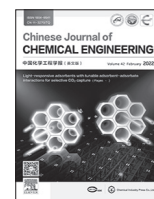




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Full Length Article

Thermal performance and entropy generation for nanofluid jet injection on a ribbed microchannel with oscillating heat flux: Investigation of the first and second laws of thermodynamics



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ABSTRACT

In current numerical study, forced flow and heat transfer of water/NDG (Nitrogen-doped graphene) nanofluid in nanoparticles mass fractions (ϕ) of 0, 2% and 4% at Reynolds numbers (Re) of 10, 50, 100 and 150 are simulated in steady states. Studied geometry is a two-dimensional microchannel under the influence of nanofluid jet injection. Temperature of inlet fluid equals with $T_c = 293$ K and hot source of microchannel is under the influence of oscillating heat flux. Also, in this research, the effect of the variations of attack angle of triangular rib (15° , 30° , 45° and 60°) on laminar nanofluid flow behavior inside the studied rectangular geometry with the ratio of $L/H = 28$ and nanofluid jet injection is investigated. Obtained results indicate that the increase of Reynolds number, nanoparticles mass fraction and attack angle of rib leads to the increase of pressure drop. By increasing fluid viscosity, momentum depreciation of fluid in collusion with microchannel surfaces enhances. Also, the increase of attack angle of rib at higher Reynolds numbers has a great effect on this coefficient. At low Reynolds numbers, due to slow motion of fluid, variations of attack angle of rib, especially in angles of 30° , 45° and 60° are almost similar. By increasing fluid velocity, the effect of the variations of attack angle on pressure drop becomes significant and pressure drop figures act differently. In general, by using heat transfer enhancement methods in studied geometry, heat transfer increases almost 25 %.

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1. Introduction

The increase of heat transfer in different industries and equipment with decreasing related expenses and improving convection heat transfer in novel cooling fluids, called nanofluids, has made the researchers to analyze the use of nanofluids in various engineering problems. Flow of suspension fluid with nanoparticles have been investigated by [1,2] due to the broad application of the nanofluid in food, industry area, and manufacturing of microdevices areas.

By developing technologies especially in electronic industry and producing low-weight parts in small dimensions, some problems

have been emerged in cooling of these parts. Due to the significant heat generation in modern microelectronic systems and parts and reduction of the efficiency of this equipment because of heat concentration in a limited space, the use of compatible and novel cooling systems is demanded [3–8].

Microchannels and minichannels, due to their dimensional characteristics and high potential in removing higher temperature have attracted the researchers. Also, another efficient heat transfer enhancement method is using nanofluid jet injection in channel with cross-flow which can be used for optimizing physical capabilities of jets as well as thermal capabilities of nanofluid. Therefore, numerous studies have been carried out about heat transfer enhancement methods including using nanofluid jet injection and rough surfaces. Zang and New [9] experimentally investigated the parallel twin jets in cross-flow and declared that, jump and

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penetration of fluid in twin jets are more than single jet and by increasing the space between two jets and the velocity of jet injection, this issue becomes more significant. Akbari *et al.* [10] investigated non-Newtonian nanofluid behavior in a 2D rectangular microchannel and revealed that, adding solid nanoparticles with different diameters has greater effect on heat transfer enhancement than nanoparticles with large radius and at higher Reynolds numbers, Nusselt number significantly enhances. Alipour *et al.* [11] numerically studied the use of nanofluid with various mass fractions and Reynolds numbers in a trapezoidal microchannel and concluded that, using appropriate rib form leads to the significant reduction of pumping power, friction factor and pressure drop and consequently, the enhancement of performance evaluation criterion (PEC).

Gravndyan *et al.* [12] numerically investigated forced convection of nanofluid inside a ribbed channel under the influence of constant heat flux and found that, increase of Reynolds number and nanoparticles mass fraction results in the enhancement of average Nusselt number and pressure drop. Wegner *et al.* [13] numerically investigated the effect of jet injection angle to cross-flow jet and confirmed that, jet injection with the angle contrary with cross-flow creates better conditions for mixture of two flows. Barik *et al.* [14] numerically analyzed nanofluid flow with jet injection in cross-flow jet. Torshizi *et al.* [15] and Zahmatkesh *et al.* [16] numerically investigated water/Cu and water/ Al_2O_3 nanofluids in microchannels and cross-flow jets using single-phase, two-phase and Eulerian-Eulerian models and found that, Eulerian-Eulerian model predicts more heat transfer than other models.

Akbari *et al.* [17] numerically simulated 2D flow and heat transfer of a nanofluid in a rectangular microchannel and figured out that, nanoparticles mass fraction has an insignificant effect on velocity profile; however, it affects temperature profiles which lead to heat transfer improvement. Also, by adding solid nanoparticles, pressure drop enhances and shear stress increases close to walls of microchannel. Akbari *et al.* [18] numerically simulated turbulent flow and heat transfer of water/CuO nanofluid inside a rectangular microchannel with semi-attached rib and revealed that, the most important advantage of using semi-attached rib compared to fully-attached rib, is removal of hot areas with less heat transfer behind the ribs and heat transfer improvement. Wang *et al.* [19] experimentally studied the effect of a delta-shaped vortex generator on heat transfer of cross-flow jet with constant heat flux and concluded that, presence of vortex generator leads to the increase of heat transfer which is more

obvious in rectangular vortex generator than delta-shaped vortex generator.

Akbari *et al.* [20] numerically investigated the effect of rib on laminar flow and heat transfer of water/ Al_2O_3 nanofluid with various nanoparticles mass fractions in a 3D rectangular microchannel and found that, the presence of rib has a greater effect on flow and heat transfer properties of nanofluid compared to a microchannel with no rib. Hatami and Ganji [21] numerically studied flow and heat transfer of nanofluid in microchannel with heat source and declared that, increase of aspect ratio of microchannel leads to the enhancement of Nusselt number and reduction of maximum dimensionless temperature and thermal boundary layer thickness. On the other hand, increase of nanoparticles diameter leads to the increase of temperature difference between fluid and wall and Nusselt number improvement. Halefadi *et al.* [22] investigated the optimization of thermal performance of a microchannel with heat source and indicated that, using special nanofluids results in the improvement of heat conduction and optimized thermal resistance of these nanofluids, especially in higher temperatures, is higher than pure water fluid. Gutmark *et al.* [23] experimentally investigated single and twin circular jets in cross-flow inside a wind tunnel and showed that, using two openings for jet injection leads to the enhancement of fluid jet penetration in cross-flow, therefore, its affectability on flow domain is more than a single jet. Nimbalkar *et al.* [24] numerically and experimentally investigated twin jets in cross-flow with hot water fluid in a tube with cold water and showed that, maximum average temperature of water in twin jets is higher than single jet which is due to the dominant effect of the first jet and consequently, more penetration of second jet in a cross-flow. Tambe *et al.* [25] experimentally investigated the effect of the angle of fluid jet injection with non-uniform cross-flow and by considering three angles of 30° , 45° and 60° , the maximum mixture of two flows was observed in the angle of 45° . Manca *et al.* [26] numerically investigated forced convection of nanofluid inside a ribbed channel under the influence of constant heat flux and revealed that, by increasing Reynolds number and nanoparticles mass fraction, average Nusselt number and pressure drop enhance.

