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NUMERICAL INVESTIGATION OF HEAT TRANSFER AND ENTROPY GENERATION IN A WAVY CHANNEL

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Abstract. In this thesis, the flow and heat transfer of nanofluid in a wavy channel is investigated numerically. For this purpose, the equations of continuity, momentum, turbulence, and heat transfer in the computational domain are solved numerically. The accurate correlations are used for simulation of nanofluid. The correlations of effective viscosity and effective thermal conductivity are defined. The results in the limiting case are in good agreement with the pervious published results. In this work, various parameters such as entropy generation, kinetic energy, vorticity, pressure parameter, and temperature conditions are investigated. The results show that the value of vorticity increases by approaching to the walls and the value of vorticity becomes maximum where the fluid desert the wavy part of the wall. Also, it can be found that the pressure decreases where the fluid flows through the channel. The results show that the pressure is changed periodically. It can be found that the pressure decreases where the fluid flows in wavy part of the wall and the pressure increases where the fluid flows out of wavy part of wall. It can be seen that the maximum of temperature is happened at the top wall. Also, it can be found that the thermal boundary layer becomes thicker by passing through the flow field. It can be found that the Nusselt number increases with the increase in nanofluid concentration. The variations of entropy generation function are very similar to the function of temperature and it can be found that the maximum of entropy generation is happened at the top wall.

Key words: nanofluid, wavy channel, entropy generation

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1. GENERAL

1.1 Introduction

Several methods have been used to increase the heat transfer rate to achieve optimum thermal efficiency over the past few years. Heat transfer rate can be improved by changing the flow geometry, the boundary conditions and improving the thermo-physical properties of the fluid such as increasing thermal conductivity. Conventional fluids in industry such as water, oil and ethylene glycol have a low thermal conductivity and are considered as a heat transfer deterrent. Solving this problem requires to achieve a fluid with higher heat conductivity, so that being able to construct heat exchange devices with smaller dimensions. The solution to increase the thermal conductivity of the fluid is to add solid particles to the base fluid. These particles can be metal materials powder, non-metallic or polymeric. In this regard, Maxwell has done a research in 1973 and indicated that the addition of particles in the millimeter and micrometer scale can increase the mixed thermal conductivity and helps heat transfer. The main problem of Maxwell's research was the particle deposition in millimeter and micrometer scale, therefore, in some cases, caused obstruction of flow channels, so a new generation of solid / liquid blends called nanofluids proposed by Choi in 3771 (Choi, 1995).

The first work on the convection heat transfer of nanofluids was done by Pak and Cho (Pak & Cho, 1998) into a tube with 10/66 mm diameter. The size of particles used were 13 and 27 nm. Their first observation was a significant increase in convection heat transfer coefficient in turbulent flow. Based on experiments heat transfer coefficient of nanofluids was higher than the values for fluid. An incremental value of about 45 percent to 1/34 percent of aluminum oxide particles and 75 percent to 2/78 percent of these particles were observed. He stated that convection heat transfer coefficient increasing is higher than the thermal conductivity increasing and thus, cannot link the increase in heat transfer only to the increase in thermal conductivity of nanofluids. Wang et al [4] were the first researchers that offered new mechanisms of the cause of thermal conductivity increasing of nanofluids. These mechanisms involved the movement of particles and the surface effect. They expressed the importance of nanofluids' size in increase of nanofluids thermal conductivity. Xuan and Li (Xuan & Li, 2003) proposed some mechanisms to increase the thermal conductivity of nanofluids, such as increasing the surface area of nanofluids, particles collision and nanofluids dispersion. For a better analysis in the field of heat transfer in nanofluids we need to examine the physical properties of nanofluids, in most published research, the physical properties of nanofluids such as thermal conductivity and viscosity have been reported as a function of volume fraction of nanofluids (Xie, Wang, Xi, et al., 2002). In the field of force convection heat transfer, researchers have reported that the increase of heat transfer rate is a result of adding nanofluids (Hashemi, & Akhavan-Behabadi, 2012). The effect of adding nanofluids to the base fluid in increasing the natural convection heat transfer has been considered. From the research conducted in this area, the effect of natural convection flow of water-cooper nanofluids in a two-dimensional chamber by Khanafer et al. 2011 can be mentioned (Khanafer, Vafai, & Lightstone, 2003). Their results showed that adding nanofluids to the base fluid can increase the heat transfer of any Grashof number. Similar results were presented by Oztop and Abu-Nada in 2008, which the increase of heat transfer via adding nanofluids has been observed on them (Oztop, & Abu-Nada, 2008). Other empirical research has been done by Van and Ding in 2004 which represents a sensible reduction in heat transfer by adding nanofluids. Generally natural conviction heat transfer affected by properties of nanofluids such as viscosity and thermal conductivity. What we said here and previously was about the effects of nanofluids in different geometries, and now wavy walls geometry is examined by higher accuracy. Due to the ability of wavy channels in increasing heat transfer and mass transfer, numerous studies have been done to understand existing physics on these issues. Most studies have been done on converge and diverge channels that phase difference between the upper and lower walls is 180 degrees or zero. Numerical (Metwally & Manglik, 2004) (Munson, Young & Okiishi, 2002) and laboratories (Ahmed, Yusoff, Ng, & Shuaib, 2014) (Nishimura, 1995) studies are done in association with the effects of wavy channels.

