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Simulation of fluid flow and heat transfer inside a heat exchanger corrugated channels

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- ✓ Forced Convection;
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Abstract

The present work concerns the study of Numerical analysis on the fluid flow and heat transfer in corrugated channel with various geometry configurations, under constant heat flux conditions is considered. This is largely studied both experimentally and numerically due to their wide industrial application in various fields such as nuclear reactor urgency, solar boiler, heat exchangers and thermo siphon solar capturers, etc. A great deal of relevant research work consists of numerical simulations of forced convection mechanisms with turbulent flows in corrugated channel. We are interested in determining the flow for various amplitudes and periods. The influence of geometry on several factors such as: temperature, the local Nusselt number, friction number, turbulent kinetic energy *k* and its dissipation ε are considered. Based on the Navier-Stokes equations, these equations were solved by a CFD technique using the Finite Volume Method. The results show that when we gradually increase the amplitudes of the protuberance part (say a=0.03, a=0.06,) the maximal temperature increases with the increase of amplitude. This is due to the rise of the heat transfer surface of the modified wall. Regarding heat transfer parameters, the results show that the number of local Nusselt varies accordingly with the amplitudes and number of periods. This explains that the modified wall is affected locally by a pure conduction. The results of this study are expected to lead to guidelines which will allow the selected wavy channel geometry configuration for designing heat exchanger that increase thermal performance.

Nomenclature

a	Amplitude (m)	σ_ε	diffusion Prandtl number for ε
C_f	Friction number	C_{e1}	turbulent model constant
C_{e2}	turbulent model constant	$C\mu$	turbulent model constant
Cp	specific heat, kJ/(kg .°C)	k	turbulent kinetic energy, m^2/s^2
N	Number of periods	ε	dissipation kinetic energy, m^2/s^3
Nu	Nusselt number	μ	viscosity, kg/m
ρ	density, kg/m^3	σ_k	diffusion Prandtl number for k
Φ	viscosity energy dissipation function.		

1. Introduction

Important research achievements have been done during last years on thermal transfer and flow by convection and conduction on wavy and plane surfaces [1-34]. Taking into account the importance of this method in improving the thermal performance of heat transfer dispositive these achievements show essentially that flow is characterized by circulations that allow important heat transfer.

Adams et al [1] have experimentally studied the turbulent forced convection and have shown that the Nusselt numbers are higher than those predicted by classical correlations in conventional channels, such as the correlation Gnielinski. They have shown that the convective heat exchange coefficient increases as the diameter decreases. Wahib et al [2]. Studied the single-phase flows in forced convection R134a for diameters of 1.7; 1.2 and 0.8 mm. Their results in the turbulent region were in very good agreement with classical correlations. Boukadida [3]. Analyzed coupled transfers of heat and mass forced convection in a horizontal channel. The phenomenon of evaporation of the water has been studied in a dry air flow of moist air and superheated steam. He showed that the analogy between heat transfer and mass is only valid for low temperatures and low concentrations where the heat transfer by radiation is negligible. Hwang et al. [4] presented a numerical study of turbulent flow in a pipe containing an obstacle. Numerical results show that an extension of the recycling region upstream of the obstacle does not depend on its length in the direction of flow. The recirculation zone is strongly influenced by the length of the obstacle; this area decreases as the barrier length is increased. Huang and Cheng [5] have also analyzed laminar flows, forced convection in the inlet region of a horizontal channel. Calculations for the semi-infinite channel in which one or two pairs of baffles are symmetrically attached to the respective walls in the inlet region were analyzed. Azzi A, D and Lakehal [6] their study is based on the work of Rodi et al. [7]. Have studied numerically the dynamic and thermal characteristics of a turbulent flow of forced convection along a corrugated-wall pipe, the analysis of the turbulent flow and prediction of thermal exchanges, a plurality of tubes of different corrugation amplitudes performed using the finite volume method and the turbulence model kw SST, because the undulation of the wall contributes to the destruction of the thermal boundary layer, this improvement is accompanied by an increase in pressure drop, and therefore requires more pumping power. Comparing with a smooth cylindrical tube, corrugated tube allowed to have an increase of 1.31% up to 18.04% in the Nusselt number. Ahmed Zineddine Dellil, Abbes Azzi Mohammed Lachi [8]. Have a present modeling of the heat transfer by forced convection along a corrugated wall. A model of two equations turbulent viscosity (bi-layer model) is used. It is to combine the standard model of turbulence k-ε away from the wall and a model to an equation for solving the equations in the region near the wall. Their study was made on the work conducted by Mass and Schumann [9]. The results showed that the bilayer model used is interesting, as it provides important information on most properties such a physical flow. Comparison of the results of a corrugated wall with those of a right channel indicates that the Nusselt number increases with the amplitude of the wave. However, intensification of heat transfer is accompanied by a significant decrease in the friction coefficient. At another level, hence the same case of figure was studied by Rodi et al [10].