According to the mentioned references, using heat transfer enhancement methods leads to the increase of friction factor and pressure drop and consequently, the increase of convection heat transfer coefficient. If heat exchangers are designed by each of these methods, heat transfer rate and pressure drop should be analyzed. In present numerical study, in order to increase heat transfer, in addition to the use of nanofluid and microchannel, the

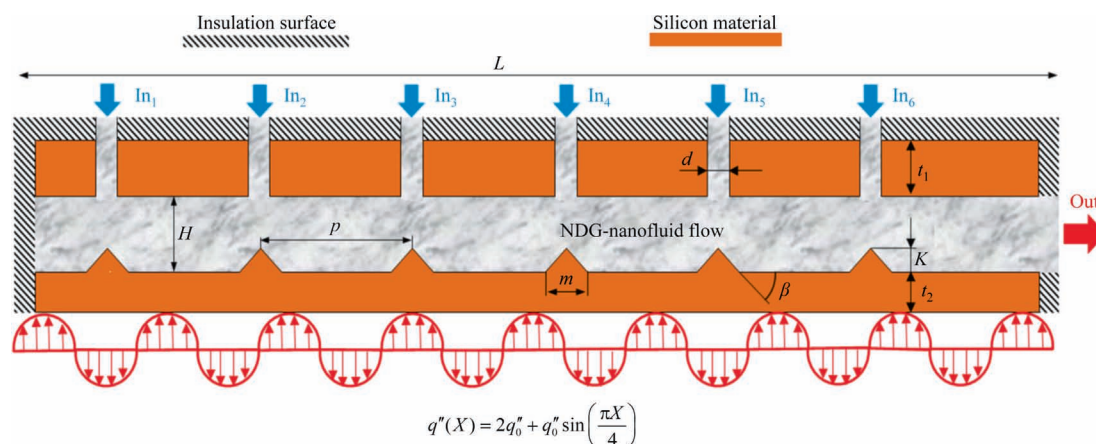


Fig. 1. Studied geometry and boundary conditions in this research.

Table 1

Dimensions of studied microchannel in this research

L/m	$\beta/(\circ)$	H/m	d/m	m/m	K/m	P/m	t_2/m	t_1/m
1400×10^{-6}	0–60	50×10^{-6}	20×10^{-6}	Variable	15×10^{-6}	200×10^{-6}	20×10^{-6}	20×10^{-6}

effect of using nanofluid jet injection and triangular ribs with different attack angles is investigated. Also, in current research, laminar flow and heat transfer of water/NDG nanofluid inside a 2D rectangular microchannel under the influence of nanofluid jet injection with triangular ribs in different attack angles are numerically investigated using finite mass method.

2. Problem Statement

In present research, in order to increase heat transfer, in addition to the use of nanofluid and microchannel, the efficiency of using nanofluid jet injection and triangular ribs with various attack angles is investigated. In this research, laminar flow and heat transfer of water/NDG nanofluid inside a 2D rectangular microchannel under the influence of nanofluid jet injection with triangular ribs in various attack angles are numerically simulated using finite mass method. Fig. 1 indicates studied 2D rectangular microchannel with nanofluid jet injection.

In current numerical study, laminar and forced flow of water/NDG nanofluid with nanoparticles mass fractions of 0, 2% and 4% at $Re = 10, 50, 100$ and 150 is simulated in steady states. Temperature of inlet fluid equals with $T_c = 293 \text{ K}$ and hot source is under the influence of oscillating heat flux with the function of $q''(X) = 2q''_0 + q''_0 \sin(\frac{\pi X}{4})$. Also, the effect of the variations of attack angle of triangular rib for the angles of $15^\circ, 30^\circ, 45^\circ$ and 60° on laminar nanofluid flow inside the microchannel with jet injection is investigated. Fig. 1 indicates the schematic and geometrical dimensions of studied 2D microchannel with six jet injections on six triangular ribs. Bottom section of microchannel is under the influence of oscillating heat flux and the top of microchannel is insulated. There are also places for nanofluid jet injection. Considered microchannel is located on a silicone surface and the thickness of this silicone surface on top and bottom sections is indicated with t_1 and t_2 , respectively. According to this figure, at the top of triangular rib, there is a place improvised for nanofluid jet injection and under the influence of attack angle of rib, it affects heat transfer and flow physics. Left side of microchannel is insulated and blocked and injected fluid is evacuated from the right side. In Fig. 1, P is the pitch of rib, K is the height of rib, H is the height of microchannel, L is the length of microchannel, β is attack angle of rib, m is the width of rib and d is the diameter of the opening of nanofluid jet injection. In this study, laminar flow and heat transfer of water/NDG nanofluid in different mass fractions, Reynolds numbers and attack angles of rib are numerically simulated. Dimensions of studied microchannel and nanofluid properties are indicated in Tables 1 and 2, respectively.

Table 2

Thermophysical properties of base fluid and nanofluid in different mass fractions [27]

Parameter	water	$\varphi = 2\%$	$\varphi = 4\%$	Silicon
$\rho/\text{kg}\cdot\text{m}^{-3}$	997.1	949.326	907.43	2239
$k/\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	0.613	0.739	0.755	134
$C_p/\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	4179	3772.6	3710.1	702
$\mu/\text{Pa}\cdot\text{s}$	0.000891	0.00107	0.00107	—

Considered nanofluid flow is laminar, Newtonian, incompressible and single-phase and radiation effects are ignored. Thermophysical properties of working nanofluid are presented based on the experimental study of Goodarzi *et al.* [27] in Table 2.

3. Governing Equations

Governing dimensional equations including continuity, momentum and energy equations are defined as follow [28],

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

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho_{\text{nf}}} \frac{\partial p}{\partial x} + \frac{\mu_{\text{nf}}}{\rho_{\text{nf}}} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (2)$$

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho_{\text{nf}}} \frac{\partial p}{\partial y} + \frac{\mu_{\text{nf}}}{\rho_{\text{nf}}} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \quad (3)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha_{\text{nf}} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (4)$$

Dimensionless equations of continuity, momentum and energy are as follow [29],

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \quad (5)$$

$$U \frac{\partial U}{\partial X} + V \frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{\mu_{\text{nf}}}{\rho_{\text{nf}} \nu_f} \frac{1}{Re} \left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} \right) \quad (6)$$

$$U \frac{\partial V}{\partial X} + V \frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{\mu_{\text{nf}}}{\rho_{\text{nf}} \nu_f} \frac{1}{Re} \left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2} \right) \quad (7)$$

$$U \frac{\partial \theta}{\partial X} + V \frac{\partial \theta}{\partial Y} = \frac{\alpha_{\text{nf}}}{\alpha_f} \frac{1}{RePr} \left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \right) \quad (8)$$

For non-dimensioning Eqs. (5)–(8), following parameters are used,

$$\begin{aligned} X &= \frac{x}{H} & Y &= \frac{y}{H} & V &= \frac{v}{u_{\text{in}}} \\ \theta &= \frac{T - T_{\text{in}}}{\Delta T} & U &= \frac{u}{u_c} \\ \Delta T &= \frac{q''_0 H}{k_f} & Pr &= \frac{\nu_f}{\alpha_f} & Re &= \frac{\rho_f \times u \times H}{\mu_f} \end{aligned} \quad (9)$$

4. Numerical Solving Method, Boundary Conditions and Assumptions

4.1. Boundary conditions

In the current study, because of using sinusoidal oscillating heat flux applied to the bottom wall of microchannel, following function is defined:

$$q''(X) = 2q_0'' + q_0'' \sin\left(\frac{\pi X}{4}\right) \quad (10)$$

Oscillating heat flux (above equation) is applied as heat flux vector along y -axis to the bottom wall. Thermal and hydrodynamic boundary conditions used in this problem are inlet velocity boundary condition in inlet section of microchannel, outlet pressure at outlet section of microchannel, oscillating heat flux to the bottom wall of microchannel, insulated wall boundary condition for external walls of microchannel and coupled temperature boundary condition for internal walls of microchannel.