1.2 Current research

The aim of this study is numerical modeling of flow phenomena and heat transfer within a wavy channel. Nanofluids are selected as base fluid and placed into the system. For this purpose, differential equations must be considered that included the continuity equations, momentum, heat transfer and turbulence. Equations discrete on the computation points of the intersection of networks and examine by finite volume numerical method, and analyze the effect of various parameters such as nanofluids concentration.

In this study, an introduction in associated with flow geometry and nanofluids is presented so that these defined items and their applications have been mentioned. In the following we express the equations by which the problem is examined, how that modeling is met, how is the solve space, and how solve the problem in this space. And finally conclude the research results.

2. THE EQUATIONS

2.1 Introduction

To examine fluid flow in channel, the equations for modeling depending on the input flow regime, type of fluid, and shape of the walls, are different. Also, depending on what and how parameters are important to calculate the flow, specific equations must be used.

2.2 Continuity Equation

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) = 0 \qquad (1)$$

2.3 Momentum Equations

These equations are obtained by the following assumptions:

1- Being non-permanent fluid flow;

2- Being stable of thermal and physical properties of the fluid to temperature

3- Lack of physical and foreign forces;

4- Being two-dimensional fluid flow.

In the following it is pointed out that heat transfer and hydrodynamics in a manner that is independent of time is studied here. Therefore, the above equations have been modified and expressed in the following form.

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{1}{\rho}\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right) + \frac{1}{\rho}\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) \qquad (2)$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + \frac{1}{\rho}\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right) + \frac{1}{\rho}\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right) \qquad (3)$$

2.4 Energy Equation

The energy equation (First Law of Thermodynamics) is examined in laminar flow and unstable conditions with constant properties of the fluid and independent of time that its equation is expressed in the following form.

$$\rho C_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \mu\left(\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2\right) \qquad (4)$$

In the above equation it is shown that how two terms of diffusion and convection energy are associated.

2.5 Selecting turbulence solution

In an overview, the numerical simulation of turbulent flow is divided into three categories, which described above. Using the Navier-Stokes equations is the first numerical simulation. In this case, the equations bring in average time and together with a suitable turbulence model, turbulence stresses are calculated. The second numerical simulation is using the time function equation by great vortices. The third type of numerical simulation is direct method. In this way, there are vortices turbulence with different sizes in system. Second and third methods are at the first and their birth stage. In this study, because of being simple and practical of the first method, this model is used. The base of this method is that some of the basic parameters of fluids can be written as the permanent average amount and oscillatory components of time function. This classification causes to create different turbulence models (in the first method means that the Navier-Stokes equation) which is already explained. So that the average is obtained by multiplying of oscillatory components velocity, causing the Reynolds stress.

One of turbulence models should be applied to calculate the Reynolds stresses.

2.6 Line k-ε Turbulence Model

Line k-ε turbulence model due to its simplicity and frequent usage in most engineering issues has a particular importance. In this study, due to its good application in some engineering issues and its simplicity, this model is used.

