Numerical investigation of thermal pulsating alumina/water nanofluid flow over three different cross-sectional channel

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Abstract

Purpose – The purpose of this study is to investigate the pulsating flow in a three-dimensional channel. Channel flow is laminar and turbulent. After validation, the effect of different channel cross-sectional geometries (circular, hexagonal and triangular) with the pulsating flow are investigated. For this purpose, the alumina nanofluid was considered as a working fluid with different volume percentages (0 per cent [pure water], 3 per cent and 5 per cent).

Design/methodology/approach – In this study, the pulsatile flow was investigated in a three-dimensional channel. Channel flow is laminar and turbulent.

Findings – The results show that the fluid temperature decreases by increasing the volume percentage of particles of Al_2O_3; this is because of the fact that the input energy through the wall boundary is a constant value and indicates that with increasing the volume percentage, the fluid can save more energy at a constant temperature. And by adding Al_2O_3 nanofluid, thermal performance improves in channels, but it should be considered that the use of nanofluid causes a pressure drop in the channel.

Originality/value – Alumina/water nanofluid with the pulsating flow was investigated and compared in three different cross-sectional channel geometries (circular, hexagonal and triangular). The effect of different volume percentages (0 per cent [pure water], 3 per cent and 5 per cent) of Al_2O_3 nanofluid on temperature, velocity and pressure are studied.

Keywords Computational fluid dynamics, Alumina/water, Cross-sectional geometry, Pulsate nanofluid flow

Paper type Research paper

1. Introduction

Increased heat transfer by moderate flow pulsation has therefore been considered, as vibrational behavior anyway occurs in many practical applications (Bagheri *et al.*, 2019; Rama Narasimha *et al.*, 2010; Hoseinzadeh *et al.*, 2019). Another method to enhance heat transfer is the use of nanofluids, which has been widely considered in recent years (Hoseinzadeh *et al.*, 2017; Hoseinzadeh *et al.*, 2018; Hoseinzadeh *et al.*, 2019). Because of their high thermal conductivities and their distribution in the base fluid, nanoparticles increase the thermal conductivity of the fluid, which is considered one of the basic parameters of heat transfer. It is known that increases in the volume percentages of water and aluminum oxide, as well as water and copper oxides (Safaei *et al.*, 2014; Hoseinzadeh *et al.*, 2019; Wakif, 2019), increase the conductivity coefficient of nanofluid. Metal nanofluids of ethylene glycol and copper (Cu) with 0.6 Vol.% increase the thermal conductivity by 14 per cent (Wakif *et al.*, 2017; Esfe *et al.*, 2015; Goodarzi *et al.*, 2019; Bahrami *et al.*, 2015; A. Reddy and Chamkha, 2018). Usually, numerical or experimental simulations are used to examine the behavior and heat transfer of the nanofluids in pipe channels under particular conditions. These days, many articles compared the thermal performance of water, ethylene glycol, alumina and carbon nanotube nanofluids (Rahimi Gheynani *et al.*, 2019; Mousavi *et al.*, 2019; Mahdy and Chamkha, 2018; Madhu *et al.*, 2016; Vemula *et al.*, 2016; Goodarzi *et al.*, 2019; Gholamalizadeh *et al.*, 2019; Rahimi Gheynani *et al.*, 2019; Selimefendigil and Chamkha, 2019; Goodarzi, 2019; Akbari, 2016; Malvandi *et al.*, 2015; Goshayeshi *et al.*, 2016; Goshayeshi *et al.*, 2016; Goshayeshi *et al.*, 2015).

Pulsating flow is one of the critical types of flows used early in the analysis of the propagation of sound waves and the study of the sustainability of the laminar flows (Hemida *et al.*, 2002). The analytical solution provided by Blythman *et al.* (2019) was in contrast to the results of the heat transfer of laminar pulsating flow in a rectangular channel. They stated that the heat transfer for the pulse system is reduced. Fattahi *et al.* (2012) studied the effect of wave wall on combinational heat transfer of water–aluminum oxide nanofluid in a cavity with a movable door using the Boltzmann grid method. They concluded that the increase in the amplitude of the wave wall reduced the mean value of the Nusselt number at high Richardson numbers.

Rahgoshay *et al.* (2012) studied the flow of laminar pulsating nanofluid in a constant temperature pipe numerically. Akdag *et al.* (2016) and Akdag *et al.* (2014) conducted his studies on a channel whose part of the bottom wall was under the thermal flux, and a portion was subjected to adiabatic flux, with Reynolds number of 125 and Prandtl number of 0.71.