4.2. Equations related to measured parameters

In this section, definitions of used parameters and equations for calculating considered parameters in this simulation are presented:

Friction factor depends on the geometrical parameters of channel and it is calculated by following equation [30]:

$$C_f = \frac{2 \times \tau_w}{\rho u_{in}^2} \quad (11)$$

Average Nusselt number can be calculated as follow [31]:

$$Nu_{ave} = \frac{h \times H}{k_f} = \frac{q_0''}{k_f(T_w - T_m)} \quad (12)$$

where T_w is microchannel wall temperature and T_m is average Bulk temperature. Performance Evaluation Criterion (PEC) is defined as follow [32]:

$$PEC = \frac{\left(\frac{Nu_{ave}}{Nu_{ave, \phi=0}}\right)}{\left(\frac{f}{f_{\phi=0}}\right)^{1/3}} \quad (13)$$

Pressure drop at the inlet and outlet sections of microchannel is defined as follow [33]:

$$\Delta P = P_{in} - P_{out} \quad (14)$$

Thermal resistance of hot wall of microchannel is calculated by following equation [34]:

$$\begin{aligned} \bar{R} &= \frac{T_{max} - T_{min}}{q_0'' \times A} = \frac{T_{max} - T_{in}}{q_0'' \times A} \rightarrow A = W \times L \rightarrow R = \bar{R} \times W = \\ &\frac{T_{max} - T_{min}}{q_0'' \times L} \rightarrow R = \frac{T_{max} - T_{min}}{q_0'' \times L} \end{aligned} \quad (15)$$

Table 3

Average Nusselt number and its enhancement percentage compared to base fluid for $\phi = 2^\circ$

C_{fave}	Nu_{ave}	Grid size
0.008052	23.013	28,577
0.007885	20.0217	38,558
0.007846	18.1717	50,497
0.00777	18.1015	77,503
0.00769	17.859	108,552

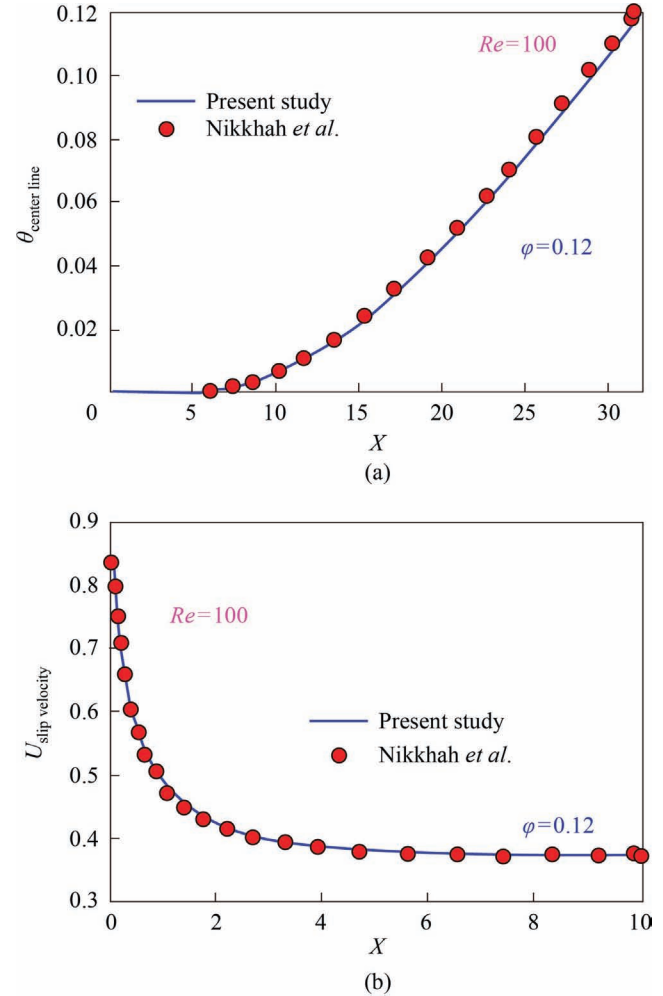


Fig. 2. Validation of this study with numerical study of Nikkhah et al. [53].

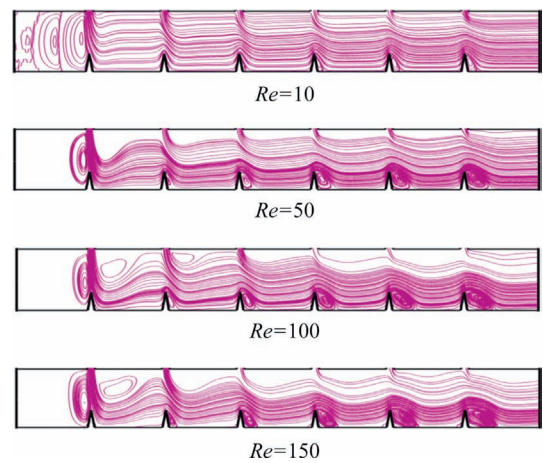


Fig. 3. Streamlines contours with the increase of Reynolds number for pure water fluid in attack angle of 60° .

In Eq. (15), T_{max} , T_{min} , A and q_0'' are respectively the maximum temperature of bottom wall, minimum temperature (inlet fluid temperature), cross section of applied heat

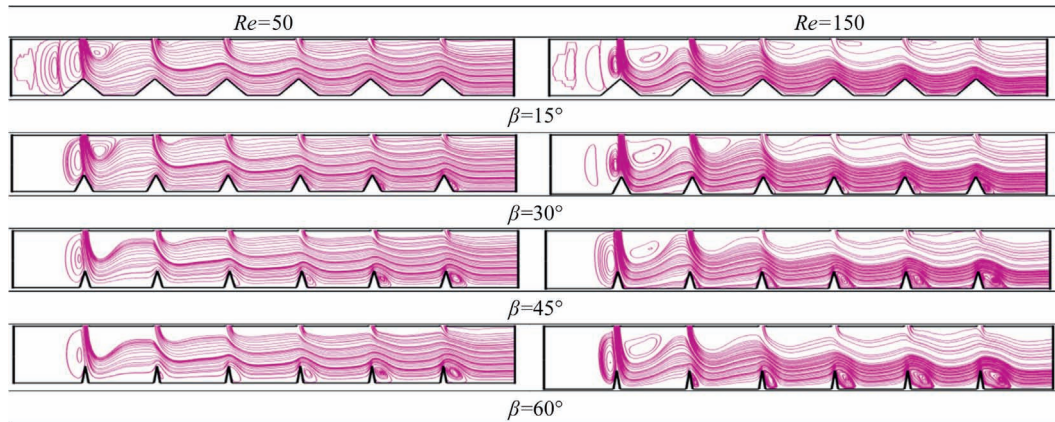


Fig. 4. Streamlines contours with the increase of Reynolds number and attack angle of rib for pure water fluid.

