shape on the hydrothermal of a corrugated channel was investigated numerically by Abbas [16]. Different corrugation shapes were tested for the Reynolds number range from 6000-20,000 and hear flux of 6000 W/m2. In comparison with a smooth channel, seven types were tested with different corrugations in three groups of trapezoidal corrugated channels namely; one face inward, one face out, and one face inward on one face, and one face in contrast to the face. Moreover, two faces out, two sides inward, and an inner and outer face on both surfaces were aligned, and the inner and outer face were overlapping on both surfaces. The schematic diagram of all channel configurations shown in Figure 9. The simulation results showed that the use of the inner and outer trapezoidal corrugated channel was a strong function of Reynolds number and corrugation shape. Also, the double-sided inward provides the maximum heat transfer rate and friction coefficient in comparison with other shapes. As the Reynolds number increases, the overall performance factor values decrease, expecting a high for one face outward and two for an outer face in a turbulent flow.

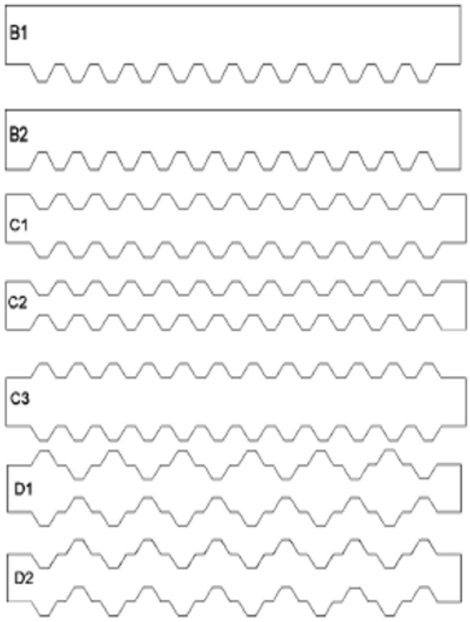

Figure 9. Schematic diagram of various channel configurations [16]

Deylami et al. [17] Numerically investigated the effect of using various shapes of corrugated channels on thermal hydraulic performance. Using the finite volume technique, the governing equations were solved in a wide range of corrugations height for Reynolds number of 5400-23,000. Figure 10 shows the computational domain of the corrugated channel. Shapes of corrugated channels were compared with the overall performance factor. The overall performance factor represents the ratio between the heat transfer improvement of the modified model to the increased pressure drop penalty under the same pumping force. The outcomes demonstrated that increasing the corrugation height enlarge both the Nusselt number and the coefficient of friction. Moreover, increasing corrugations height and Reynolds number contribute to decreasing in the thermal overall performance factor. This behavior was similar to that obtained by Dutta et al. [15].

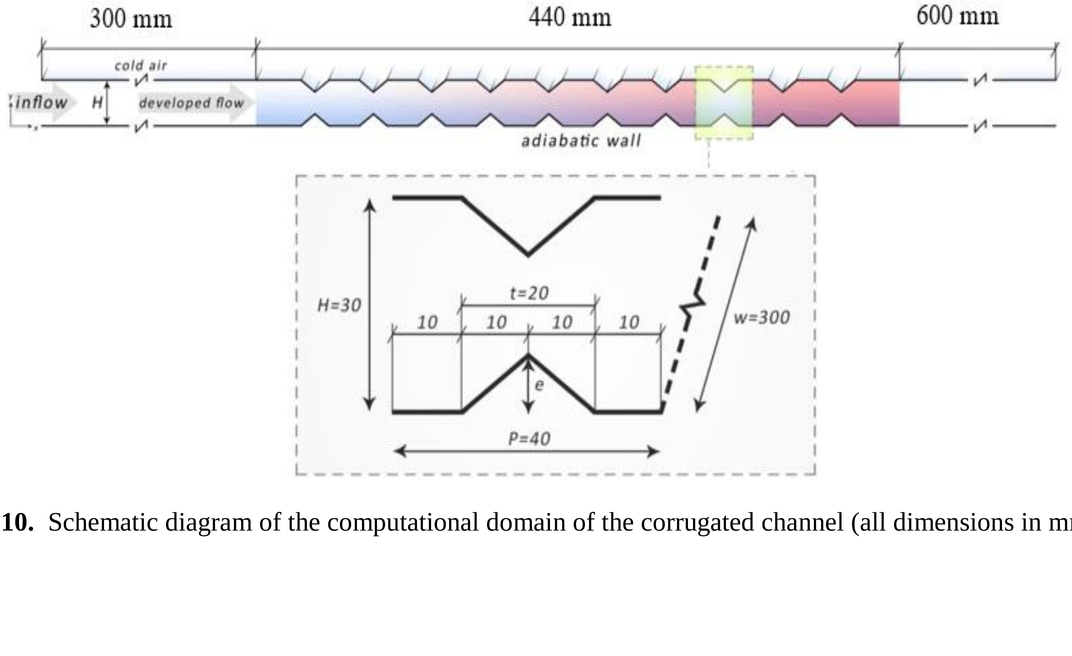

Figure 10. Schematic diagram of the computational domain of the corrugated channel (all dimensions in mm) [17]

Ahmed et al. [18-22] analyzed numerically the effect of the channel corrugation on the thermal hydraulic characteristics. The study was conducted under the different range of Reynolds number. In [18, 19], the impact of phase shift angle on the corrugated channel with sharp triangular corrugation under laminar flow conditions less than 1000. The triangular corrugated channel with 90° phase shift angle and 0° phase shift angle was shown in Figures 11 and 12 respectively.

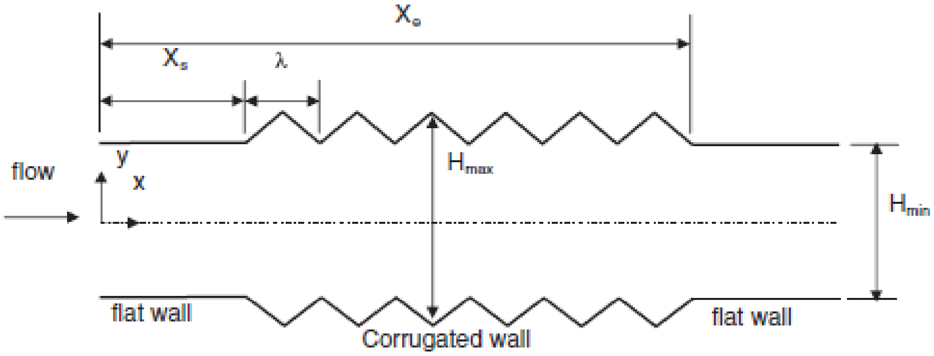

Figure 11. View of the triangular corrugated channel [18]

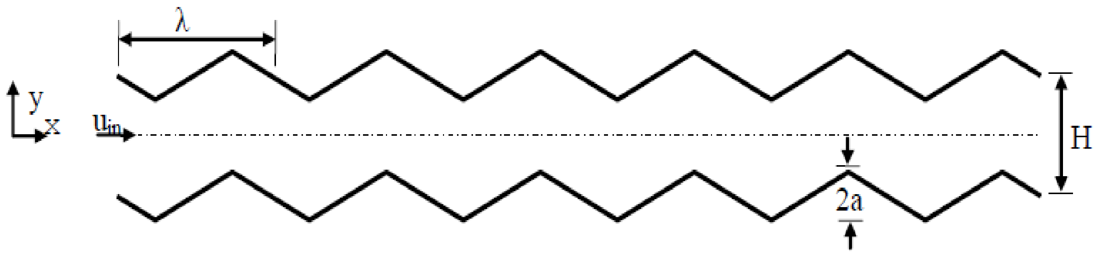

Figure 12. Schematic of the corrugated channel [19]

The outcomes revealed that the heat transfer was augmented by increasing the Reynolds number while there was a slight increase in the pressure drop. In [20], three different shapes of the corrugated channel were studied under the laminar flow for the range of Reynolds number within (100-800): trapezoid, triangular, and sinusoidal. The schematic of the corrugated channel with different corrugations was shown in Figure 13. The influence of Reynolds number on the Nusselt number and overall performance factor was shown in Figure 14. It was found that the trapezoidal channel has a higher heat transfer improvement, followed by the sinusoidal and triangular channels. Also, it was observed that when the Reynolds number was less than 220, the optimum channel shape was trapezoidal, and when the Reynolds number was greater than 220, the optimal channel shape was sinusoidal.