Li *et al.* (2016) performed their studies in the range of laminar flow on a pipe with expanded flow conditions. The constant heat flux wall, taking into account the pulsating inlet velocity and pressure gradient and concluded that increasing the pulsation amplitude, increases the heat transfer rate in the circular cylinder. Mehta and Khandekar (2015) numerically studied the laminar pulsating flow in a constant temperature pipe and two parallel plates with constant thermal flux. They used FLUENT software to solve the problem and used the Simple algorithm to discriminate the equations and conclude that at the frequency of 1-10 Hz and amplitude of 0.2-0.4 m, increasing the frequency of pulsations, the amplitude of the pulsations and the Reynolds number had no significant effect on heat transfer.

Akbari and Saidi (2018) performed their studies on the turbulent flow in the pipe experimentally and found that by placing a pulsating source in the flow input, the average Nusselt number at constant frequency increases with increasing Reynolds number.

In this study, the effects of various parameters such as volume fraction of nanoparticles, Reynolds number and pressure drop are investigated. The effect of the difference in the volume percentage of different nanofluid volume percentages (0, 3 and 5) is investigated. In addition, the impact of different geometries (circular, hexagonal and triangular) of the channel cross-section with nanofluid was studied. According to the results of using high percentages of nanofluid, the same increase in heat transfer efficiency is obtained without dependence on geometry.

2. Problem definition

In this study, three cross sections are considered: a channel with a circular cross-section, a channel with a hexagonal cross section and, lastly, a channel with an equilateral triangular cross section. To allow a better comparison of the results, the scale and dimensions of the sections of the cross-section areas were considered equal in all three cases. The length of the channel in all three cases is 2 m. Figure 1 depicts the three models with the meshes used. The dimensions of the channels are shown in Table I.

After having introduced three specific geometries, the results are now investigated. Figure 2 shows the change in the thermal flux of pure water flowing through a circular channel as a function of time. It is clear that it takes many times for the transient behavior to be reached to steady conditions. Based on this observation, all simulation results presented further have been allowed to ensure that mostly steady conditions were reached.

Also, in this research, alumina nanofluid was used in channels. Table II shows the physical properties of nanoparticles of alumina (Al_2O_3) (Hoseinzadeh *et al.*, 2019).

3. Modeling and validation

The discrete numerical transfer equation includes an unspecified scalar variable in the cell center. This equation is generally nonlinear. A linearized form of this equation can be presented as follows:

$$a_p \varphi = \sum_{nb} a_{nb} \varphi_{nb} + b \tag{1}$$

The sub-index nb is related to the adjacent cell a_p and a_{hb} are the linear values associated with φ_{nb}. Similar equations can be written for each cell in the mesh.

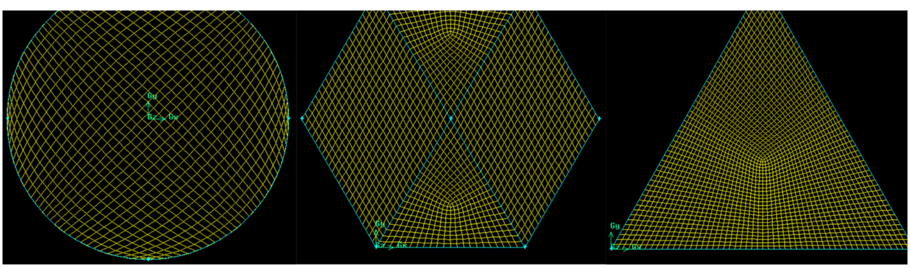

Figure 1. Three different sections of the considered channels (circular, hexagonal and triangular)

Table I. The geometrical dimensions of the three channels examined

Cross-sectional geometry	Input surface area (m^2)	Diameter or side length (m)	Channel length (m)
Circular	3.14×10^{-2}	0.2	2
Hexagonal	3.14×10^{-2}	0.11	2
Triangular	3.14×10^{-2}	0.27	2