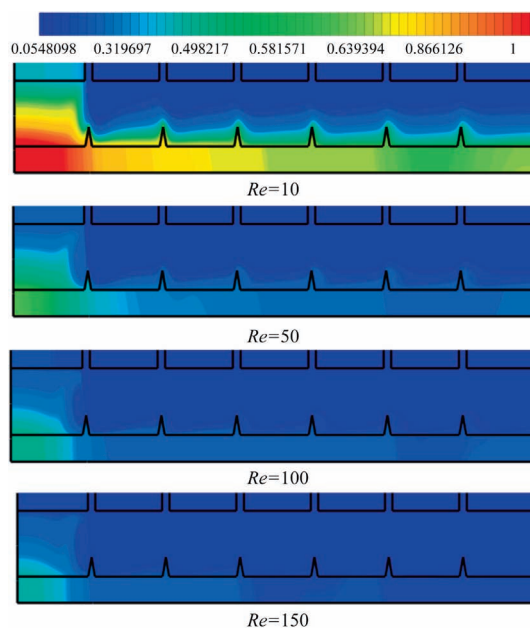


Fig. 5. Dimensionless temperature contours for pure water fluid in attack angle of 60°.

flux and applied heat flux to heated wall. Total entropy generation including entropy generation caused by heat transfer and flow friction can be calculated by following equation [35]:

$$S_{\text{gen}} = \frac{k_{\text{eff}}}{T^2} \left[\left(\frac{\partial T}{\partial x} \right)^2 + \left(\frac{\partial T}{\partial y} \right)^2 \right] + \frac{\mu_{\text{eff}}}{T} \left\{ 2 \left[\left(\frac{\partial \bar{u}}{\partial x} \right)^2 + \left(\frac{\partial \bar{v}}{\partial y} \right)^2 \right] + \left(\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} \right)^2 \right\} \quad (16)$$

4.3. Assumptions

This numerical research has been done in two-dimensional space using computer code by finite volume method. Nanofluid properties are considered constant, Newtonian and independent from temperature (Table 2). Solid-liquid suspension is modeled in single-phase mode. On microchannel floor, oscillating heat flux is applied and lateral and top walls of microchannel are insulated. Also, the radiation and Thermophoresis effects are ignored. No-slip boundary condition is applied to microchannel walls. At the inlet section of microchannel, inlet velocity

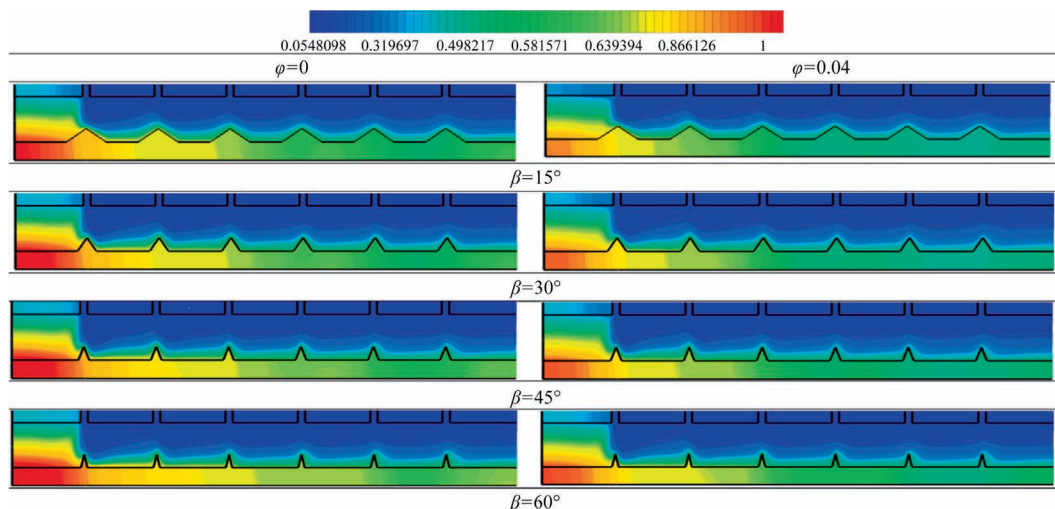


Fig. 6. Dimensionless temperature contours for fluid with different attack angles and nanoparticles mass fractions at $Re = 10$.

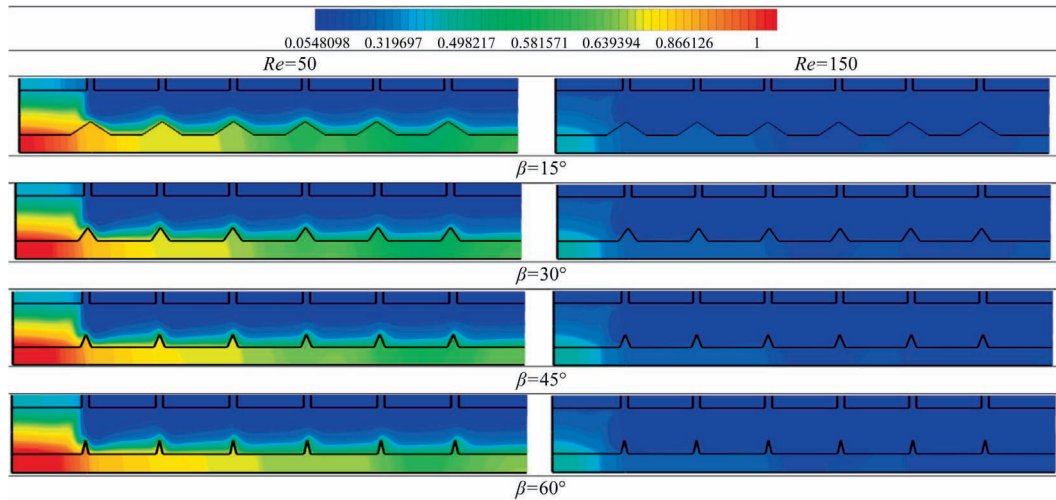


Fig. 7. Dimensionless temperature contours for pure water fluid with different attack angles of rib and Reynolds numbers.