2.7 SIMPLE algorithm

SIMPLE algorithm is a semi-implicit method for solving equations that are connected to each other by pressure. In this method, first the velocity field by applying pressure values and terminal velocity is calculated. Then this velocity field at the same time with the pressure field is corrected so that a truth velocity field in the continuity equation is obtained. In continue, the correction steps through these truth velocity field in the continuity equation to convergence may be repeated. Generally, steps to solve problems by using this algorithm are as follows:

- solving momentum equations
- Correcting pressure and velocity components
- Solving the energy equation
- Turbulence equations

By reviewing the convergence criteria, at this stage if the intended answers be converged, repetition process terminates, otherwise, momentum equations again using the values of pressure, solved velocity and expressed procedures are repeated.

2.8 Linear equations solution

The $TDMA$ method to solve linear equations is used in the intended program. To solve the equations of momentum, energy, the turbulent kinetic energy, and energy dissipation rate turbulence above method has been used.

3. MODELING

3.1 Geometry

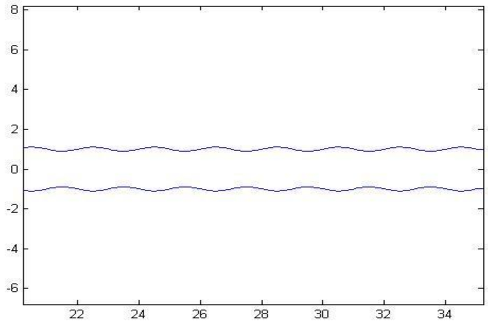


Figure 1. The geometry of solve space

In the above figure, solve space geometry is displayed. This geometry first by using a set of points which is extracted from them causes to achieve the wavy tube, and displays in MATLAB software. These points are entered Gambit and as follow determine by boundary conditions.

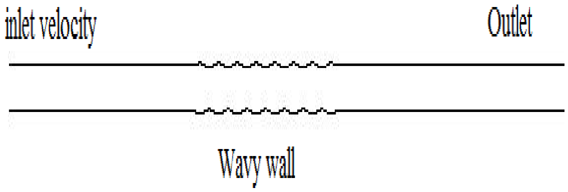


Figure 2. Geometry in Gambit solution space with boundary condition

To be able to solve the problem in this geometry numerically, must discrete equations on the solve network. At first the solve space should be networking.

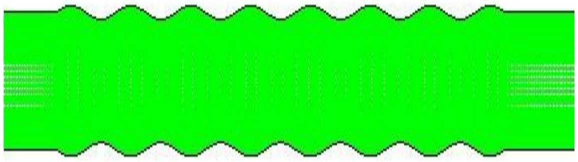


Figure 3. Networking the solve space

To be able to properly display network, a view of networking near the upper border is shown in the following figure. As that is seen, networking near the border is very little and has the ability of cross-border effects modeling.

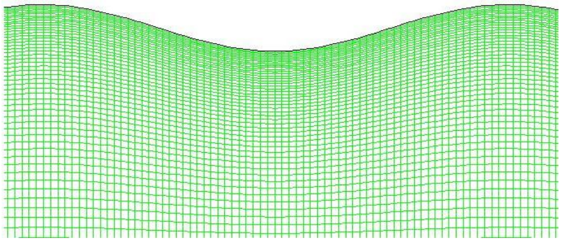


Figure 4. Networking of solve space near the border

3.2 The entry conditions and problem model

Conditions of entry and base modeling of this problem are presented in the following tables:

Table 1: the entry conditions and problem model

Velocity m/s	**0/01256**
To impose velocity	**x**
Input temperature (Kelvin)	**300**
Temperature walls of waves (Kelvin)	**400**
Temperature conditions of Other walls (Kelvin)	**Insulator**

System modeling conditions is given in the following table which examined system is a two-dimensional sample in steady state and independent of time. The turbulence model is not used for phenomena modeling at low Reynolds because results being imprecise, but in some cases turbulence model is used which is expressed in the following way. Behavior near a wall is a standard function of model.