Goldstein and Sparrow [11] were among the first to experimentally measure local and average heat transfer coefficients in a corrugated channel, in laminar, transitional and turbulent flow regimes. Their results showed secondary flows inside the triangular waves which resulted in up to 300% increase in the averaged heat transfer in turbulent regimes. Balamurugan [12] has studied theoretically the convective heat transfer in a corrugated micro channel under constant heat flux conditions. Chen .C and H Huang [13] have essentially showed that the flow is characterized by strong deformations and big recirculation regions which lead to an increase in the number of nusselt and friction coefficient with the Reynolds number. Zimmerer et *al*. [14] have studied the effects of the inclination angle, the wavelength, the amplitude, and the shape of the corrugation on the heat and mass transfer of the heat exchanger. Wang and Vanka [15] have studied numerically the heat transfer in periodic arrays of wavy channels. They observed self-sustained oscillatory flow for Reynolds numbers higher than about 180. These self-sustained oscillations lead to the destabilization of the laminar boundary layers which enhance the mixing between the core and the near-wall fluid. However, the friction factors for wavy channels were noticed to be nearly double those of flat channels in the laminar regime. Wang and Chen [16] have determined the heat transfer rates flowing through a sinusoidally curved converging–diverging channel. Pretot et *al.* [17] have studied experimentally and numerically on the flow over the horizontal wavy plates. Comini et *al*. [18] studied effect of aspect ratio on convection heat transfer enhancement in the wavy channels. Islamoglu and Parmaksizoglu [19] have studied numerically and experimentally the effect of channel height on the enhanced heat transfer characteristics in a corrugated heat exchanger channel.. Metwally and Manglik [20] have simulated the laminar periodically developed forced convection in sinusoidal corrugated- plate channels by using the control volume –finite difference method. Kruse and Von Rohr [21] experimentally studied on the structure heat flux in a flow over a heated sinusoidal wavy wall. Mohamed et *al*. [22] have studied the laminar forced convection in entrance region of a wavy wall.

Naphon [23] experimentally studied on the heat transfer characteristics and pressure drop in the corrugated channel with different wavy angles and channel heights. The corrugated plates in an in- phase and out-of-phase arrangements were tested. Fabbri and Rossi [24] studied the laminar convective heat transfer in the smooth and corrugated channels. Paisarn Naphon et *al* [25] studied a numerical analysis on the heat transfer and flow development in the channel with one-side corrugated plate under constant heat flux conditions is presented. The corrugated plate with the corrugated tile angles of 40° is simulated with the channel height of 7.5 mm. The flow and heat transfer developments are simulated by the k-ε standard turbulent model.
Loh, S. A. and H. M. Blackburn [26] studied the stability of steady flow through an axially corrugated pipe.
Budiman et al [27] have studied the visualization of pre-set vortices in boundary layer flow over wavy surface in rectangular channel.
In experimental study Budiman and al [28] have studied the effects of wavy Channel entrance design on streamwise Counter-rotating Vortices: a Visualization Study.
The objective of this paper is numerical study the heat transfer and flow developments in a corrugated-channel. The temperature and velocity distributions are simulated by the finite volume method. The effects of various relevant parameters on the heat transfer and flow developments are also considered.