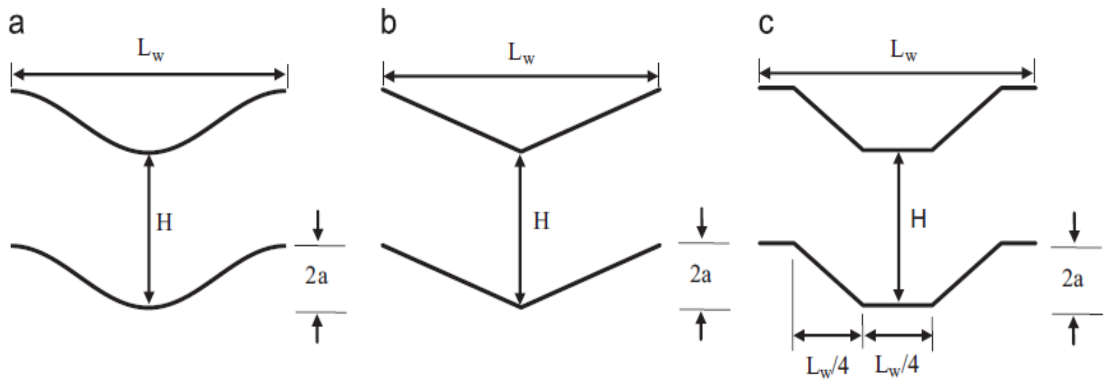

Figure13. The schematic of the corrugated channel with different shapes:(a) sinusoidal, (b) triangular (c) trapezoidal [20]

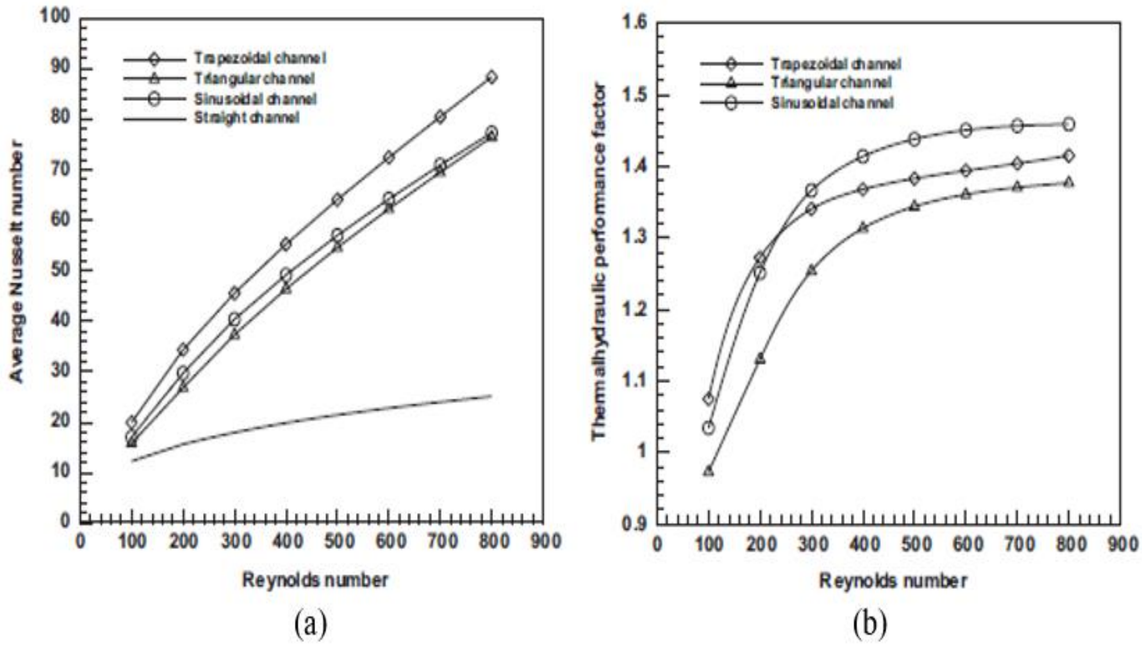

Figure 14. Influence of Reynolds number on: (a) Nusselt number and (b) thermal hydraulic performance factor [20]

In [21], the hydrothermal characteristics of the flow inside the triangular corrugated channels were performed for a Reynolds number range between (1000-5000). The schematic of the corrugated channel was shown in Figure 15. The governing equations of mass, momentum, and energy were solved by using finite volume method with the k-ε turbulent model. the results indicated that the Nusselt number and pressure drop were increased with the increasing the Reynolds number. In [22], the impact of designing factors such as wavelength, the amplitude of the trapezoidal corrugated channel, Reynolds number (100-700) on the Nusselt number and pressure drop were examined. The trapezoidal corrugated channel with various configurational parameters was shown in Figure 16. The results showed a remarkable improvement in the Nusselt number with increasing in the amplitude of the corrugated channel. However, this improvement was associated with a high pressure drop. Furthermore, it was found that the Nusselt number decreased with increasing the wavelength, while the pressure drops increased.

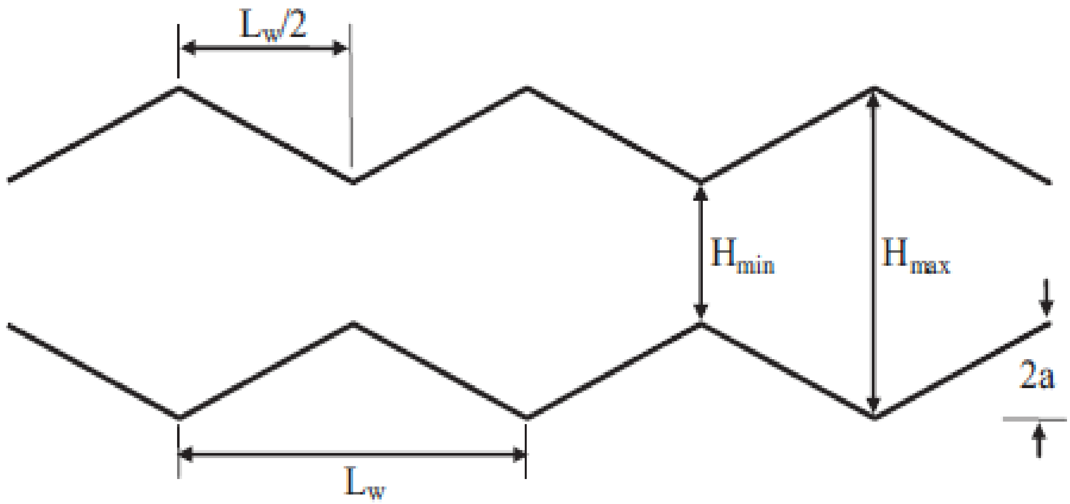

Figure 15. Schematic of the corrugated channel [21]

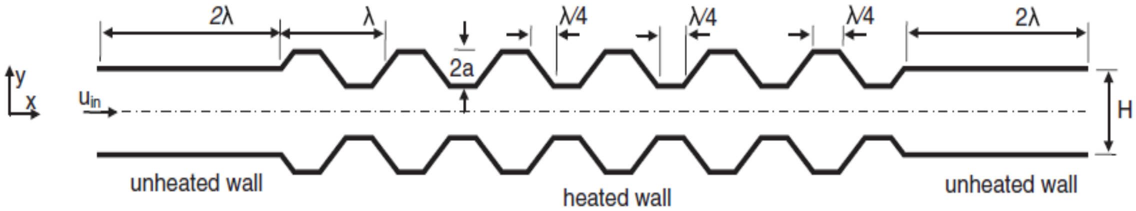

Figure 16. View of the corrugated channel with different configurational parameters of the trapezoidal shape [22]

Ajeel et al. [23-32] numerically examined the effects of various parameter designs of a corrugated channel on the thermal hydraulic performance under different Reynolds number ranges. In [23], the effects of various parameter design on the thermal hydraulic performance of the corrugated channel were studied. These parameters included pitch/length ratio, aspect ratio (height/width), and house ratio. The results referred that the aspect ratio was more impact on heat transfer enhancement than the pitch ratio. The results showed that the reduction in pitch ratio from 0.175 to 0.075 attained an enhancement of 16.63% in Nusselt number at Reynolds number of 30,000. In [24], the hydrothermal characteristics of turbulent flow inside a corrugated channel with semicircular zigzag shape were studied. Compared with the traditional smooth channel, the results showed that the semicircular corrugated channel was significantly effect on the thermal performance. The highest improvement in heat transfer was 2.7 times better than the smooth channel. In [25], the hydrothermal characteristics of turbulent flow in a trapezoidal channel with two arrangements of trapezoidal corrugations: symmetry and zigzag were investigated. The schematic diagram of different arrangements of the trapezoidal corrugated channels: symmetry and zigzag were shown in Figure 17. The results showed that for the corrugated trapezoidal channel, the symmetry arrangement accomplished the most elevated thermal performance, followed by the zigzag.

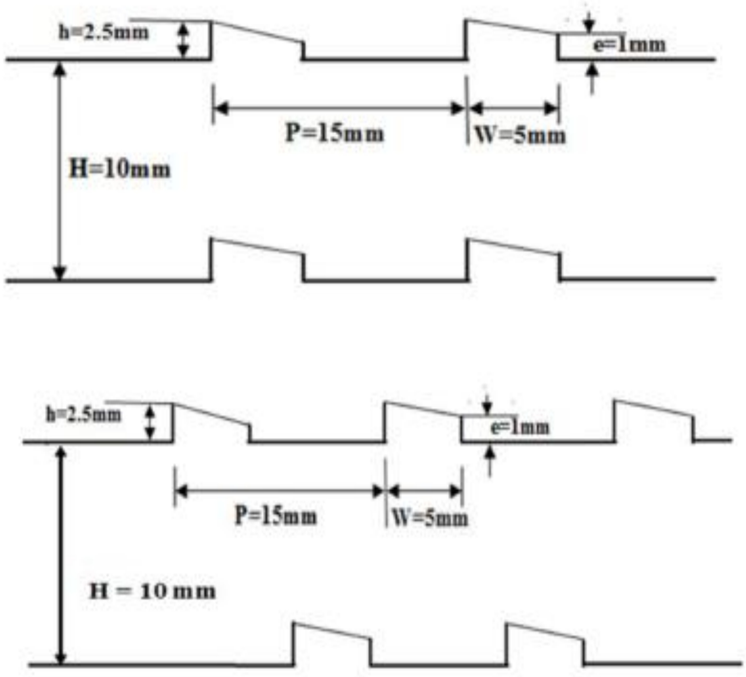

Figure 17. Schematic diagram of different arrangements (symmetry and zigzag) of the trapezoidal corrugated channels [25]

In [26, 27], a comparative numerical study was conducted of the thermal hydraulic performance for three corrugated channels; semicircular, trapezoidal, and house. The comparsion was performed with a range of Reynolds number of (10,000-30,000). The computational model and channel shape were shown in Figure 18. The finite volumes technique and the SIMPLE algorithm were used to solve governing equations. The results indicated that corrugations increase the turbulence of the fluid flow which leads to improving the heat transfer. Besides, the corrugation increases the heat transfer area in heat exchangers. The outcomes demonstrated that the Nusselt number and the pressure drop of the corrugated channels were around 1-4 times higher than that of the smooth channel. Furthermore, it was discovered that the trapezoidal channel achieved a highest thermal performance followed by the semicircular shaped channels and then the house channel.