Table 2: Model

Computing environment	Two-dimensional
Dependence on time	Stable
Turbulence model	Standard $\boldsymbol{k}$-ε
Behavior near the wall	Use standard wall function
Energy equation	Active

In the following table existing equations display in numerical solution. As is clear from the above table, six equations for modeling fluid flow and heat transfer are required. One is the continuity equation, which states that mass is not create from fluid and cannot be destroyed. Two momentum equations are required, one in the flow direction and the other perpendicular to it. Two turbulence equations are used because modeling in this project of the high Reynolds is based on a two- equation model. Also, an energy equation is used.

Table 3: Required equations and their number to modeling

Number	**Equations**
1	Continuity
2	Navier-Stokes
1	Energy
2	Turbulence

As previously explained, a numerical method is used for solving that is based on repetition. Table 4 is used to align results of the discount factors.

Table 4: The discount factors

0.3	Pressure
0.7	Momentum
0.8	Turbulence energy
0.8	Energy dissipation rate turbulence
1	Energy

The following table shows how discrete equations are. SIMPLE algorithm is in this problem and all equations have been discretization in wind direction. To obtain suitable approximate the second mode of discretization is used and all equations discrete on computational points, so as to become algebraic equations. At the present, we should define a function that specify the relationship between pressure and velocity. This function is introduced as SIMPLE algorithm.

Table 5: Discrete method

Method	Term equations
Standard	Pressure
Wind direction	Momentum
Wind direction	Turbulence energy
Wind direction	Energy dissipation rate turbulence
Wind direction	Energy

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Verification Results

In following figure verification of the results is given. As can be seen, Nusselt number obtained with acceptable accuracy adapt with what earlier in certain situations and certain Reynolds is achieved by researchers.

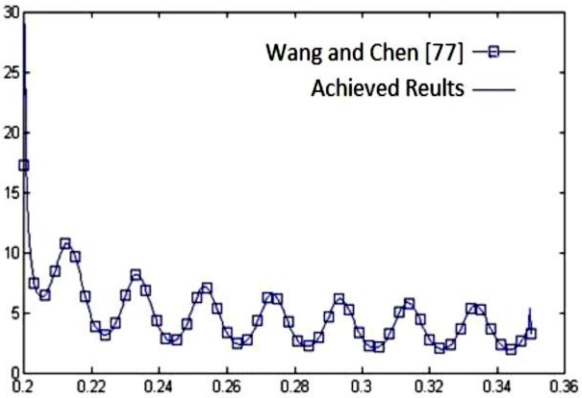


Table 5. Verification

After verification, we examine the contour and different charts consisting of geometry and in different situations.

4.2 Independence of network

Then, in the following figure the curve related to independence from network is given. As can be seen, when networks being smaller little by little changes being independent of the network size.

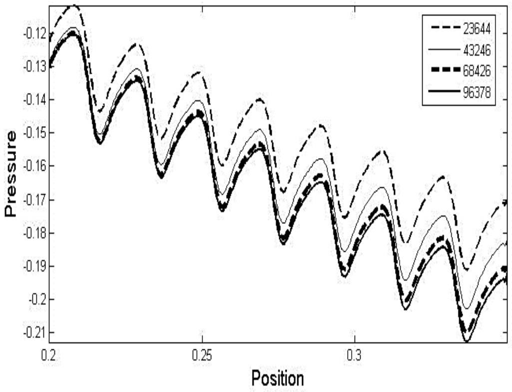


Figure 6. Independence of network

4.3 Description of Nano fluids

Nanofluids used in this thesis, is aluminum oxide in the water. The reason of using this nanofluids is its ample application in the industry that also is being used to investigate by many scientists. The related properties of the nanoparticle and the base fluid are given in the following table.

Table 6: Related properties of the nanoparticle and the base fluid

Material	**Density**	**Thermal capacity**	**Heat transfer coefficient**
water	998	4182	0/6
aluminum oxide	3970	765	40

4.4 The velocity study

As specifies from the following figure, the velocity in the central channel has the highest amount and by moving to the walls has been reduced. Two major reasons can be outlined for this reduction. One is that near the wall by sticking fluid close to the wall the velocity is reduced, and other is that being stuck in the sinus causes the velocity to be reduced. The contour related to velocity is given in the following figure.