1. Mathematical modeling

The physical problem, considered in this work is shown in Fig. 1, adopting the k-ε standard turbulent model to simulate the turbulent heat transfer and flow characteristics. The governing equations are written as:

- Continuity equation:

$$\frac{\partial \rho}{\partial t} + div(\rho U) = 0 \tag{1}$$

- Momentum equation:

$$x - momentum: \ \rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + div(\mu grad u) + S_{mx} \tag{2}$$

$$y - momentum: \ \rho \frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + div(\mu grad v) + S_{My} \tag{3}$$

- Energy equation

$$\rho \frac{Di}{Dt} = -p div U + div(\Gamma grad T) + \Phi + S_i \tag{4}$$

Turbulent kinetic energy (k) equation:

$$\frac{\partial(\rho k)}{\partial t} + div(\rho k U) = div\left(\frac{\mu_t}{\sigma_k} grad k\right) + 2\mu_t E_{ij} . E_{ij} - \rho \mathcal{E} \tag{5}$$

Turbulent kinetic energy dissipation (ε) equation:

$$\frac{\partial(\rho \varepsilon)}{\partial t} + div(\rho \varepsilon U) = div\left(\frac{\mu_t}{\sigma_\varepsilon} grad \varepsilon\right) + C_{1\varepsilon} \frac{\varepsilon}{k} 2\mu_t E_{ij} . E_{ij} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \tag{6}$$

The empirical constants for the turbulent model are arrived by comprehensive data fitting for a wide range of turbulent flow of Launder and Spalding [1973]:

$$C_u = 0.09 , C_{1\varepsilon} = 1.47 , C_{2\varepsilon} = 1.92 , \sigma_k = 1.0 , \sigma_\varepsilon = 1.3 .$$

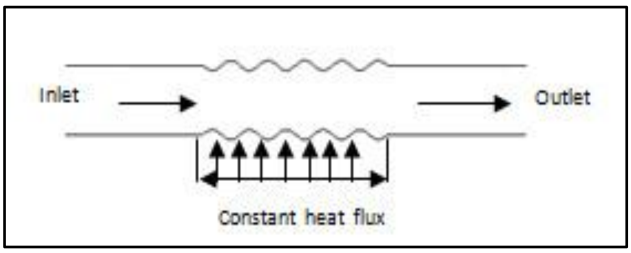

Figure 1: Schematic for physical model.

The boundary conditions are based on experimental data:

u=25m/s, v=0 m/s, k=0.09m2/s2, ε=16m2/s3

2. Numerical resolution

The governing equations are solved by CFD software which is primarily based on the method of finite volumes and is realized using the simpler logarithm. The choice of the meshing grid is selected in such a way that the refinement of the grid is of a high degree of accuracy in sides precisely at the protuberances region.

3. Validation

The results of the present numerical simulation code were validated by the results obtained by Dorin Stanciu Mircea Marinescu, Alexandru Dobrovicescu [29] figure. 2 show the coefficient of friction (C_f). Our results are illustrated in (a) and those Dorin Stanciu Mircea and A. Dobrovicescu in (b).

Figure.3 gives the results concerning the Nusselt number (Nu): (a) our calculate and (b) those of Dorin Stanciu Mircea et al. With these parameters, our calculations were similar to those Dorin Stanciu Mircea et al.