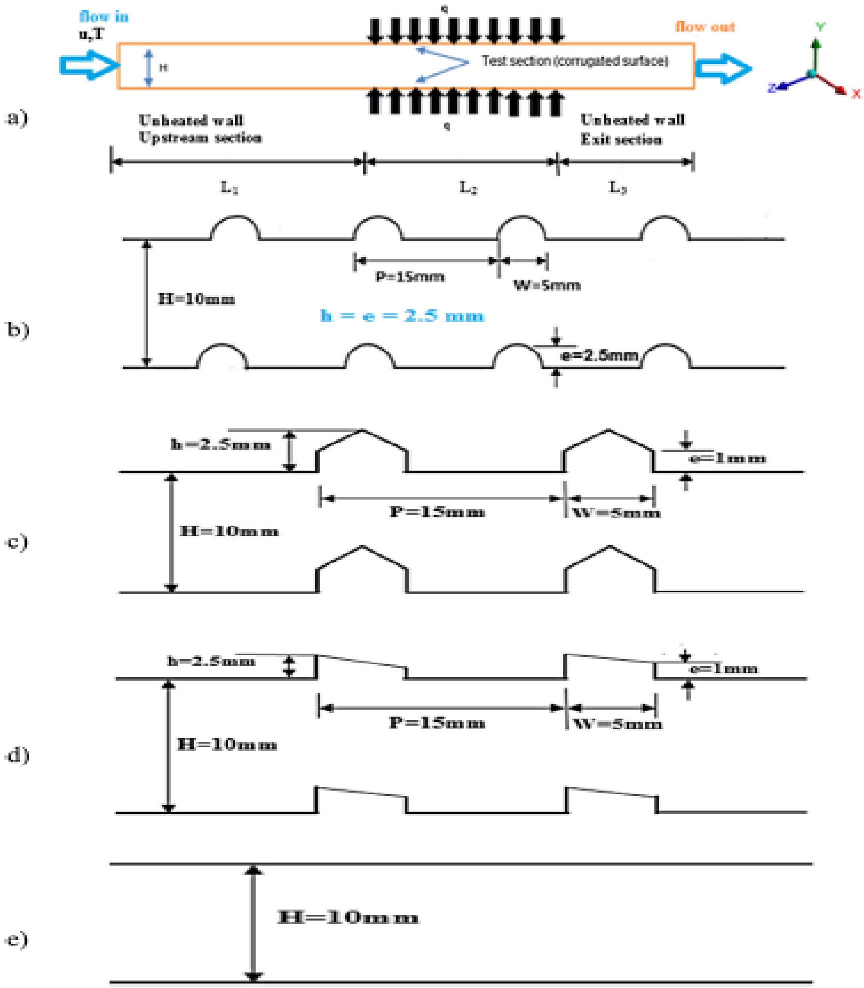

Figure 18. View of computational model and channels shapes [27]

The results indicated that the pressure drop and heat transfer were enhanced with increasing the Reynolds number. In [28] and [29] and [30], the impact of the corrugated surfaces shape on the thermal hydraulic characteristics of the corrugated channels were numerically investigated. Figure 19 shows the velocity contours, temperature contours, turbulent kinetic energy and vortices contours at Reynolds number of 10,000, for various corrugation channels. The results implied that the corrugation has a great influence on improving heat transfer. It was noted that the best thermal improvement was found in the trapezoidal corrugated channel.

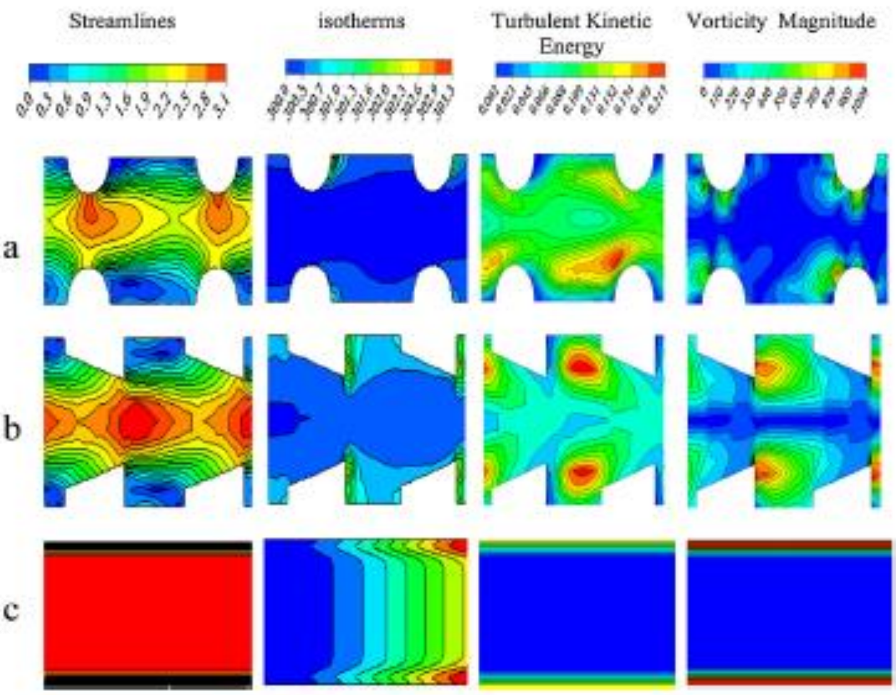

Figure 19. Velocity contours, temperature contours, turbulent kinetic energy and vortices contours under Reynolds number of 10000, for various corrugation channels: (a)semicircle channel (b) trapezoidal channel, and (c) conventional smooth channel [28]

In [31] similar factors above for a similar range of Reynolds number were numerically performed in symmetrical half-circle channel. Figure 20a shows the test segment of a half-circle corrugation. The streamline and temperature contours for zigzag semicircle corrugated channel under Reynolds number of 30000 were shown in Figure 20b. The outcomes showed that the pitch ratio of 0.075 with the aspect ratio of 0.05 achieved the highest overall performance factor. Under similar factors above for a similar range of Reynolds number, [32] explored numerically the performance of symmetrical trapezoidal corrugated channel. The trend of Nusselt number with various pitch ratios and aspect ratios were illustrated in Figure 21. The outcomes demonstrated that the pitch ratio has less impact on heat transfer augmentation than the aspect ratio.

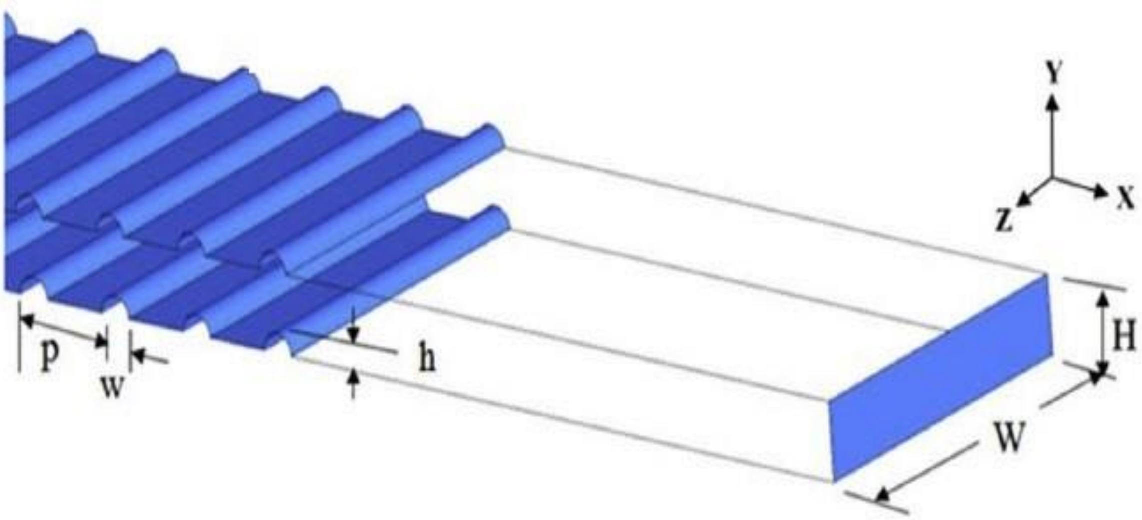

Figure 20a. 3D diagram of a test section of a semicircle corrugated channel [31]