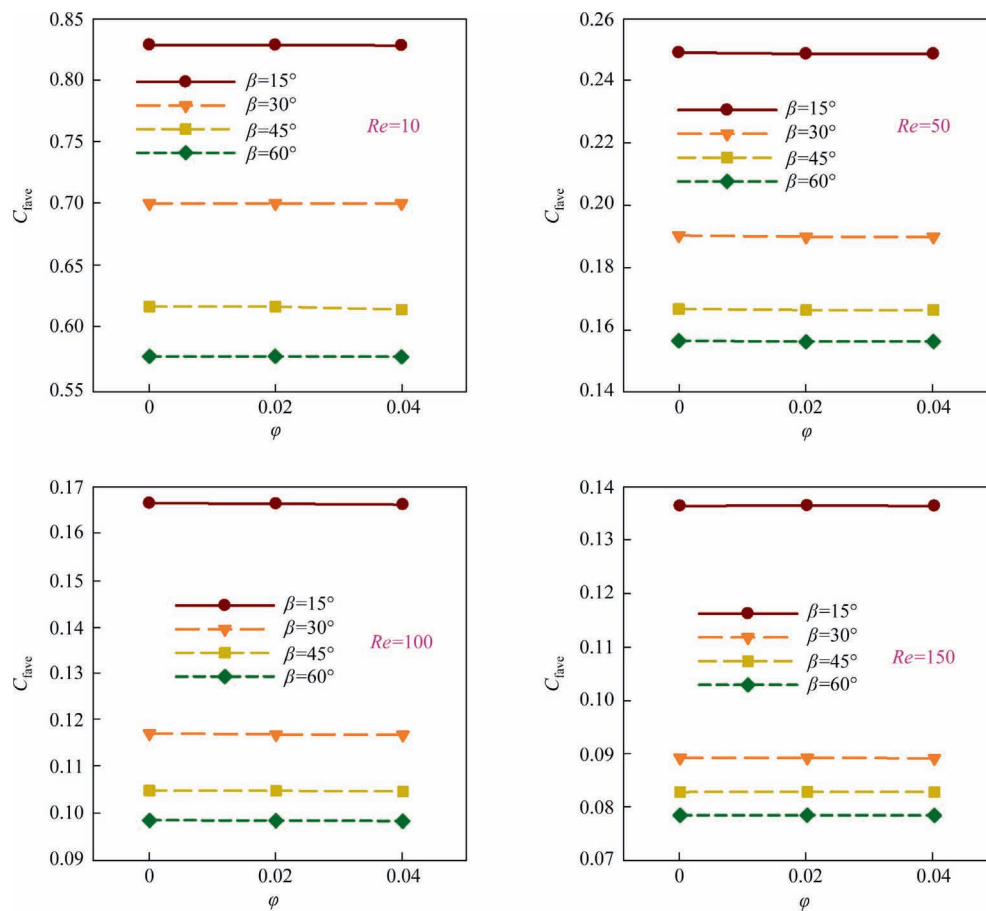


Fig. 8. Average friction factor variations on ribbed wall at different Reynolds numbers, mass fractions and attack angles of ribs.

boundary condition, at the outlet section of microchannel outlet pressure boundary condition are applied and except the bottom wall, which is under the influence of constant heat flux, all walls are insulated. For stopping the changes of numerical solving domain, an appropriate residual should be selected. Although repeating the solving process enhances the accuracy of calculations, it raises calculation errors. In this research, maximum residual of 10^{-6} is considered and SIMPLEC algorithm is used for discretizing velocity–pressure equations up to the second-order.

4.4. Grid independency

In present research, unorganized triangular gridding is used. According to Table (3), for determining proper grid number in numerical solving domain, grid numbers are investigated from 28,577 to 108,552. This investigation is performed for nanofluid with $\phi = 2\%$ at $Re = 150$ for attack angle of 60° . According to the calculated error of other grids, error less than 10 % in grid number of 50,497 is confident. Therefore, due to the accuracy and less error, grid number of 50,497 is considered in this simulation (Table 3). After increasing grid number to a specific value, local pressure drop and dimensionless temperature in centerline of flow are not significantly changed and in general, the maximum error is less than 5 %. Hence, optimized grid number of 50,497 is selected in present numerical simulation.

5. Results and Discussion

In this study, like other studies, the study of flow behavior and heat transfer has been studied [36–52]. In this study, the effects of nanoparticles mass fraction, different attack angles of triangular ribs and Reynolds numbers are numerically investigated. In this section, different parameters including Nusselt number, friction factor, pressure drop, thermal resistance, entropy generation, temperature contours and streamlines contours are compared and analyzed.

5.1. Validation

Fig. 2 indicates the validation of present research with numerical study of Nikkhah *et al.* [53]. This investigation is performed for dimensionless temperature in centerline of flow and local slip velocity on microchannel walls. Ref. [53] numerically investigated laminar flow of water/CNT (carbon nanotube) nanofluid in a rectangular microchannel by applying oscillating heat flux on walls. According to the obtained results from this simulation, at $Re = 100$ and $\phi = 0.12$ with no-slip boundary condition, the accuracy of this numerical solving process is confirmed.

5.2. Streamlines contours

In Fig. 3, streamlines contours along microchannel at $Re = 10$, 50 and 100 for pure water flow in attack angle of 60° are indi-

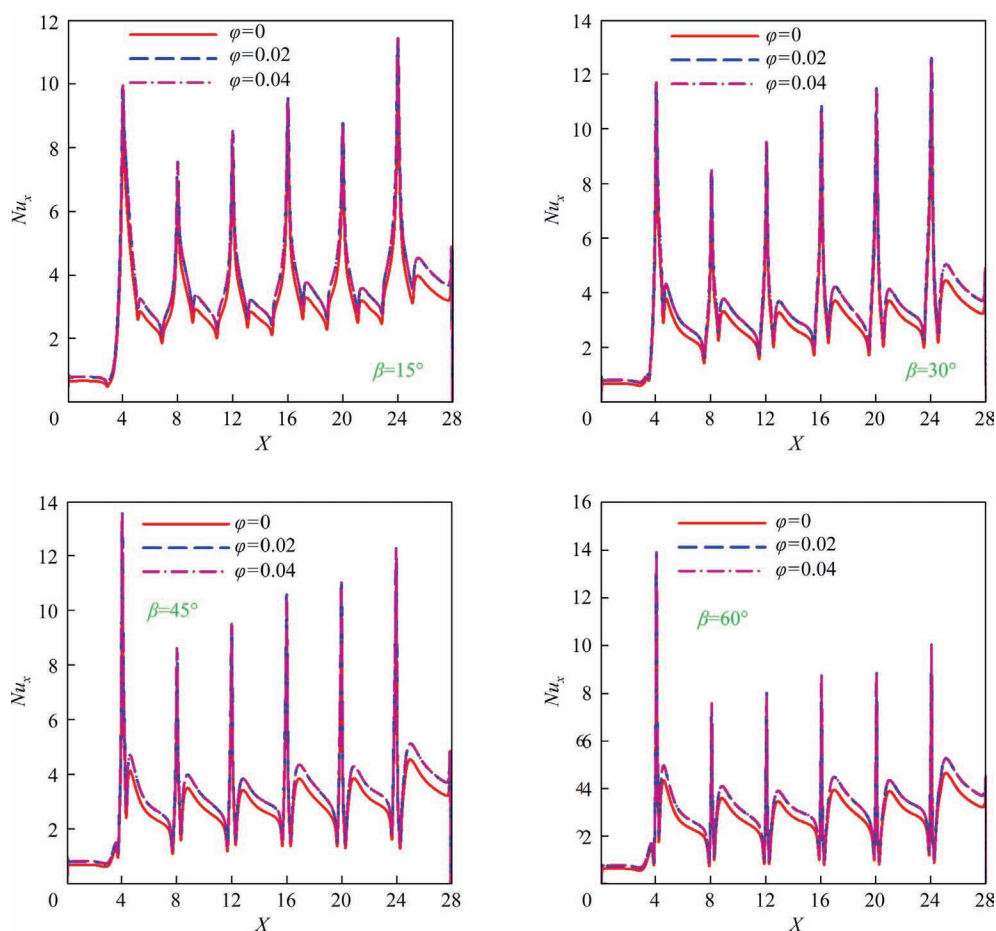


Fig. 9. Local Nusselt number on ribbed wall at $Re = 10$.