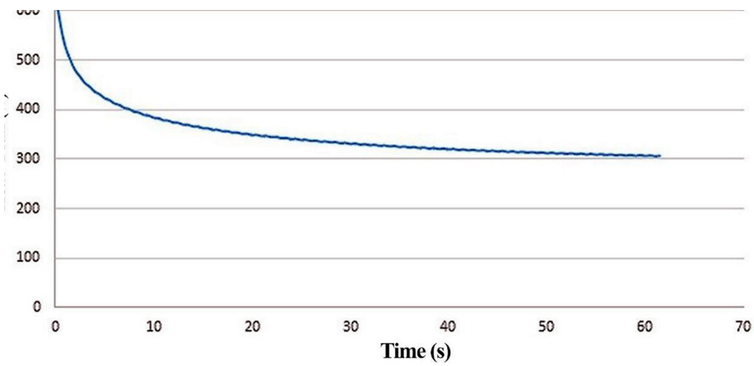

Figure 2. The variations of wall heat flux in a circular channel with pure water

Table II. Physical properties of nanoparticles

Nanoparticle type	Density	Conductivity	Heat capacity
Al_2O_3	3900	36	773

The Simple algorithm is used for the dependence between velocity and pressure, which uses the relationship between pressure and velocity correction to satisfy the mass conservation law and obtain the field of pressure. The second-order discretization is used for the momentum equation and, for other options, including kinetic energy and turbulence dissipation. And the first-order discretization is used for the volume ratio transfer *equation*.

3.1 k-ε modeling

Power, cost-effectiveness and acceptable accuracy for a wide range of turbulence stream and its popularity in industrial flows and simulations with heat transfer caused that the *k-ε* standard were chosen for this study. The simplest complete turbulence models are two-equation models in which two separate transfer equations are solved to determine the turbulence velocity and longitudinal scales independently. The standard *k-ε* model in ANSYS FLUENT is provided with this class of the turbulent model (Yari *et al.*, 2015; Yari *et al.*, 2014; Goodarzi *et al.*, 2019; Kohzadi *et al.*, 2018; Hosseinzadeh *et al.*, 2019; Hoseinzadeh, 2019; Hoseinzadeh *et al.*, 2019; Hoseinzadeh and Azadi, 2017; Yousef Nezhad and Hoseinzadeh, 2017).

The equation of momentum is expressed as follows (Versteeg and Malalasekera, 2007):

$$\frac{\partial \rho U}{\partial t} + \nabla . (\rho U . U) = -\nabla p' + \nabla . \left(\mu_{eff} \left(\nabla U + (\nabla U)^T \right) \right) + S_M \quad (2)$$

where S_M is the sum of the volumetric forces, μ_{eff} is the effective viscosity that also includes turbulence and p' is the modified pressure defined as:

$$p' = p + \frac{2}{3}\rho k + \frac{2}{3}\mu_{eff}\nabla . U \tag{3}$$

The $k - \varepsilon$ model, like the next zero equation, is based on the concept of eddy viscosity. Thus (Versteeg and Malalasekera, 2007):

$$\mu_{eff} = \mu + \mu_t \tag{4}$$

where μ_t is the turbulence viscosity. The $k - \varepsilon$ model assumes that viscosity of turbulence is related to the kinetic energy of turbulence and the degradation rate, in other words:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \tag{5}$$

The quantities k and ε are obtained directly from the differential transport equations of kinetic energy of turbulence and the degradation rate of turbulence:

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho U k) = \nabla \cdot \left(\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right) + P_k - \rho \varepsilon \tag{6}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho U \varepsilon) = \nabla \cdot \left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right) + \frac{\varepsilon}{k} (C_{\varepsilon 1}(P_k) - C_{\varepsilon 2} \rho \varepsilon) \tag{7}$$

P_k is the production of turbulence because of viscous forces defined as follows:

$$P_k = \mu_t \nabla U \cdot (\nabla U + \nabla U^T) - \frac{2}{3} \nabla \cdot U (3\mu_t \nabla \cdot U + \rho k) \tag{8}$$

For incompressible flows $\nabla .U$ is small and the second term of the right side of the above equation does not have much effect on production. The constant coefficients of the above model are given in Table III.

In the following, the validation and independence of the network are investigated. Then, the results related to the effect of geometry are assessed, and finally, the effect of using a nanofluid is evaluated.