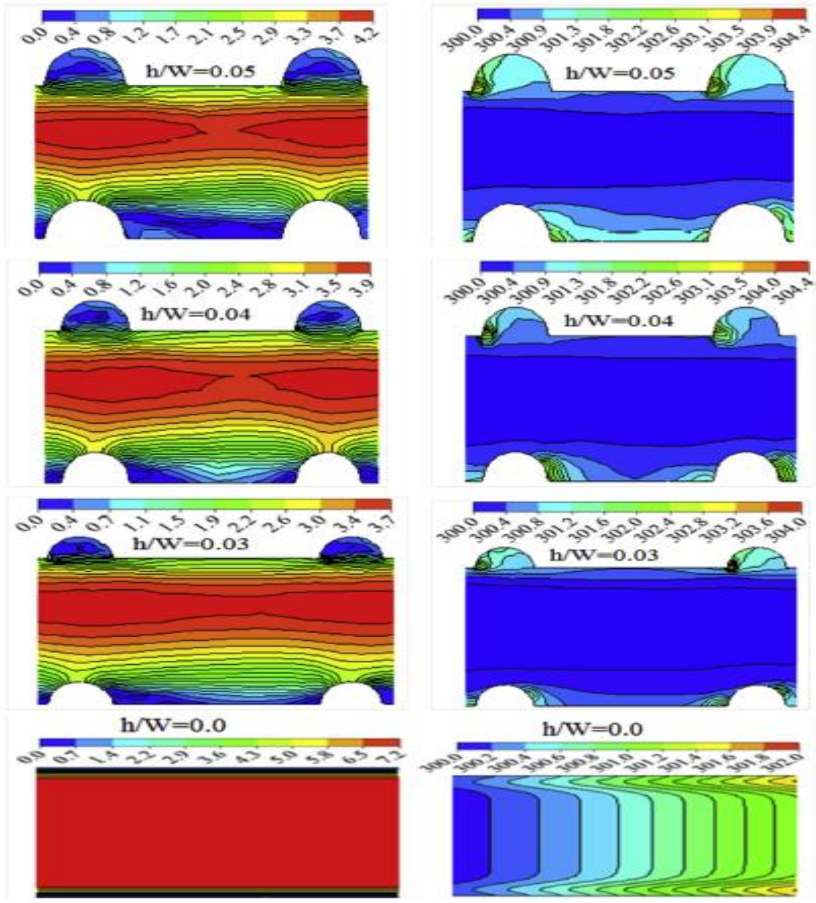

Figure 20b. Streamline (left) and temperature controls (right) for flow inside corrugated channel with symmetric semicircle for various aspect ratio [31]

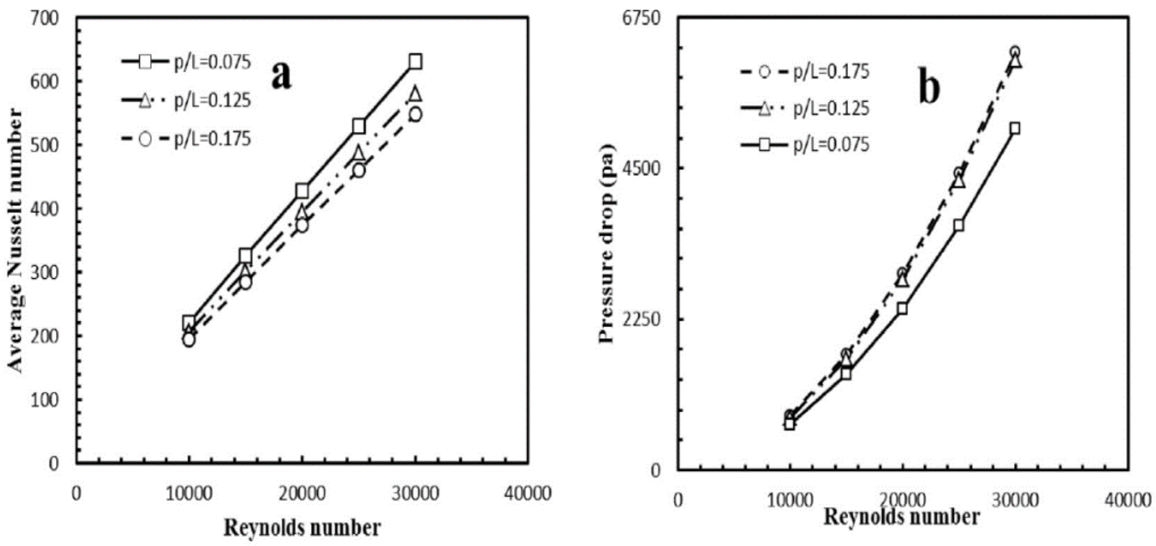

Figure 21. The Nusselt number and pressure drop variations of a corrugated channel with symmetry trapezoidal for various pitch/length ratio and height/width ratio [32]

Ozbolat et al. [33] invstigated numerically the hydrothermal charactrestics of two types of corrugated channels: rectangular and sinusoidal. Fully developed flow for simulations of conditions were performed in 12 corregations channel inlet sections. Schematic of corrugated channels in various shapes: rectangular and sinusoidal was shown in Figure 22. The effects of wall geometry, distance between channel walls, Reynolds number on thermal, and hydraulic were presented and analyzed. Compared with the traditional smooth channel, the results showed that the heat transfer was always enhances by corrugation walls. It was also noted that the distance between the walls has an effective influence on the heat transfer between the corrugated walls.

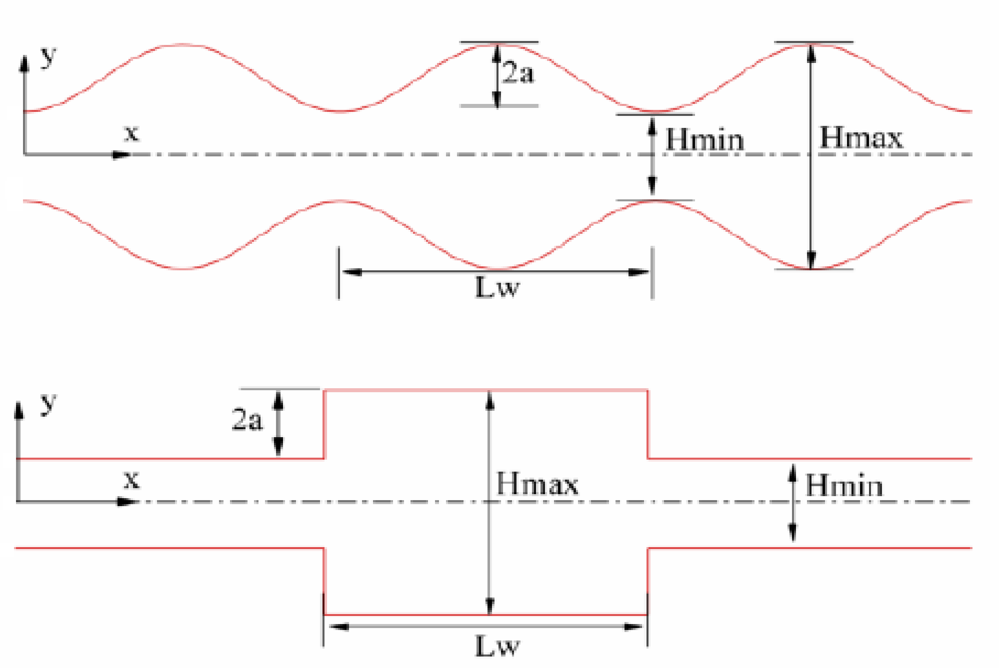

Figure 22. Schematic of corrugated channels in various shapes: rectangular and sinusoidal [33]

Salami et al. [34] numerically studied the thermal hydraulic characteristics of flow inside corrugated channels of different shapes. The effect of phase shifts (0, π / 2, and π) was studied for three different corrugation shapes (trapezoid, triangle, and sinusoidal) for Reynolds number range of 6000- 22,000. The schematic of computational domain and corrugated channels with different configuration was shown in Figure 23. Compared to the traditional smooth channel, the outcomes showed that the corrugated channel provide the highest friction factor and Nusselt number. Besides, trapezoidal corrugations have the highest Nusselt number and friction coefficient followed by triangular and sinusoidal. Moreover, it's found that the phase shift leads to increase in both of Nusselt number and the coefficient of friction. On the other hand, thermal hydraulic performance analysis shows that lower phase shifts lead to better thermal hydraulic performance for corrugated channels and sinusoidal were the better choice for corrugated channels.

Mohammed et al. [35] performed a numerical simulation to study the characteristics of the thermal hydraulic performance in a two-dimensional corrugated channel. The study conducted under turbulent flow for the Reynolds number range (8000-20,000) and the heat flux range (0.4 - 6 kW/m2). The influence of different geometrical parameters was examined including channel height (12.5, 15, and 17.5 mm), corrugation angle (20 °, 40 °, 60 °), and wavy heights (2.5, 3.5, and 4.5 mm). The schematic of the computational domain and corrugated channels with different configuration angles was shown in Figure 24. The results indicated an increase in both of Nusselt number and pressure drop with an increment of corrugations. At the same time, it was found that pressure drop diminishes with the increase of the channel height. The optimum parameters that achieve the best enhancement in heat transfer were the channel height of 17.5 mm, the wavy height of 2.5 mm, and the wave angle of 60 °.