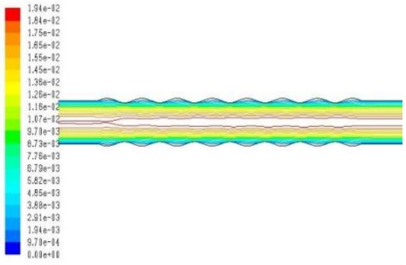


Figure 7. Velocity Contour into wavy channel

The below figure shows the contour in the direction perpendicular to the prevailing fluid. As can be seen, the contour related to vertical velocity has a very interesting shape that indicates the arrival of fluid to the sinus and its exit.

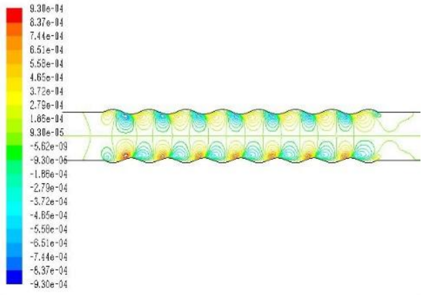


Figure 8. Vertical speed contour into a wavy channel

4.5 Vortices study

Figure below shows how vorticity changes are in the flow. As can be seen, vorticity in the central part of channel is almost zero, which means that don't constitute any vortices in the central part. By moving to the sinus sections of walls vorticity will increase.

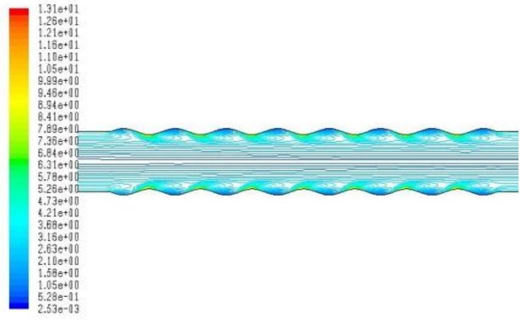


Figure 9. vorticity into wavy channel

Then, in the following figure vorticity near one of the curves of the walls has been displayed to that the results have been discussed more carefully.

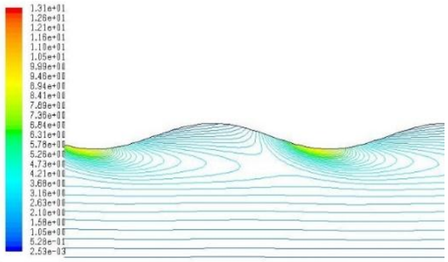


Figure 10. vorticity into wavy channel and near the wall

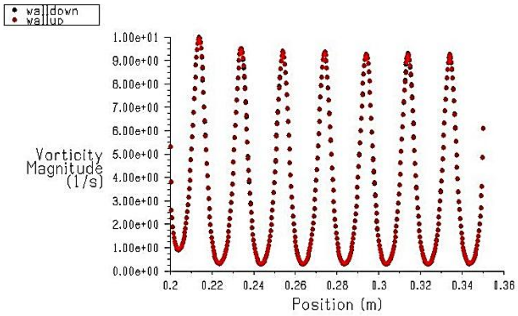
In the above figure can be seen that vorticity near the wall, being maximum where the fluid leaves wave and, therefore at output areas it is more probable to constitute vortex that caused by the adverse pressure gradient and in the related section to pressure will be fully investigated.

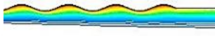
In the below figure vorticity is displayed on the upper and lower wall. As can be seen in the outflow of fluid from each curvature the vorticity is increased, and almost over moving along the channel with little slope the vorticity is decreased.

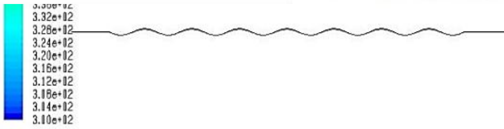
Figure 11. vorticity into wavy channel and on the walls

4.6 Pressure study

As seen in the following figure, pressure contour can be seen as a set of two behaviors. In the moving of tube direction, independent of the type of wall, there is pressure drop and so with moving in the channel direction, the pressure decreases. Other changes part includes the curvature of the walls. By arrival to the sinus area, pressure is reduced in this area and caused to flow fluid to this area. By moving along







the sinus parts little by little conditions being as the fluid in x-direction faces obstacle and, thus velocity reduces and pressure increases. What displayed in the following is the sum of these items.