3.2 Pulsating flow modeling

The input function of pulsating flow is as follows (Hoseinzadeh *et al.*, 2019):

Table III. Constant coefficients of turbulence of the $k - \varepsilon$ equation (3)

Coefficient	σ_ε	σ_κ	$C_{\varepsilon 2}$	$C_{\varepsilon 1}$	C_μ
Value	1.3	1	1.92	1.44	0.09

$$u = u_{avg}(1 + A \cdot \sin(2\pi \mathrm{St}\, t)) \tag{9}$$

where U_{avg} represents the mean velocity, A represents the pulsation amplitude and St denotes the Strouhal number indicating the pulsation parameter for all different geometries (circular, hexagonal and triangular). The input values used in this investigation are given in Table IV. For modeling pulsating flow in FLUENT, it is necessary to use user-defined functions (UDFs cod).

4. Results and discussion

4.1 Effect of cross-sectional geometry on thermal flux

This section investigates the effect of channel shape on heat transfer parameters. Figure 3 shows the flux variation of the three-channel configurations with circular, hexagonal and triangular cross-sections. As it is clear from the results, the circular and hexagonal channels transfer higher flux to the flow than the triangular channel. On the other hand, the circular and hexagonal channels have a close performance, which is because of their stable geometry.

4.2 Effect of cross section on temperature

Figure 4 shows the effect of the geometry of the channel cross-section on the output temperature in degrees Kelvin. From Figure 3, the thermal flux in the circular and hexagonal channels is close to each other and higher than for the triangular channel. Because of the higher input flux into these two channels and their close values, it is expected that the output temperature for the circular and hexagonal channels should be close, with the temperature in the triangular channel being lower. This is indeed as expected, and in Figures 4 and 5, respectively, the output temperatures and pressure drop of the circular and hexagonal channels are close and higher than the output temperature for the triangular channel.

Table IV. Input flow parameters

Input parameter	Mean velocity (m/s)	Pulsation amplitude	Strouhal no. (St)
Numerical value	5×10^{-4}	1	1

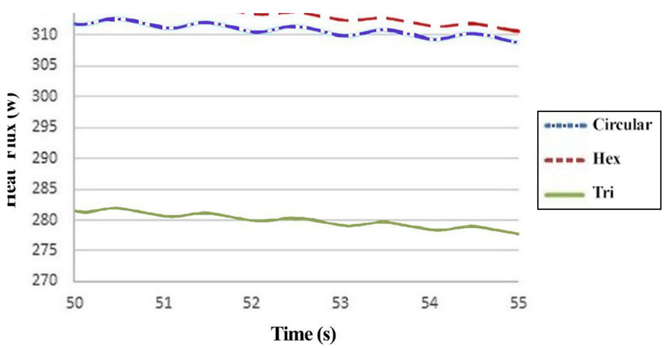

Figure 3. The effect of cross-section shape on heat flux of the wall

4.3 Effect of nanofluid in circular cross-sectional channel

Figure 6 shows the effect of using nanofluid at different volume percentages of (0 per cent [pure water], 3 and 5 per cent). It is expected that the physical properties of the thermal conductivity increase, and the heat capacity of the fluid decrease by adding (Al_2O_3) nanoparticles to pure water. These changes increase the potential of the fluid to absorb heat. According to Figure 6, the heat flux through the wall increases by adding the nanofluid.

4.4 Effect of nanofluid in hexagonal cross-sectional channel

Figure 7 shows the effect of using nanofluid at different volume percentages of (0 per cent [pure water], 3 and 5 per cent). As expected, the physical properties of the thermal conductivity increase, and the heat capacity of the fluid decreases by adding (Al_2O_3) nanoparticles to water. These changes increase the potential of the fluid to absorb heat. According to Figure 7, the heat flux through the wall increases by adding the nanofluid.