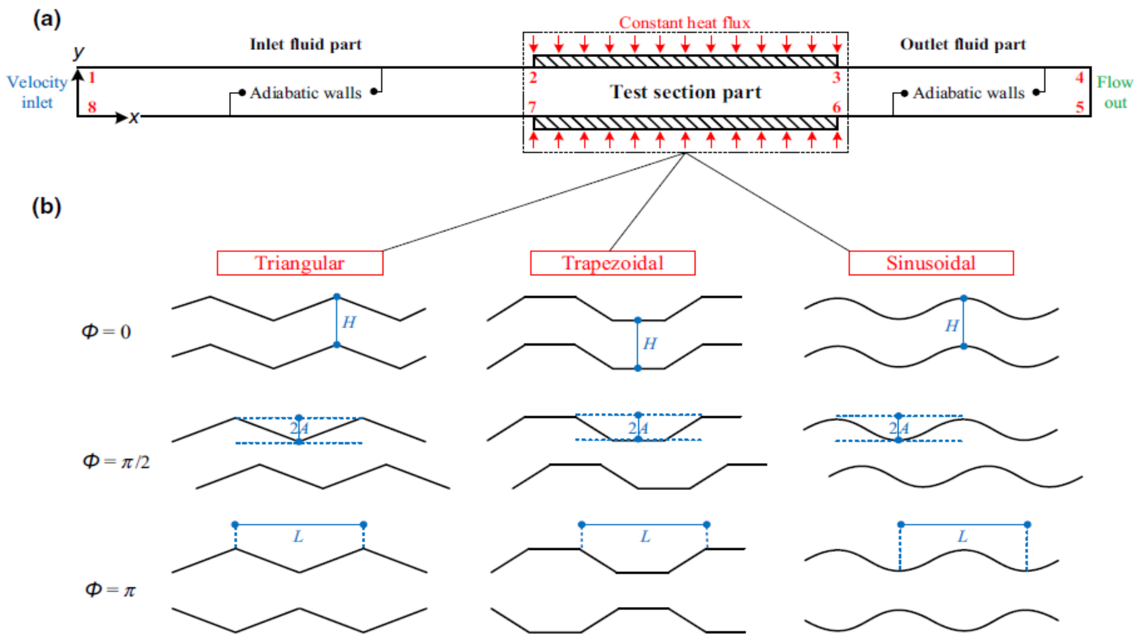

Figure 23. Schematic of computational domain and corrugated channels with different configuration [34]

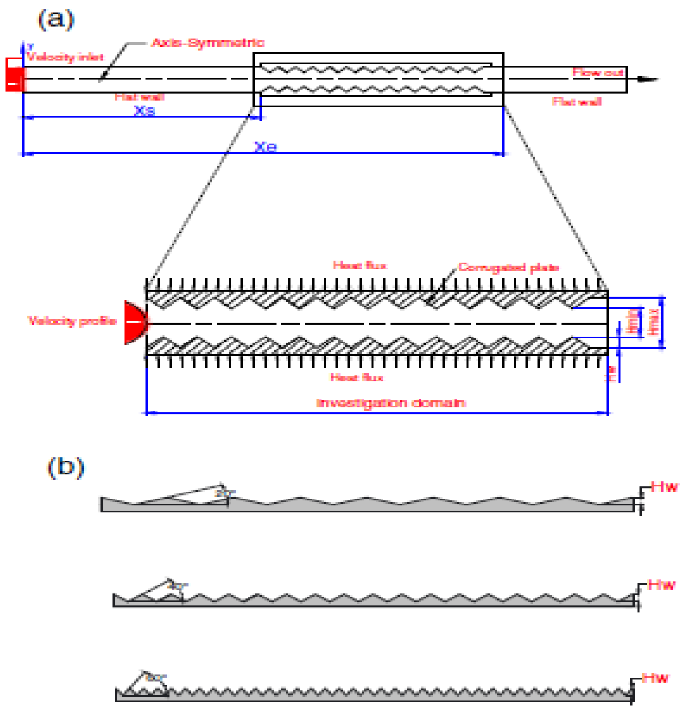

Figure 24. Schematic of computational domain and corrugated channels with different configuration angles [35]

Abd Rabbo et al. [36] numerically studied the hydrothermal characteristics of the trapezoidal corrugated channels. The Reynolds number range for air (100-1000), cutting edge ratio (0-0.6) and corrugation aspect ratio (0.2-0.5) were studied on the heat transfer and flow pattern. Figure 25 shows the computational domain and the most important geometric parameters of a trapezoidal corrugation. The evaluation of trapezoidal configuration was based on a comparison with a triangular shape. The Nusselt number and shear stress in the trapezoidal channel were witnessed a significant reduction compared with the triangular channel. The study attributed this behaviour to the damping of vortices due to the cutting in the sharp edge of triangular configuration.

The characteristics of the thermal hydraulic performance in the sinusoidal corrugated channel of different phase shift between the upper and lower corrugated walls were investigated numerically by Yin et al. [37]. The study was performed within the Reynolds number range (1000-2000) at a uniform wall temperature. The outcomes showed that the corrugated channel has a critical improvement in heat transfer associated with a penalty of pressure loss. Moreover, the effect of phase shift became more pronounced on heat transfer and fluid flow, especially at high Reynolds number values. Besides, it's found that the performance factor (thermal/hydraulic) in all channels was found to be diminished with increasing in the Reynolds number due to the increasing in pressure drop. The values of the overall performance factor were exceeded 1 except when the phase shift angle of 180 °. The influence of the phase shift on the Nusselt number and overall performance factor was shown in Figure 26.

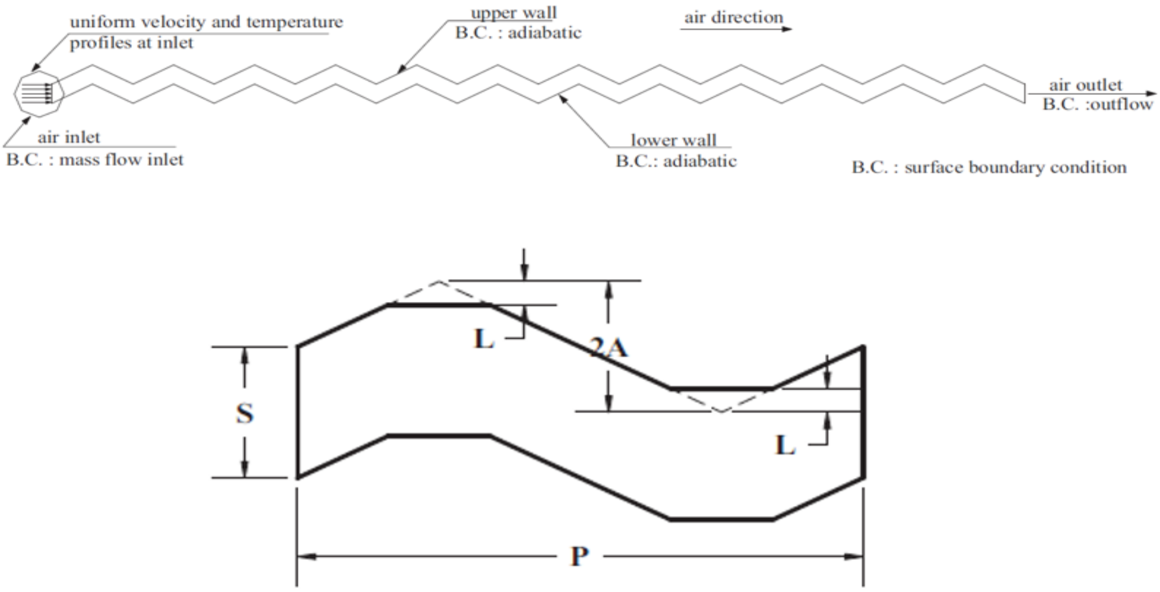

Figure 25. Computational domain of the trapezoidal corrugation with different geometric parameters [36]

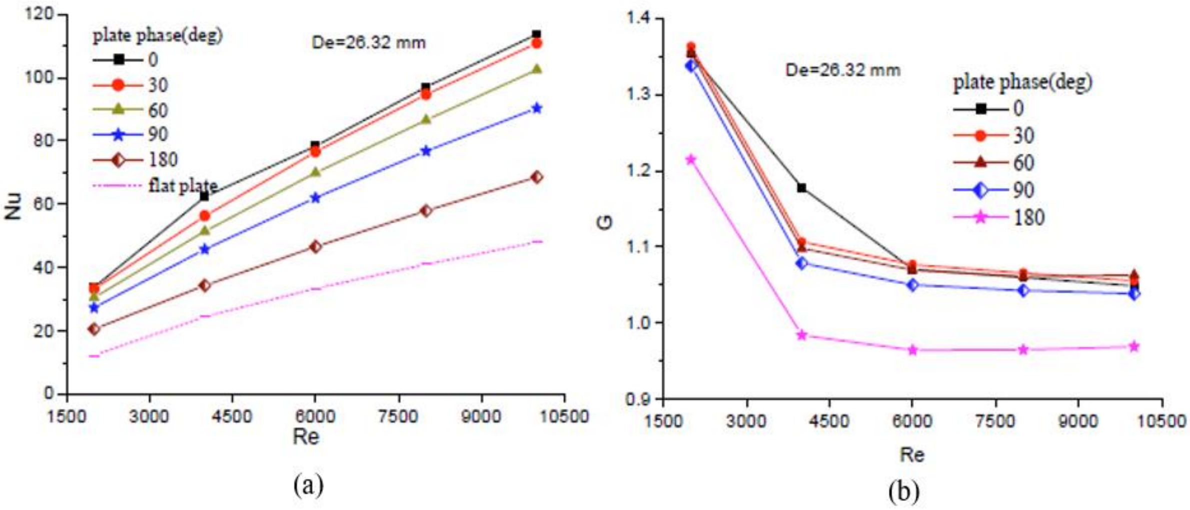

Figure 26. Phase shift influence on different parameters: (a) Nusselt number and (b) overall performance factor [37]

The effect of three phase shifts (0 °, 90 °, and 180 °) of the rectangular corrugated channels on the thermal hydraulic performance characteristics under turbulent flow studied numerically by Tokgoz et al. [1]. The study referred to the existence of significant effects on hydrodynamics and temperature distribution with the effect of aspect ratio and phase shift. The influence of Reynolds number on the friction factor and Nusselt number of the corrugated channels with various phase shift angles was shown in Figure 27. Compared to the phase shift angle of 180 °, the local maximum value of the velocity for a phase shift of 0˚ happens close to the divider in the corrugated channel. As a result, compared to the smooth channel, it was noted that the corrugated channels performance factor was anyway high with a pressure loss penalty. The study reported that corrugated duct was contributed to activate the vortices inside cavities and thin the thermal boundary layers.