cated. Also, the effect of the increase of fluid velocity on streamlines behavior in attack angle of 60° is investigated. Under the influence of nanofluid jet injection, fluid motion along microchannel leads to the creation of axial and vertical velocity parameters. When fluid velocity is minimum ($Re = 10$) presence of attack angle of 60° creates insignificant changes on fluid motion. Most of the changes in axial velocity parameters happen in areas behind the ribs especially at the ending section of microchannel. The reason is fluid momentum depreciation with more process of fluid along microchannel and at the end of fluid direction, fluid momentum becomes minimum and fluid cohesion to heated surface happens as a vortex. By increasing Reynolds number, due to the improvement of fluid momentum, fluid cohesion to frontal surface of rib enhances, however, because of the creation of wake area behind the rib, this behavior is not considerable and fluid is separated. By increasing fluid velocity, separation area covers more surfaces which has a great effect on frontal ribs along fluid direction.

Variations of streamlines contours with the increase of Reynolds number ranging from 50 to 150 and attack angles of 15° , 30° , 45° and 60° for pure water fluid are illustrated in Fig. 4. The aim is estimating simultaneous effect of the increase of fluid velocity and attack angle on laminar flow pattern along ribbed microchannel. By increasing Reynolds number, momentum of fluid jet enhances and inlet fluid penetrates to areas close to the heated surface. This factor can reduce flow separation because nanofluid jet injections are located at the top of ribs. Also, fluid motion on ribbed surface with various attack angles is different.

Attack angle of rib and velocity of working fluid are main factors resulting in fluid coincidence on surface. By increasing attack angle of rib, flow separation enhances. In attack angles of 15° and 30° , even at $Re = 150$, after fluid motion on inclined surface, fluid is never separated and fluid and surface are properly coincident.

5.3. Dimensionless temperature contours

Fig. 5 shows dimensionless temperature contours for pure water fluid in attack angle of 60° and $Re = 10, 50, 100$ and 150 . In these contours, static temperature distribution in ribbed microchannel with maximum attack angle with the increase of fluid velocity for similar temperature values is investigated. The main reason of the creation of temperature gradients is temperature difference between fluid and heated surface which is under the influence of oscillating heat flux. Also, the performance of cooling fluid jet is as another factor reducing temperature gradients along microchannel. According to this figure, by decreasing Reynolds number, penetration of thermal boundary layer in fluid and solid sections enhances and continues to jet injection areas. Temperature penetration and growth of thermal boundary layer are adverse factors influencing heat transfer of microchannel which can lead to the creation of areas with higher temperature. By increasing Reynolds number, temperature penetration becomes uniform and temperature gradients are significantly removed. Creation of heated area on left-side of microchannel is caused by the created vortex flows due to

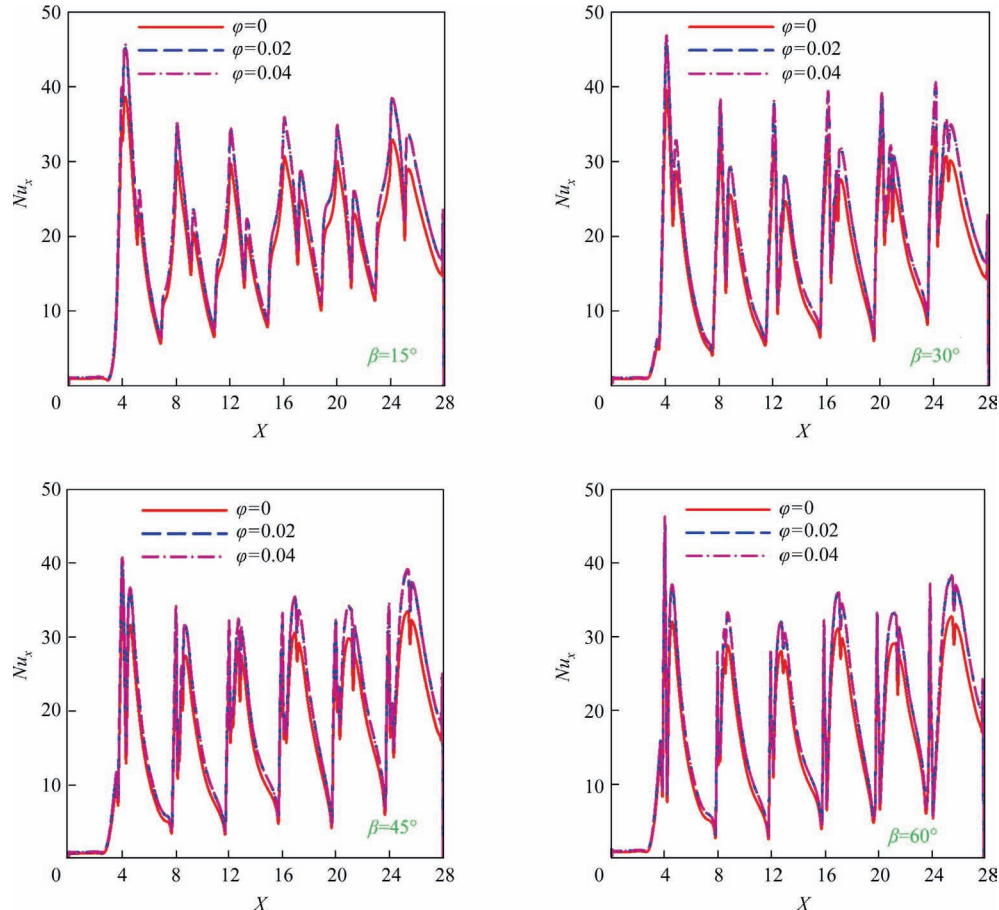


Fig. 10. Local Nusselt number on ribbed wall at $Re = 150$.

the vertical jet injection and in this area, fluid has lower axial velocity on heated surface, therefore, in this region temperature gradients are enhanced. Also, by increasing Reynolds number and due to the improvement of fluid jet momentum and higher velocity of fluid, areas with high temperature are significantly removed.