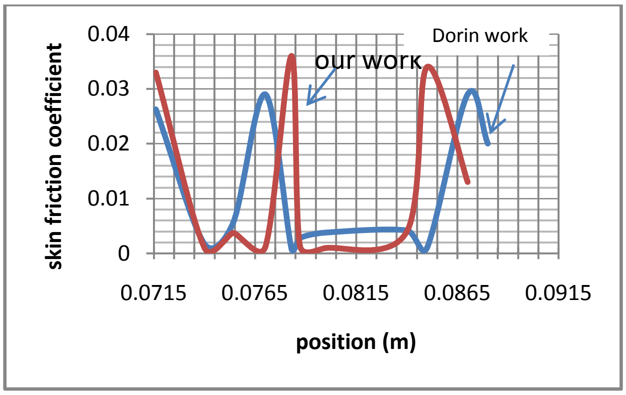

Figure 2: Coefficient of friction C_f, present study and Dorin Stanciu et al.

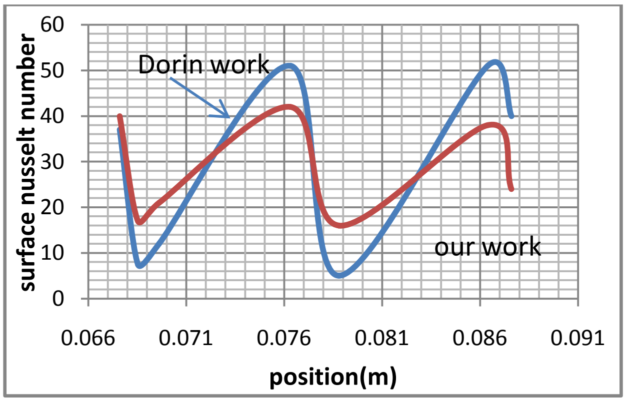

Figure 3: Nusselt number, present study and Dorin Stanciu et al.

4. Results and Discussion

We have carried out a numerical study for various amplitudes and periods. Many of factors such as: Temperature (T), local Nusselt number (Nu), turbulent kinetic energy (k) and its dissipation (ε) are obtained. Figures.4-9 Show the fluid characterized by streamlines calculated in the protuberant part of the channel, for two amplitudes a = 0.03 and 0.06 and periods N of 2, 3 and 5,are moving upward and by a set of contra-rotating cells which meet in the hollows and at the tops of the sinusoid. We observe also, that the increasing of the amplitude and period, we have noticed that lead to the formation of the vortices zone in the top and bottom regions of the deformed part.

Figures .10-15 illustrate the evolution of temperature profiles for various amplitudes and periods. It is noticed that there is a progressive increase in temperature going from the low amplitude up to the high amplitude. This is due to the increase of the heat transfer surface in the corrugated channel because the transfer in the sinusoids is carried out primarily by the mode of pure conduction and the mode of convection transfer increases beyond the tops of the sinusoids.

The distributions of friction coefficients for several periods are shown in figure.16. We can note that in the corrugated channel, the profile of the friction coefficient becomes periodic. It is also observed that for a single corrugation the friction coefficient increases in the summits and decreases in the hollows note that the increase in periods and amplitudes causes an increase in the coefficient of friction.

Figures 17 and 18 respectively we observe the evolution of the Nusselt number (Nu) and the turbulent kinetic energy (k) versus to the length of the corrugated channel for various periods. The effect of increasing the periods generates a slight increase in turbulence as well as in the rate of heat transfer.

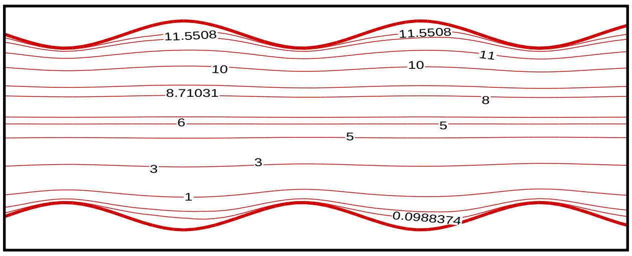

Figure 4: Streamlines for an amplitude a=0.03 and period N=5.