Ameur and Sahel [38] numerically studied the influence of the corrugation shape on the hydrothermal flow of a rectangular duct. The performance of three corrugations was compared: rectangular, semicircular, and triangular. The effect of corrugation height and the number of corrugations was also explored. The temperature contours of various corrugation shapes and circular corrugation with various heights were shown in Figure 28a and Figure 28b respectively.

The results showed the superiority of rectangular corrugations followed by triangular, and semi-circular. While this arrangement was reversed in terms of pressure drop. Moreover, it was observed that the semicircular and triangular shapes have almost similar thermal hydraulic performance.

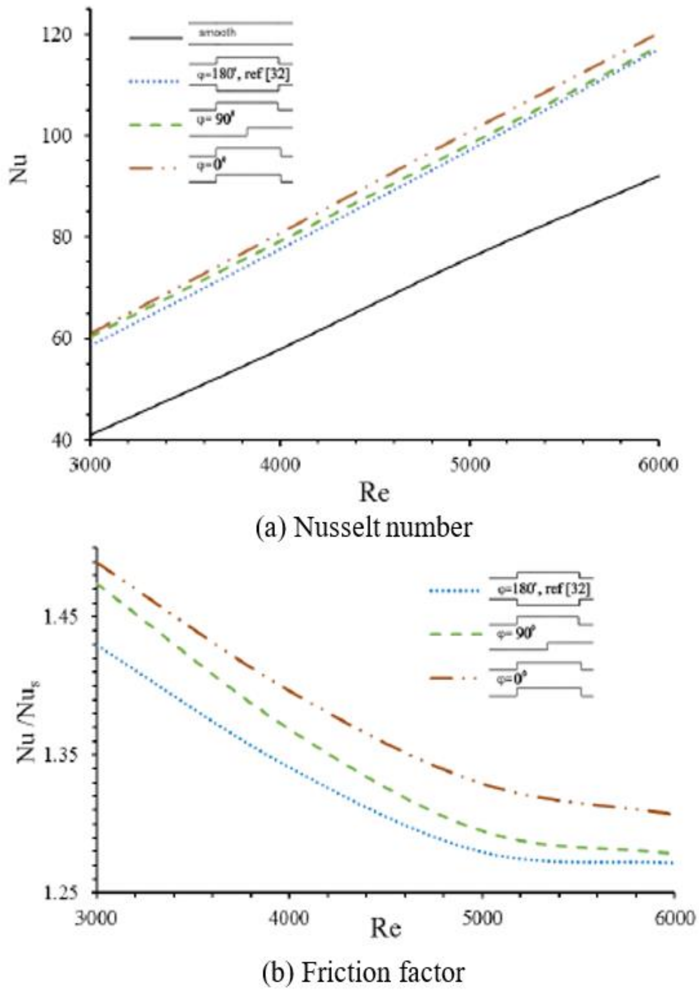

Figure 27. Variations of the Nusselt number and the friction factor with Reynolds number for corrugated channel with various phase shift angles [1]

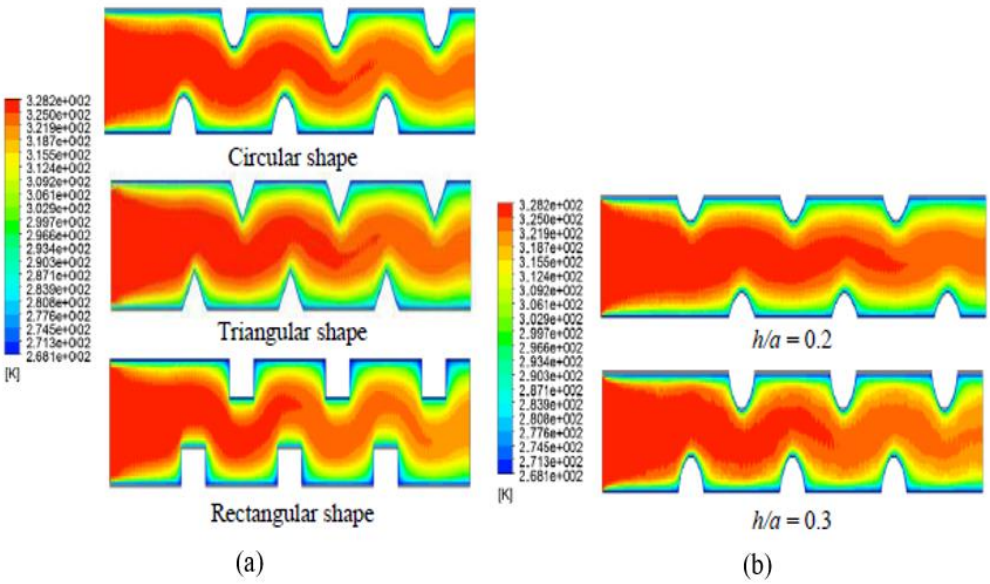

Figure 28. Temperature contours of: (a) various corrugation shapes and (b) circular corrugation under varying heights [38]

Nfawa et al. [39] studied numerically the effect of using linear vortex generators on the hydrothermal of water flow inside the trapezoidal corrugated channel. The two-dimensional study was performed in turbulent forced heat flow conditions for the range of the Reynolds number (5000-17,500). The vortex generator was placed at the entrance to each section. In addition to the effect of linear vortex generator, the study included the effects of trapezoidal amplitude heights. The schematic of the corrugation channel with vortex generators was shown in Figure 29a. Also, the velocity contours for water in trapezoidal corrugated channels with vortex generator for the various amplitude of the corrugations were shown in Figure 29b. The results showed that using a vortex generator in the corrugated channel leads to improvement in the heat transfer of the channel with a high-pressure drop penalty. In addition, the study indicated that the performance improves with the increase in the amplitude of the corrugation.

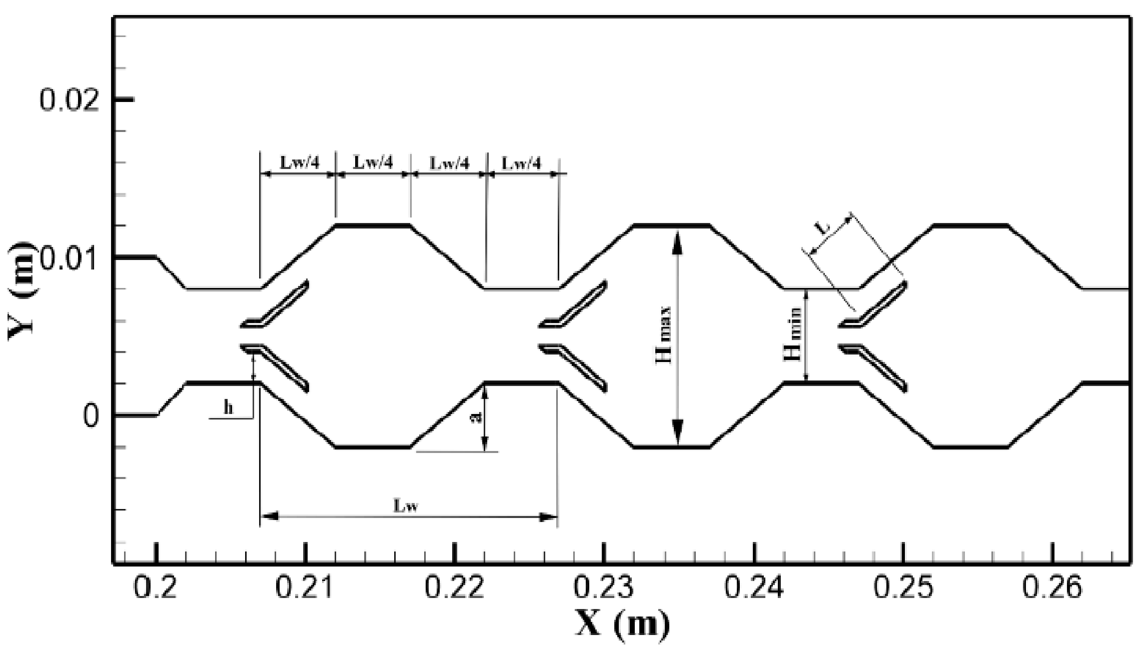

Figure 29a. Schematic of corrugation channel with vortex generators [39]