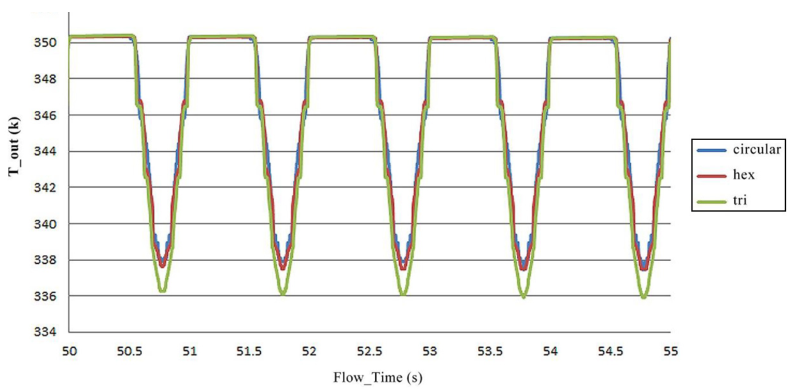

Figure 4. Effect of cross-section shape on output temperature

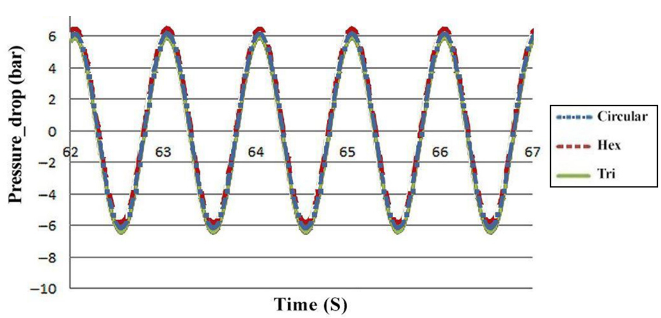

Figure 5. Effect of cross-section shape on pressure drop

4.5 Effect of nanofluid on temperature, velocity and pressure

In this section, the effect of different volume percentages (0 per cent [pure water], 3 and 5 per cent) of Al_2O_3 nanofluid on temperature, velocity and pressure is studied in the circular cross-sectional channel with Figures 7-9 that show the contours of those parameters.

In Figure 8, the temperature contours are compared for different volume percentages (0 per cent [pure water], 3 and 5 per cent) of Al_2O_3 nanofluid. As can be seen, the temperature increases during the pipe, which causes a regular rise of temperature on the outside of the pipe. Also, the fluid temperature is decreased by increasing the volume of Al_2O_3 nanoparticles. Accordingly, increasing the percentage of Al_2O_3 nanofluid, it can save more energy at a constant temperature.

In Figure 9, the velocity contours are compared for different volume percentages (0 per cent [pure water], 3 and 5 per cent) of Al_2O_3 nanofluid. As can be seen, the maximum velocity at the inlet border is lower than for the rest of the path. As shown in this figure, the maximum velocity increases with the expansion of the boundary layer inside the channel. Also, the periodic velocity changes with the time that the graph of the velocity changes in the input. Plus, the velocity in the channel changes with the evolution of inlet velocity in

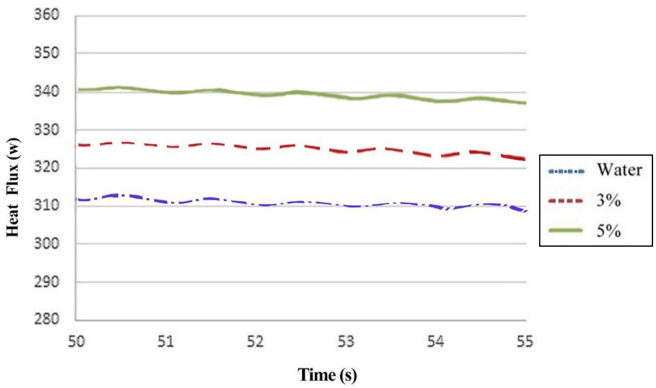

Figure 6. The effect of nanoparticle concentration in the channel with circular cross-section