Dimensionless temperature contours in attack angles of 15° – 60° and 0–4 % nanoparticles mass fractions at $Re = 10$ are compared in Fig. 6. In these contours, static temperature distribution behavior by using pure water fluid and nanofluid with $\phi = 4\%$ and higher attack angle is investigated. Higher nanoparticles mass fraction leads to the increase of thermal conductivity of cooling fluid and also, uniform temperature distribution in different areas of fluid, especially in areas on heated surface. In these contours, distinction of temperature reduction and non-uniform temperature distribution for nanofluid with $\phi = 4\%$ at $Re = 10$ in all studied attack angles is obvious. This behavior, due to better coincidence of surface and fluid with reduction of attack angle of rib has a greater effect on reduction of temperature gradients and microchannel temperature. If designing a ribbed geometry with higher attack angle is not possible due to the designing limitations, using nanofluid with higher mass fraction can help the remove of temperature gradients.

In Fig. 7, dimensionless temperature contours for base fluid in attack angles of 15° , 30° , 45° and 60° and $Re = 50$ – 150 are indicated. The main purpose is comparing the simultaneous effect of the increase of Reynolds number and attack angle of rib on temperature distribution in numerical solving domain. In these

contours, for quantitative and qualitative comparisons, temperature is considered similar for all cases. As it is seen, by processing fluid to outlet section of microchannel, the effect of temperature gradients is reduced due to the mixture of inlet cold fluid along its direction. Also, by processing fluid and entrance of cold fluid with low temperature in constant microchannel section, for establishing continuity law, fluid velocity should be enhanced which results in the increase of the removal of temperature gradients in solid and liquid regions. Also, variations of temperature contours show that, decrease of attack angle of rib with the enhancement of Reynolds number ($Re = 150$) results in more uniform temperature distribution compared to other cases.

5.4. Friction factor changes

In Fig. 8 changes of average friction factor on ribbed wall at $Re = 50$ – 150 and 0–4 % nanoparticles mass fractions and attack angles of 15° , 30° , 45° and 60° are quantitatively compared. As it is seen, increase of Reynolds number due to the increase of fluid momentum, leads to the reduction of friction factor. On the other hand, the increase of nanoparticles mass fraction has an insignificant effect on quantitative value of average friction factor at all studied Reynolds numbers. In fact, the reason of this behavior is reduction of nanofluid density with the increase of nanoparticles mass fraction. Considered solid nanoparticles have less density than pure water and during mixture, lead to the reduction of density. The other reason of insignificant variations of friction factor with the increase of nanoparticles mass fraction is small changes of density

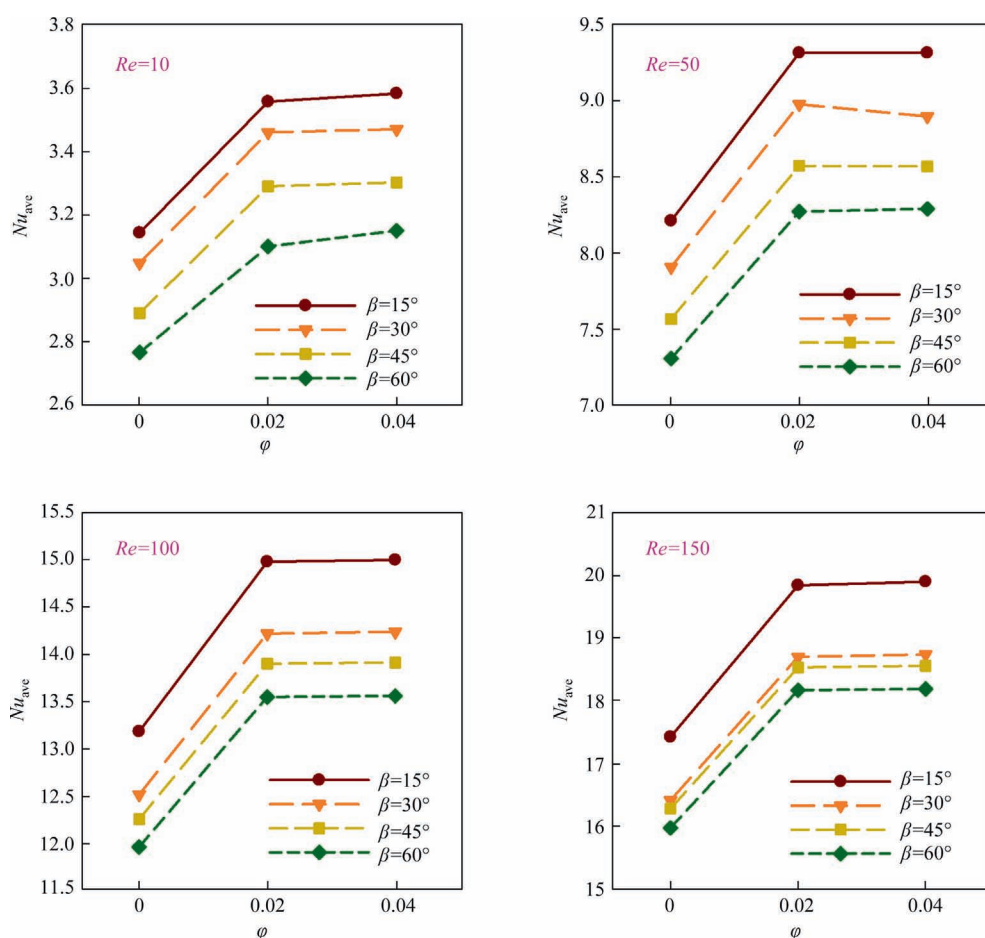


Fig. 11. Average average Nusselt number changes on ribbed wall at various Reynolds numbers, nanoparticles mass fractions and attack angle of rib.

by adding higher nanoparticles mass fractions. Therefore, according to Fig. 8, by increasing the effect of fluid viscosity on the enhancement of velocity and temperature boundary layers, in higher mass fraction, it has less effect on friction factor enhancement. Increasing the angle of attack of the ribs due to more blockage of the flow path and drastic changes in the axial velocity components of the fluid, the coefficient of friction increased sharply. By reducing the angle of attack ribs fluid movement easier by reducing friction coefficient is associated. In general, two main factors of reduction of fluid velocity and reduction of attack angle of triangular rib determine quantitative value of average friction factor on ribbed surface.

5.5. Nusselt number figures

In Fig. 9 local Nusselt number figures on ribbed wall at $Re = 10$ and 0–4% nanoparticles mass fractions are shown. Also, the behavior of local Nusselt number on heated ribbed wall for changes of thermal conductivity of cooling fluid caused by adding solid nanoparticles with the increase of attack angle along microchannel is investigated. Heat transfer along fluid direction depends on temperature difference between surface and fluid [54–59]. Some factors including solid nanoparticles, fluid mixture, less attack angle of rib and increase of fluid velocity lead to the increase of Nusselt number. In Fig. 9, adding nanoparticles mass fraction in constant fluid velocity leads to the improvement of heat transfer and level of local Nusselt number figures. On the other hand, increase of attack angle of rib, even in lowest fluid velocity, leads to the improvement of fluid mixture on hot

surfaces and by increasing attack angle of ribs, the level of Nusselt number figures reduces.