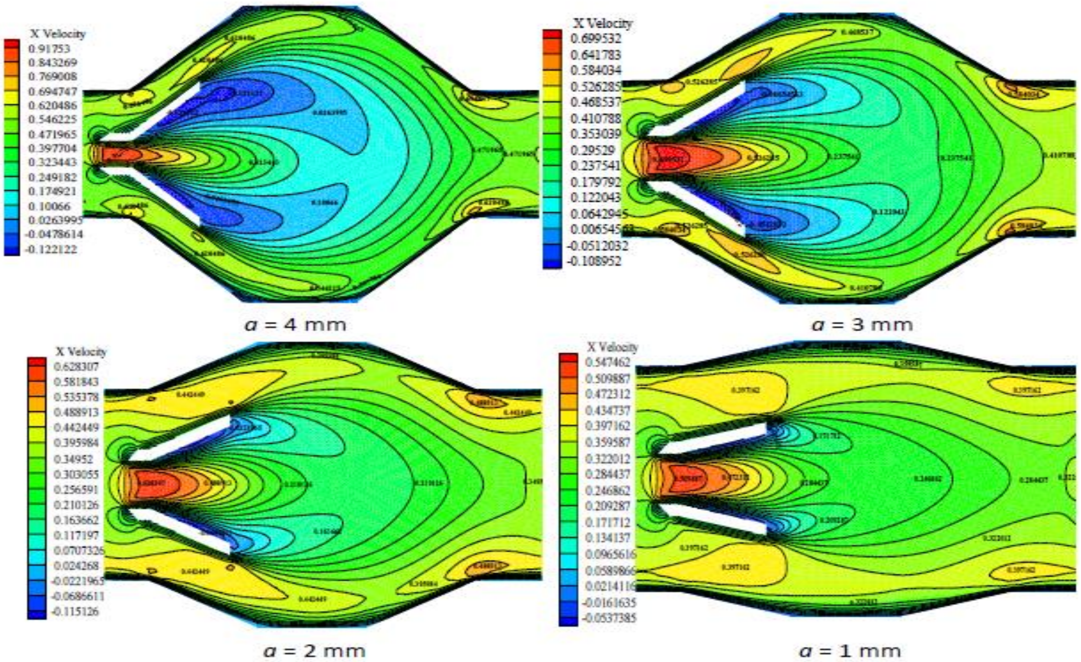

Figure 29b. Velocity contours for water in trapezoidal corrugated channels with vortex generator for various amplitude (α) of the corrugations [39]

Sakr [40] studied numerically the thermal and hydraulic of air flow inside V-shaped corrugated channels under range of Reynolds number (500-2000). The effects of phase shifts between (0-180 °) and channel height (12.5, 15, 17.5 and 20 mm) were studied. The impact of the Reynolds number on the Nusselt Number in corrugated of various channel height and channel phase shift was shown in Figure 30. The study indicated the instability of the thermal boundary layer and distribution of air velocity, which occurs as the flow pass through the corrugated surfaces that directly affects the hydrothermal performance. The study emphasized that the effect of corrugated phase shift on the heat transfer and fluid flow was more significant in a narrow channel. Therefore, the pressure drop in corrugated channels diminishes with the expansion in channel height.

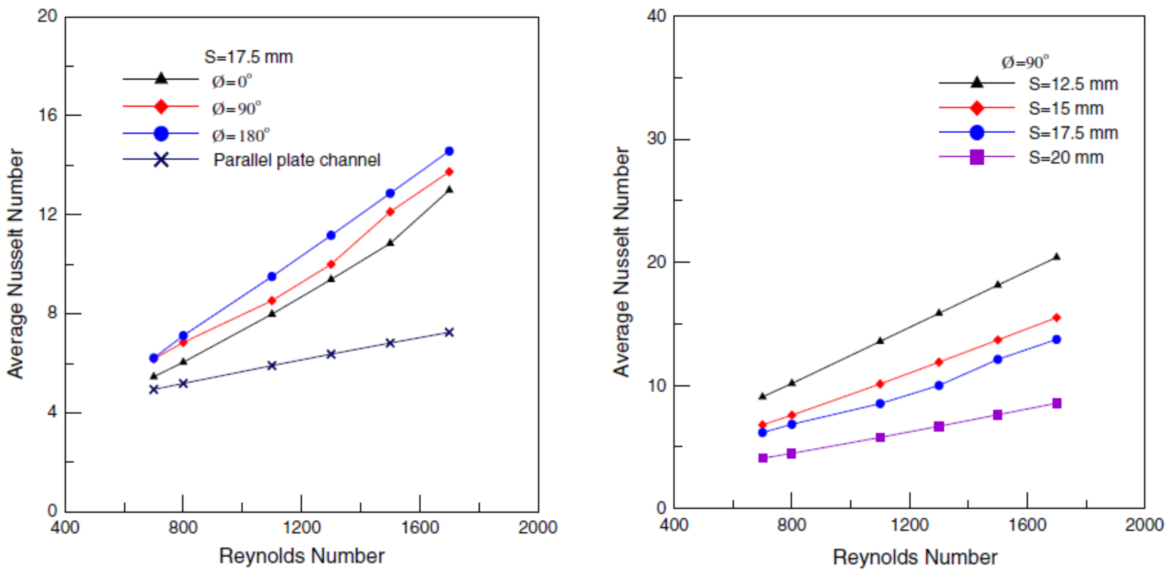

Figure 30. The impact of the Reynolds number on the Nusselt Number in corrugated of various channel height and channel phase shift [40]

Kumar and Sharma [41] numerically studied the thermal hydraulic performance characteristics of a 2-D channel with a corrugation surface. The effect of geometric parameters such as amplitude of corrugation surface and corrugation shape: trapezoidal, sinusoidal and triangular. View of grid corrugated channel with various corrugation shapes was shown in Figure 31. The results indicated that there was a significant improvement in the heat transfer with an increasing in the Reynolds number and the amplitude of the corrugation wall. For laminar flow, the maximum heat transfer enhancement was for the triangular wavy channel followed by a trapezoidal and sinusoidal channel. The maximum pressure drop was observed in the case of a trapezoidal wavy channel followed by a triangular and sinusoidal channel. Also, in the case of turbulent flow, the best thermal performance was observed in the triangular corrugated channel compared to the other corrugated channel. In addition, an increase in Nusslet number was observed when the amplitude of the corrugated wall.

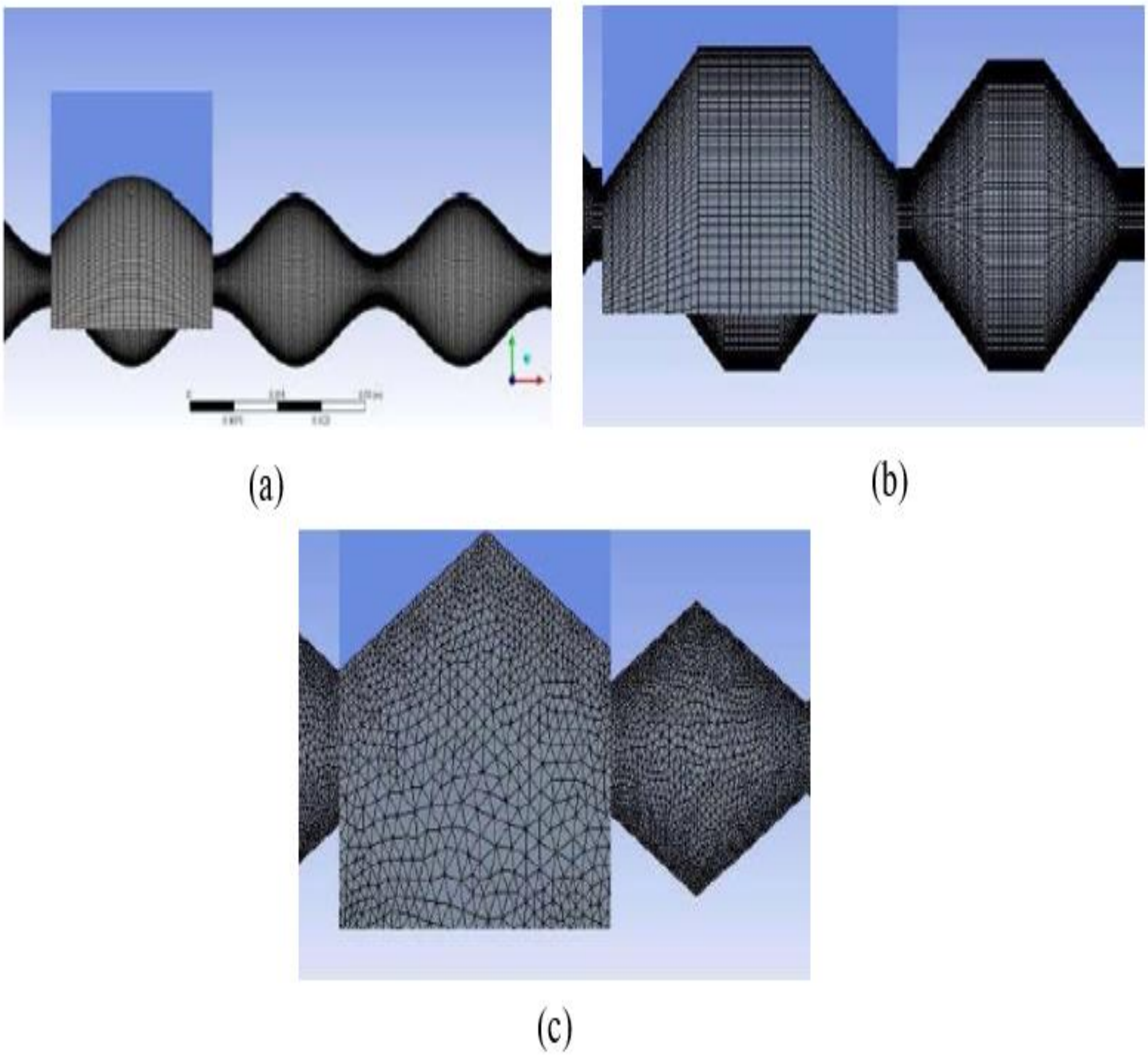

Figure 31. View of grid corrugated channel with various corrugation shapes: (a) sinusoidal, (b) trapezoidal, and (c) triangular [41]