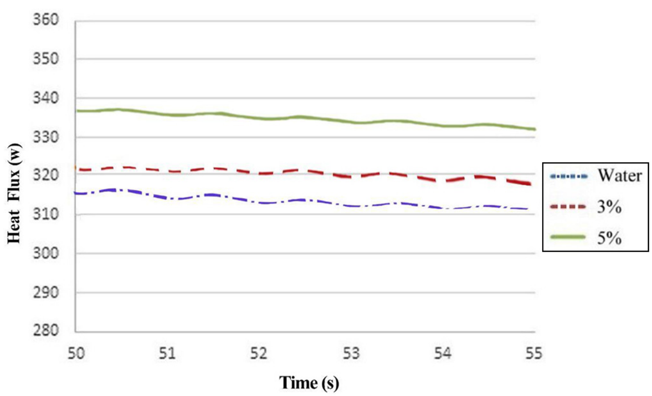

Figure 7. The effect of using nanofluid in channel with hexagonal cross-section

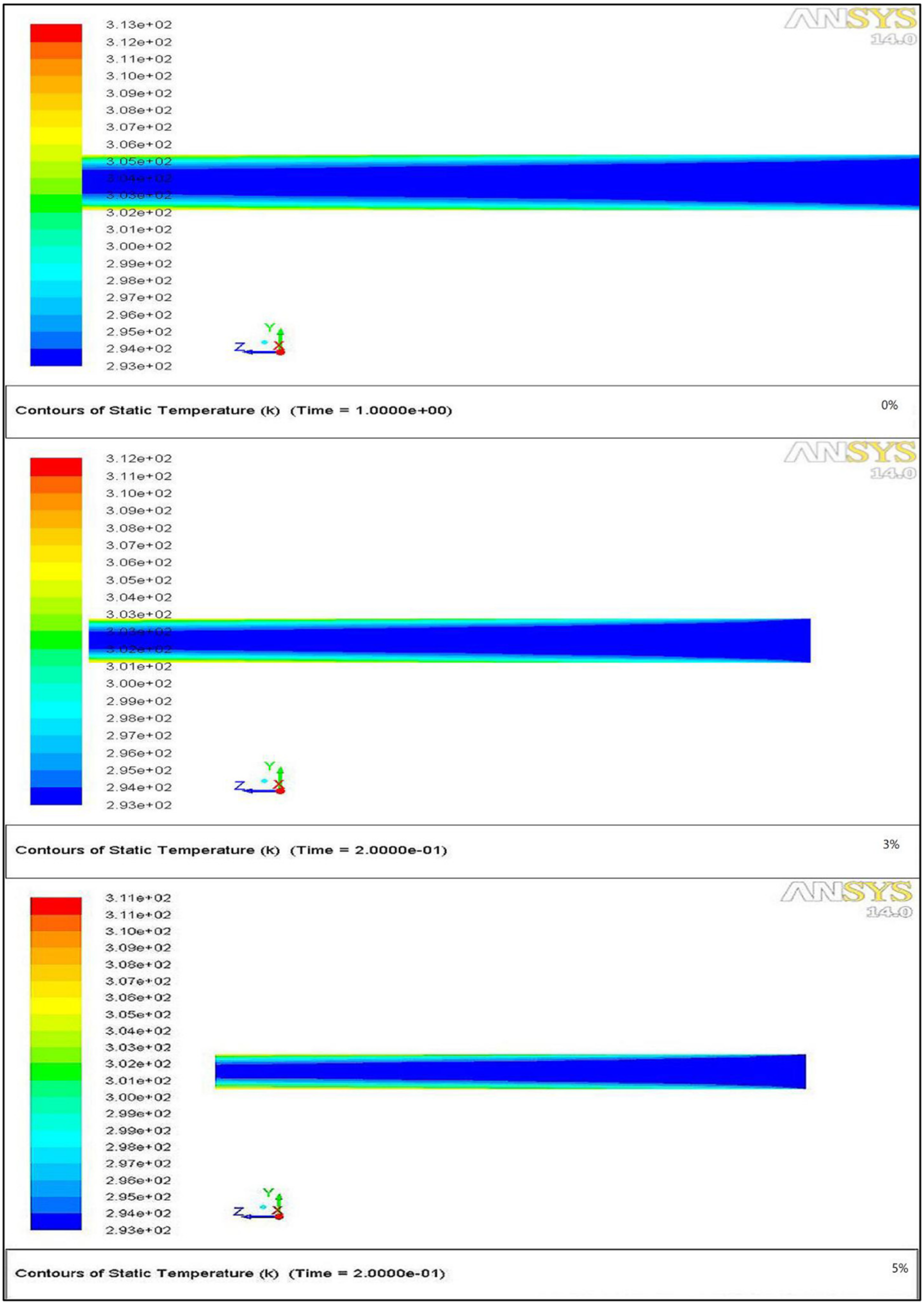

Figure 8. Temperature contours for different volume percentages (0 per cent [pure water], 3 and 5 per cent) of Al_2O_3 nanofluid