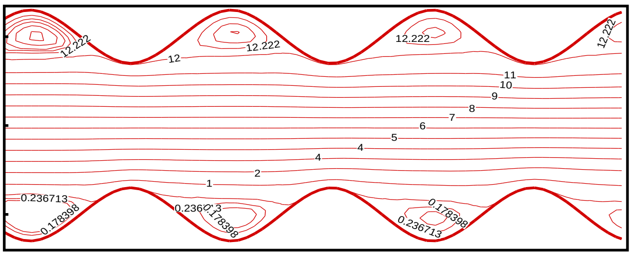

Figure 5: Streamlines for an amplitude a=0.06 and period N=5.

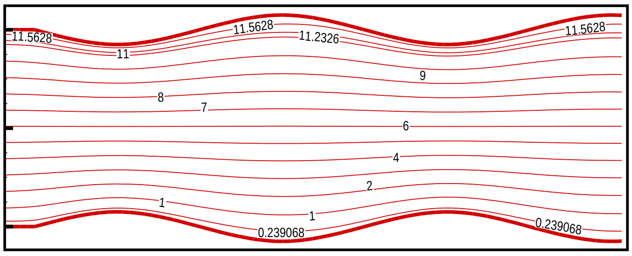

Figure 6: Streamlines for an amplitude a=0.03 and period N=3.

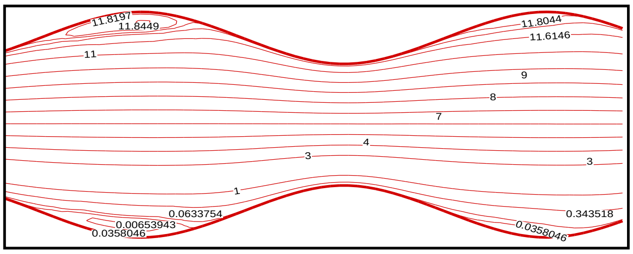

Figure 7: Streamlines for an amplitude a=0.06 and period N=3.

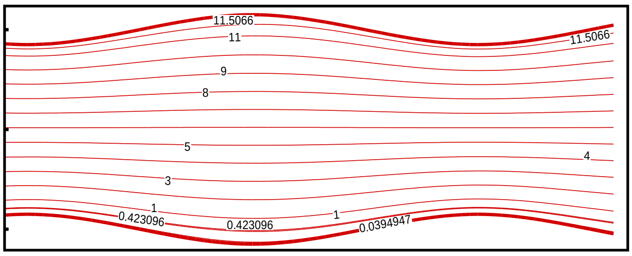

Figure 8: Streamlines for an amplitude a=0.03 and period N=2.

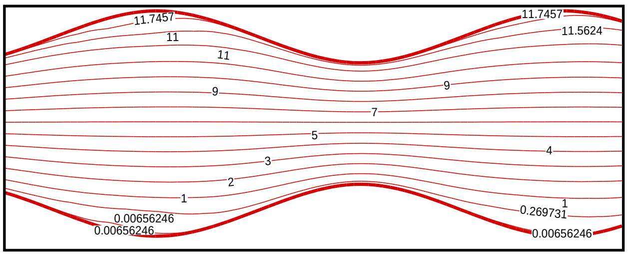

Figure 9: Streamlines for an amplitude a=0.06 and period N=2.

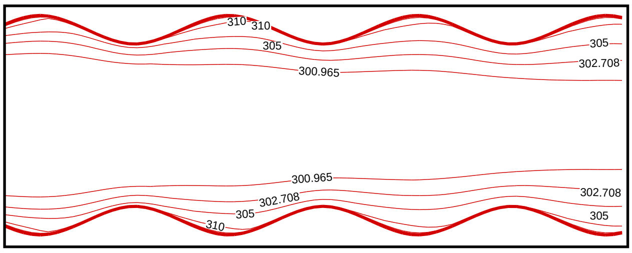

Figure 10: Isotherms for an amplitude a=0.03 and period N=5.