Kumar and Sharma [41] numerically studied the thermal hydraulic performance characteristics of a 2-D channel with a corrugation surface. The effect of geometric parameters such as amplitude of corrugation surface and corrugation shape: trapezoidal, sinusoidal and triangular. View of grid corrugated channel with various corrugation

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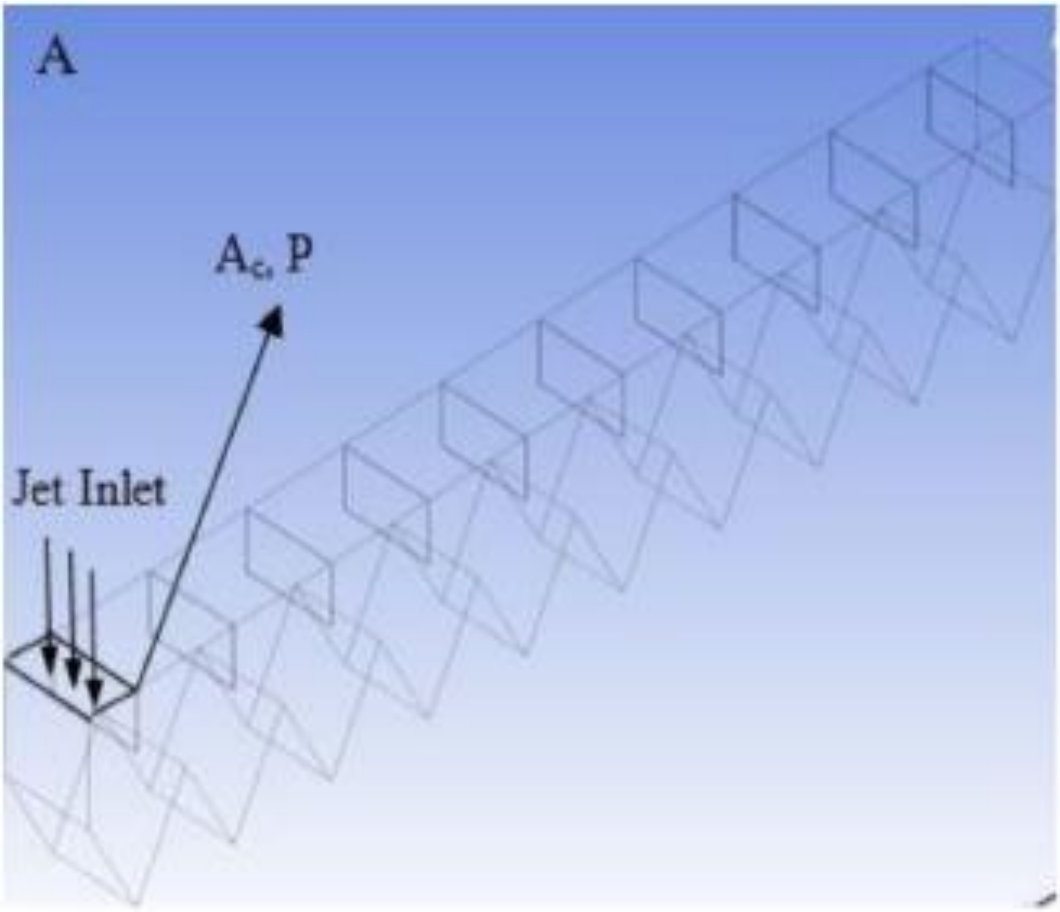

Figure 32. Computational domain of the corrugated channel demonstrates the use of baffles [42]

Table 2. shows a summary of previous numerical studies conducted on corrugated channels. The Numerical studies were the most comprehensive to test the effects of different geometries on the performance of corrugations channels. The shape of the corrugations plays an important role in improving the heat transfer characteristics. Generally, among all the shapes were corrugated channels studied, the best thermal improvement was found in the trapezoidal corrugated channel. The distance between the walls has an effective influence on the heat transfer. Therefore, a remarkable improvement in the Nusselt number with increasing in the amplitude of the corrugated channel was observed. Besides, the aspect ratio was more impact on heat transfer enhancement than the pitch ratio. In addition, the symmetry arrangement accomplished the highest thermal performance, followed by the zigzag.

Table 2. Summary of numerical studies

Authors	Year	Corrugation shape	Results
Dutta et al. [15]	2019	Triangular wavy	An increase in the performance parameter was observed with decreasing channel height
Abbas [16]	2018	trapezoidal	The double-sided inward provides the maximum heat transfer rate and friction coefficient
Deylami et al. [17]	2013	V-corrugated	Increasing corrugations height and Reynolds number contribute to decreasing in the hydrothermal performance factor
Ahmed et al. [18] Ahmed et al. [19]	2011 2013	Triangular	The heat transfer is augmented by increasing the Reynolds number while there was a slight increase in the pressure drop
Ahmed et al. [20]	2014	Trapezoid, triangular, and sinusoidal	The trapezoidal channel has a higher heat transfer improvement, followed by the sinusoidal and triangular channels
Ahmed et al. [21]	2015	triangular	The Nusselt number and pressure drop were increased with the increasing Reynolds number
Ahmed et al. [22]	2016	Trapezoidal	A remarkable improvement in the Nusselt number with increasing in the amplitude of the corrugated channel
Ajeel et al. [23]	2017	House	The aspect ratio was more impact on heat transfer enhancement than the pitch ratio
Ajeel et al. [24]	2018	Semicircular zigzag	The semicircular corrugated channel indicated the hieghesr improvement in heat transfer was 2.7 times better than the smooth channel
Ajeel et al. [25]	2018	Trapezoidal (symmetry and zigzag)	The symmetry arrangement accomplished the most elevated thermal performance, followed by the zigzag
Ajeel et al. [26] Ajeel et al. [27]	2018 2019	Semicircular, trapezoidal, and house	The trapezoidal channel gives the most elevated thermal performance followed by the semicircular shaped channels and then the house channel
Ajeel et al. [28] Ajeel et al. [29] Ajeel et al. [30]	2019 2019 2020	Semicircular and trapezoidal	The best thermal improvement was found in the trapezoidal corrugated channel
Ajeel et al. [31]	2019	Half-circle	The pitch ratio of 0.075 with the aspect ratio of 0.05 achieved the highest performance factor
Ajeel et al. [32]	2020	Trapezoidal	The pitch ratio has less impact on heat transfer augmentation than the aspect ratio
Ozbolat et al. [33]	2013	Rectangular and sinusoidal	The distance between the walls has an effective influence on the heat transfer between the corrugated walls
Salami et al. [34]	2019	Trapezoid, triangle, and sinusoidal	The trapezoidal corrugations have the highest Nusselt number and friction coefficient followed by triangular and sinusoidal
Mohammed et al. [35]	2013	V-corrugated (20 °, 40 °, 60 °)	The optimum parameters that achieve the best enhancement in heat transfer are the channel height of 17.5 mm, the wavy height of 2.5 mm, and the wave angle of 60 °
Abd Rabbo et al. [36]	2018	Trapezoidal	The Nusselt number and shear stress in the trapezoidal channel were witnessed a significant reduction compared with the triangular channel
Yin et al. [37]	2012	Sinusoidal	The effect of phase shift became more pronounced on heat transfer and fluid flow, especially at high Reynolds number values
Tokgoz et al. [1]	2018	Rectangular	Compared to the phase shift angle of 180 °, the local maximum value of the velocity for a phase shift of 0˚ happens close to the divider in the corrugated channel

4. Conclusions

Many studies were reviewed that sheds light on the most important influences of the corrugation configuration in various shapes on the thermal hydraulic performance of channels. Previous studies have compared characteristics of many shapes of corrugated channels including sinusoidal, trapezoidal, domestic, and V type. This study included a demonstration of the effects of several geometrical parameters on the heat transfer and pressure drop of the different shapes of corrugated channels. From the previous studies, there were several conclusions that can be included, which were as follows:

1. Among the studied shapes of the various operating conditions of the corrugated channels, the researchers unanimously agreed that the trapezoidal shape of the corrugations gives the best thermal improvement with the most appropriate pressure drop inside the channels.
2. The effect of space between the channels on the coefficient of heat transfer and friction factor was more pronounced than the phase shift change, especially at higher Reynolds number.
3. A small influence of the phase shift on the performance of the corrugated channel. On the other hand, hydrothermal performance analysis shows that lower phase shifts lead to better hydrothermal performance.
4. Increasing the corrugated angle improved the rate of heat transfer.
5. The performance factor of the corrugated channel improves by decreasing the corrugations height.
6. The symmetry arrangement of the corrugations recorded the highest heat transfer from the zigzag arrangement.

5. Future scope

Although numerous studies were conducted on the effect of corrugation shape in axial direction of the channel, there was no study so far analyzing the effect of these shapes in the transverse direction of the channel. So, there was a need for new studies comprise the effect of these shapes in the transverse direction. Besides, depending on the results obtained from numerical modeling of heat transfer and fluid flow due to the change in shape of the corrugated channels, new correlations of different geometries of the corrugated channels can be found to be examined and analyzed experimentally.

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