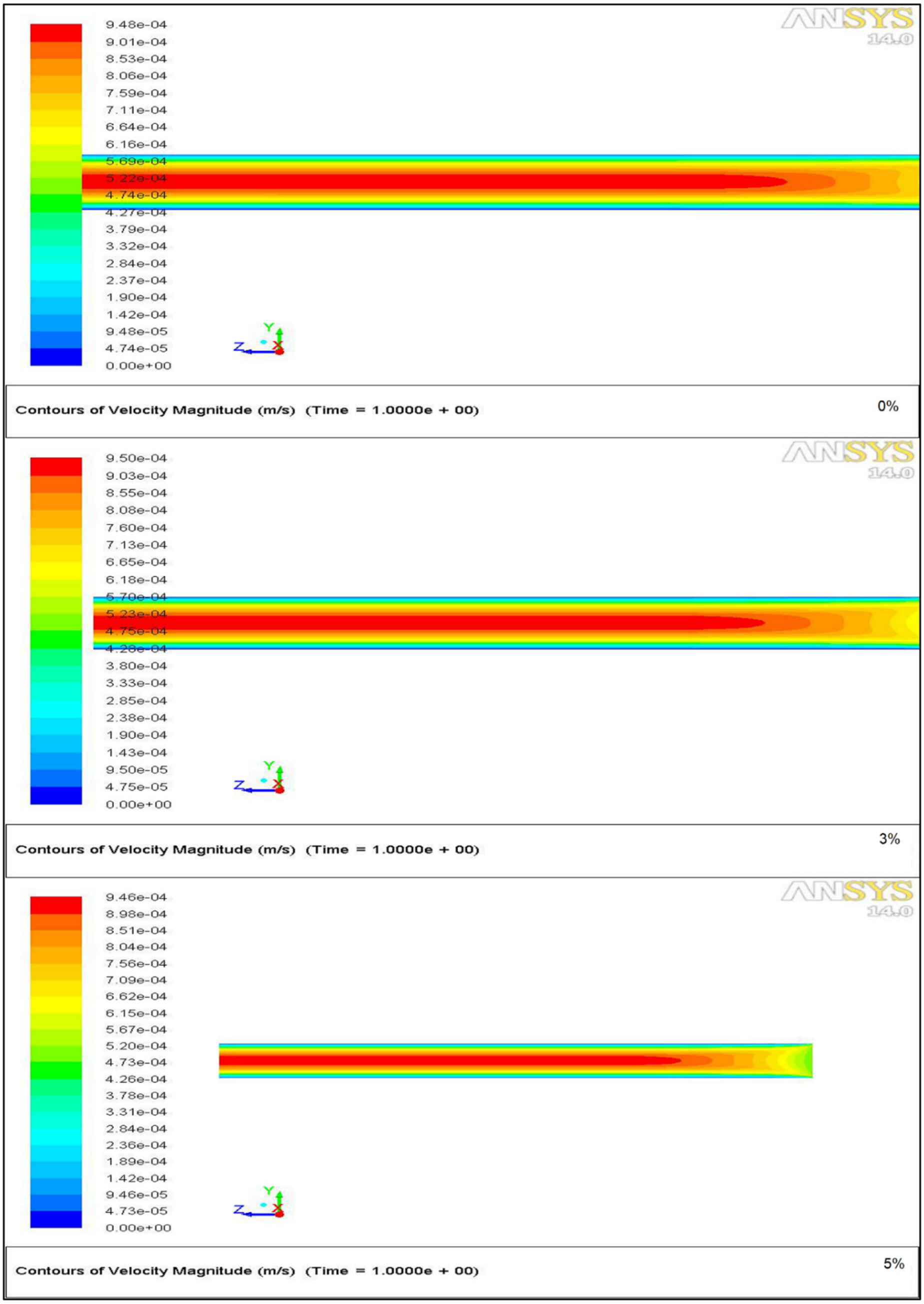

Figure 9. Velocity contours for different volume percentages (0 per cent [pure water], 3 and 5 per cent) of Al_2O_3 nanofluid