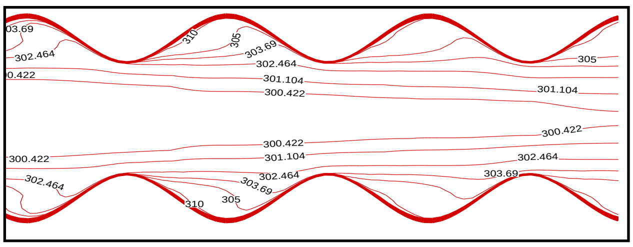

Figure 11: Isotherms for an amplitude a=0.06 and period N=5.

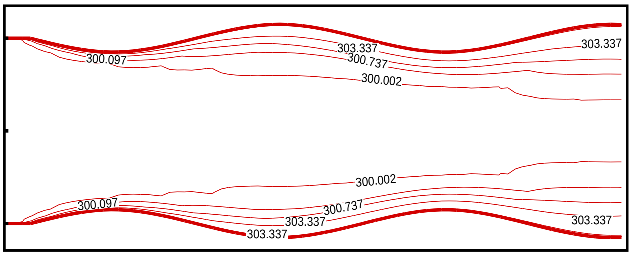

Figure 12: Isotherms for an amplitude a=0.03 and period N=3.

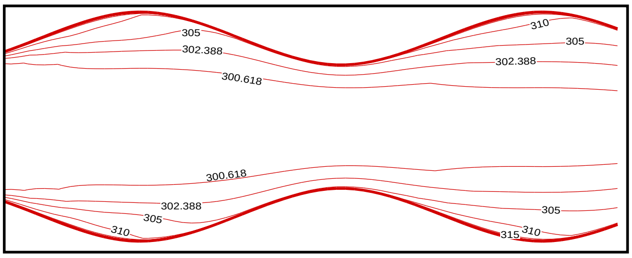

Figure 13: Isotherms for an amplitude a=0.06 and period N=3.

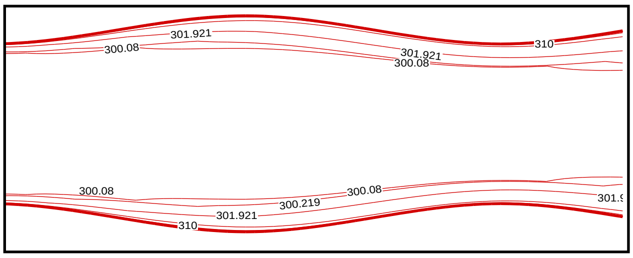

Figure 14: Isotherms for an amplitude a=0.03 and period N=2.

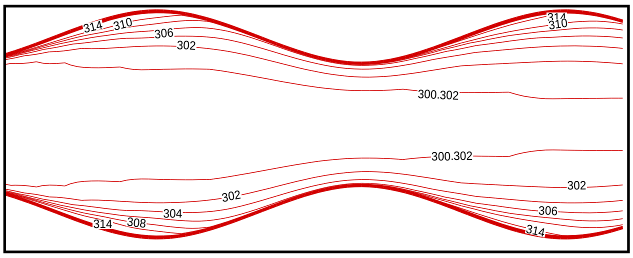

Figure 15: Isotherms for an amplitude a=0.06 and period N=2.