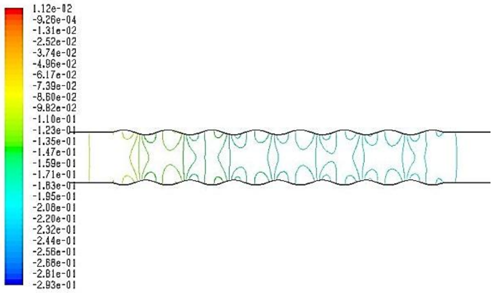


Figure 12. pressure contour into wavy channel

In the following figure the curve of the pressure coefficient variations on upper and lower walls is shown. As seen, independent of the shown fluctuations, the average value of pressure is descending that shows the pressure drop within the channel. Now we can see that the pressure fluctuates around the average value and when fluid moves into the sinus area pressure reduces, and by fluid outflow from sinus area, pressure increases. As it is specified from the figure, the variations of pressure in upper and lower part of channel are coincided.

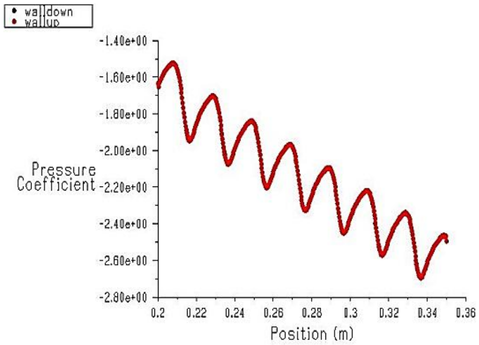


Figure 13. the curve of pressure variations within the walls of the upper and lower channel

4.7 Temperature study

As shown in the following figure, temperature has been investigated at the upper part of the wall. As can be seen, temperature near the walls has the highest amount and at the center of the channel, the temperature decreases. The remarkable thing here is that the initial parts of the sinus wall severity affect the next parts, and as we can see, the thickness of the boundary layer has increased by moving along the channel, therefore it is expected that by moving along the channel, the heat transfer rate is decreased and as a result Nusselt number is reduced.

Figure 14. Temperature contour into wavy channel

4.8 Entropy production study

The contour of entropy production has been shown in the following figure. As has been stated in the previous section, temperature increasing is occurred near the upper boundary that cause upper irreversible in the system, and therefore increases the entropy of the system.

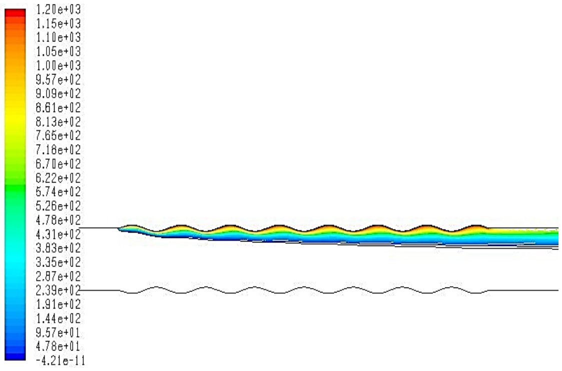


Figure 15. the contour of entropy production in wavy channel

4.9 Velocity Vectors

In the following and in the below figure, the velocity vectors are shown. As can be seen in most parts, the direction of dominant vector is x-axis, but flow enters in curling parts by low speed, and then exists that by the size of velocity vectors is obvious in the figure.