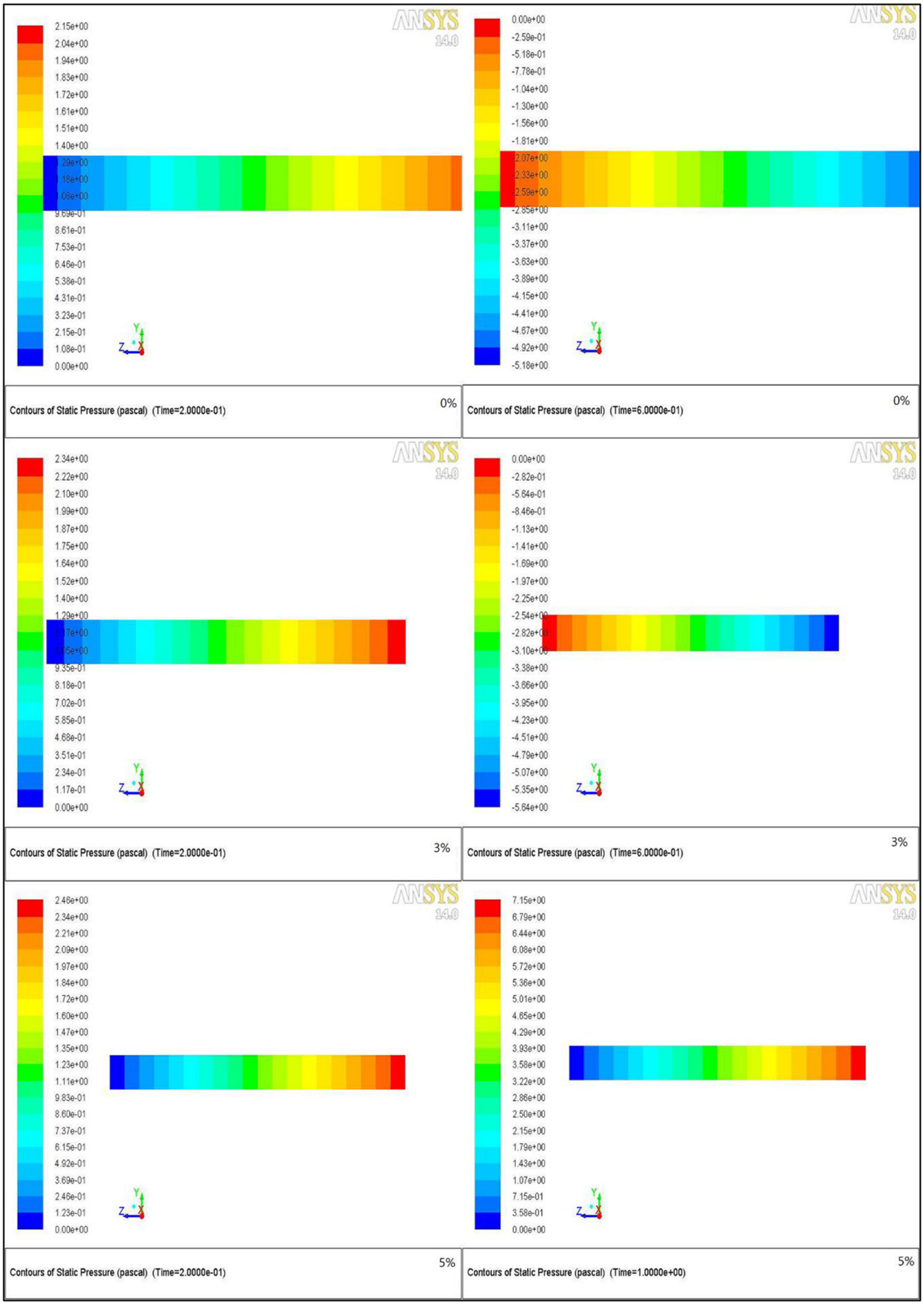

Figure 10. Pressure contours for different volume percentages (0 per cent [pure water], 3 and 5 per cent) of Al_2O_3 nanofluid

terms of time. As observed, there is not much difference in the velocity contours for nanofluids at different volume percentages because the change in volume percentages (0 per cent [pure water], 3 and 5 per cent) does not have much effect on the viscosity.

In Figure 10, the velocity contours are compared for different volume percentages (0 per cent [pure water], 3 and 5 per cent) of Al_2O_3 nanofluid. The pressure changes are so insignificant, and on the other hand, pressure difference pulsates with the pulsation of the velocity, which can be observed in the displayed contours. As a result, the surface layer profile formed inside the pipe does not change much. Besides, because of the fact that the characteristics affecting the momentum equation do not change dramatically, and also it cannot be seen several variations in pressure constants for different volume percentages.

5. Conclusion

In this research, the effects of pulsating flow on heat transfer are investigated for channels with three different cross-sectional geometries (circular, hexagonal and triangular). In addition to the industrial applications of pulsating flow, the use of pulsating flow increases the heat transfer. First, the influence of the geometries of the channel cross-section and then the effect of different percentages of Al_2O_3 nanofluid (0 per cent [pure water], 3 and 5 per cent) in the channels with the pulsating flow are investigated. Since the use of circular and hexagonal channels is cost-effective, because they do not produce additional pressure. And by adding Al_2O_3 nanofluid, the thermal performance improves in channels, but it should be considered that the use of nanofluid causes a pressure drop in the channel.

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