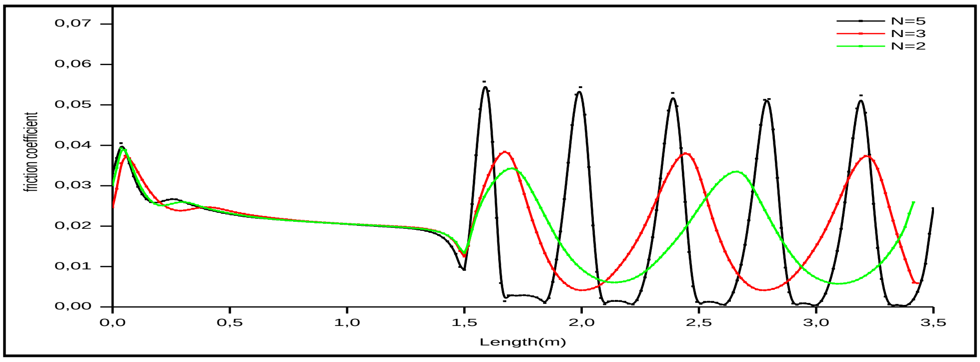

Figure 16: Evolution of the friction coefficient versus length of the channel (flat and deformed) for various periods.

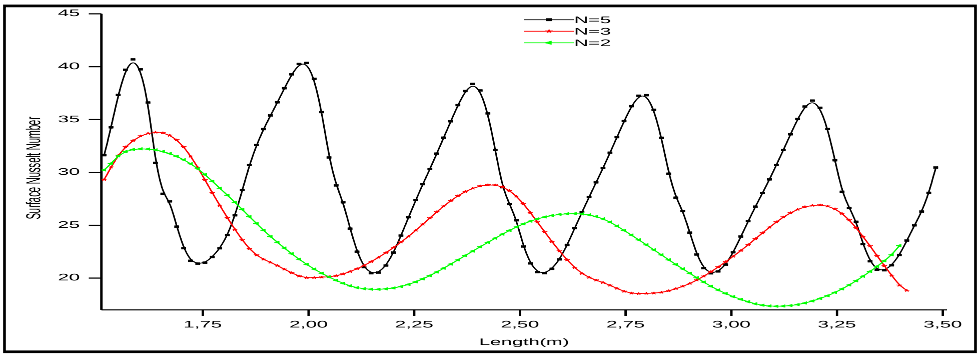

Figure 17: Evolution of nusselt versus length of the protuberances; for various periods.

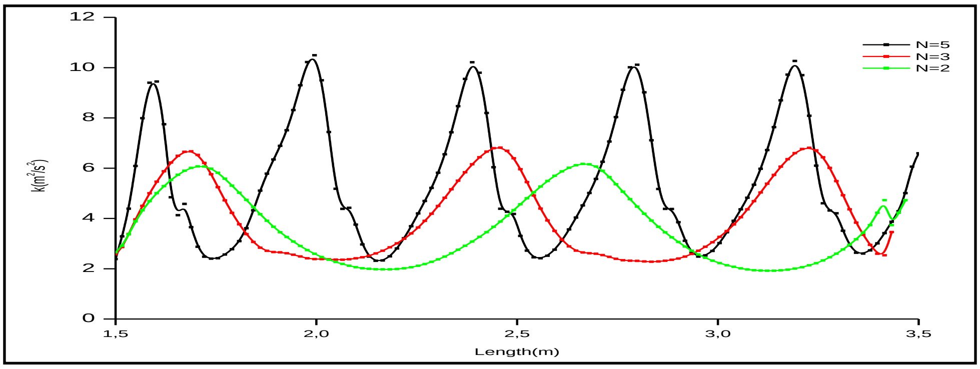

Figure 18: Evolution of the turbulent kinetic energies versus length of the protuberances; for various periods.

Conclusion

In this work, we studied the influence of five factors evolution, in corrugated channel which is partially deformed. The obtained results show that the flow is characterized by a circulation upwards and undulatory in the vicinity of the protuberances (hollow). In the vicinity of the sinusoids, we note the existence of a mode of heat transfer, purely, conductive and beyond the tops there which will be the convective mode where the numbers of Nusselt are higher compared with a heat transfer for a plat channel. Therefore, the use of channels with corrugated walls for increasing the thermal efficiency and higher compactness of the heat exchanger.

According to these results of this work, we can conclude that our calculation seems in concordance with some other works found in literature for simple geometries. This study is to improve the thermal performance of a heat exchanger for a corrugated channel walls.

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