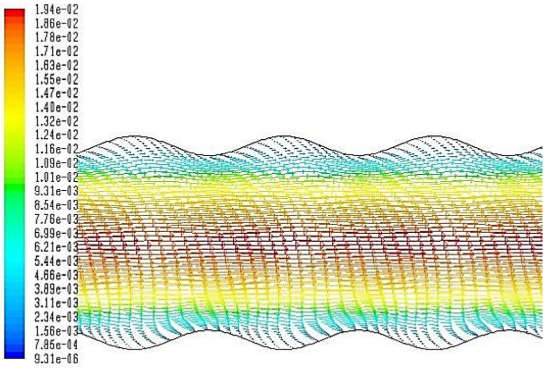


Figure 16. Velocity Vector in wavy channel

4.10 The effect of phase changes in walls

If the defining relation of walls is considered as follow, one of the parameters that can be changed is the phase difference between the walls that is displayed by φ.

$$\frac{y}{H} = 1 + \sin\left(\frac{\pi x}{H} + \varphi\right) \quad (5)$$

The results of the phase difference changes are reported below. As can be seen, Nusselt number increases by increasing phase, and this increase is more visible with increasing of the nanofluids concentration.

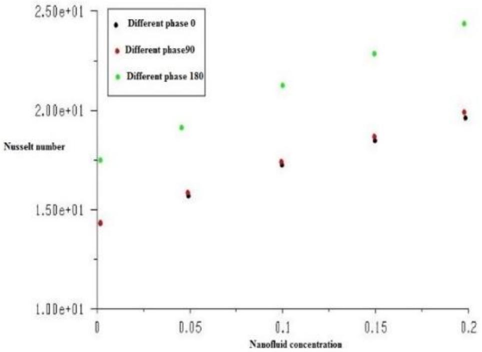


Figure 17. Nusselt number in different phases

4.11 The effect of changes to the nanofluids concentration

In the following and below figure, the effects of nanofluids concentration on Nusselt number have been reported. As can be seen with increasing the concentration of nanofluids, Nusselt number increases and this increase in initial parts is more visible.

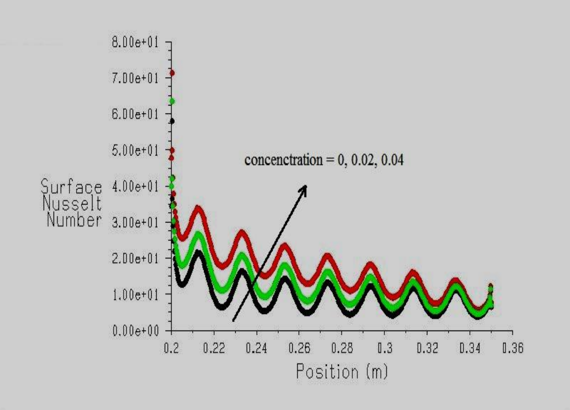


Figure 18. Nusselt number in different concentrations

As can be seen with increasing concentration, Nusselt number and thus the heat transfer rate will change and increase.

5. CONCLUSION

In this thesis, heat transfer and fluid flow in a channel are examined which channel walls are wavy. For this purpose, different equations of continuity, momentum, energy and turbulence are studied that in this thesis the standard turbulence k-ε method is used. For modeling FLUENT software is used and computing environment is drawn in Gambit. The networked environment enters to FLUENT and solve continues numerically and by repeating in the finite mass method to achieve the results. The results obtained in this thesis summarized as follow. Velocity in the center part of channel has the highest amount and by moving to the walls has been reduced. Vorticity in the central part of channel is almost zero, which means that don't constitute any vortices in the central part. By moving to the sinus sections of walls vorticity will increase.

At the outflow of fluid from each curve, the vorticity increases and almost at moving along the channel with a slight slope the vorticity will be reduced. By moving across the channel, the pressure decreases.

Whenever the fluid moves into the sinus area the pressure is reduced, and the decreased pressure increases by exiting fluid from sinus area. Temperature near the wall has the greatest amount and by moving to the walls has been reduced. The thickness of the boundary layer temperature increases by moving along the channel and, therefore it is expected that by moving along the channel, the heat transfer is reduced, and so Nusselt number reduces. Temperature increase occurs in the vicinity of the upper boundary that cause to bring high irreversibility in the system, and so increases the system entropy. In most areas dominant vector direction is X-axis, but flow enters in curling parts by low speed, and then exists. By increasing phase difference, Nusselt number increases that changes are associated to the nanofluids concentration. By increasing nanofluids concentration, Nusselt number increases and this increase is more visible at the initial parts.

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