In Fig. 10 local Nusselt number on ribbed wall at $Re = 150$ in attack angles of 15° , 30° , 45° and 60° are compared. As it is seen, compared to Fig. 9 in similar conditions, fluid velocity enhances up to 15 times and the effect of this increase of velocity on Nusselt number behavior is investigated. According to this figure, the increase of velocity leads to the improvement of Nusselt number and level of figures. The notable point observed in this figure is the effect of the increase of the level of Nusselt numbers figures after ribs, it means that, not only the jump of Nusselt number figure at the top of rib happens due to the deviation of fluid direction, but also this behavior continues with low slop.

In Fig. 11 variations of average Nusselt number on ribbed wall at $Re = 10, 50, 100$ and 150 and 0–4 % nanoparticles mass fractions and attack angles of 15° , 30° , 45° and 60° are investigated. Also, quantitative value of heat transfer caused by methods used in all studied cases is compared. The average Nusselt number is increased due to the mentioned reasons for local Nusselt number figures. Increase of nanoparticles mass fraction results in the improvement of thermal conductivity of cooling fluid and quantitative value of Nusselt number enhances. The notable point is insignificant changes of average Nusselt number enhancement in $\varphi = 4\%$ compared to $\varphi = 2\%$. In fact, presented nanofluid properties reveal that, adding higher nanoparticles mass fraction causes insignificant changes in thermal conductivity and dynamic viscosity of nanofluid compared to base fluid. As it is seen, in addition to the improvement of thermal conductivity of

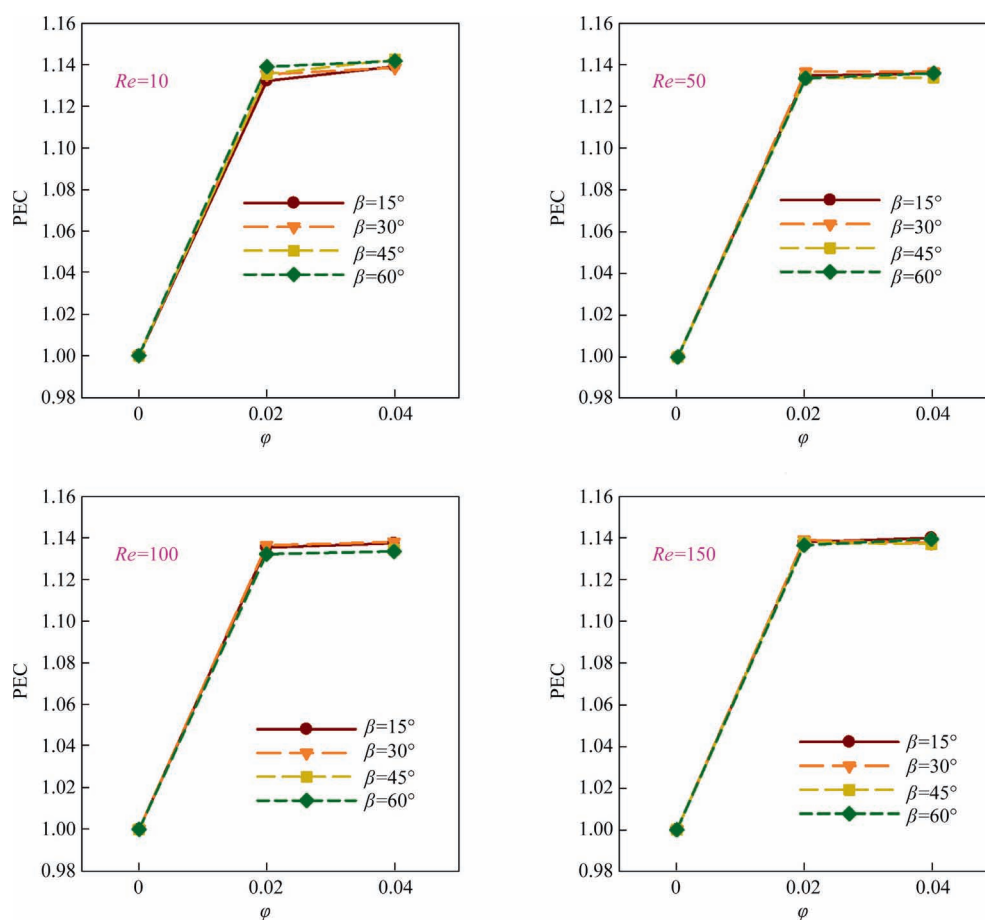


Fig. 12. PEC at different Reynolds numbers, nanoparticles mass fractions and attack angles of rib.

nanofluid, some factors such as the increase of density and viscosity of working fluid are effective on Nusselt number improvement because slight changes in these parameters result in the improvement of thermal conductivity of cooling fluid, however, adding higher nanoparticles mass fraction creates insignificant and constant changes in Nusselt number. Increase of Reynolds number is an effective factor on Nusselt number improvement. On the other hand, reduction of attack angle especially at higher Reynolds numbers, leads to the increase of Nusselt number and distinction of Nusselt number behavior in attack angle of 15° . At $Re = 10$, due to the slow motion of fluid, distinction of figures behavior for average Nusselt number variations is not considerable and figures are similar.

5.6. PECxxx

In Fig. 12 PEC at $Re = 10, 50, 100$ and 150 and 0 – 4% nanoparticles mass fractions and attack angles of $15^\circ, 30^\circ, 45^\circ$ and 60° is investigated. Due to the increase of nanoparticles mass fraction in cooling fluid, in addition to the improvement of thermal conductivity of working fluid, friction factor enhances as well. The effect of adding nanoparticles on increase of Nusselt number and friction factor varies for different kinds of nanoparticles and heat transfer geometries. In this figure the effect of the increase of Nusselt number and friction factor for similar conditions in each nanoparticles mass fraction compared to pure water fluid is investigated. Because variations of viscosity and friction factor for higher mass fractions are less, increasing trend

of friction factor and Nusselt number figures is insignificant which results in slight changes in PEC. The only factor improving PEC is adding nanoparticles mass fraction to base fluid. For other heat transfer enhancement methods including variations of fluid velocity and attack angle of rib, changes of this parameter are less than 10% .

5.7. Variations of static pressure

In Fig. 13, average pressure drop at $Re = 10, 50, 100$ and 150 and 0 – 4% nanoparticles mass fractions and different attack angles of rib is indicated. In this figure, the effect of using nanoparticles and variations of fluid velocity along ribbed microchannel on pressure drop changes for different attack angles at each studied Reynolds number is studied separately. Pressure drop changes are under the influence of three factors including (1) Increase of fluid velocity which improves fluid collision with solid surfaces, especially with ribbed wall, due to the increase of fluid momentum, on the other hand, because fluid jet momentum enhances and fluid direction in these jets is vertical, these two factors can lead to the increase of pressure drop. (2) Adding nanoparticles mass fraction leads to insignificant increase of fluid viscosity and consequently, higher pressure drop. (3) Increase of inclined surface of rib with reduction of attack angle leads to significant changes in fluid velocity and higher pressure drop. The notable point related to ribs with different attack angles is that, at lower Reynolds numbers, due to the slow motion of fluid, variations of attack

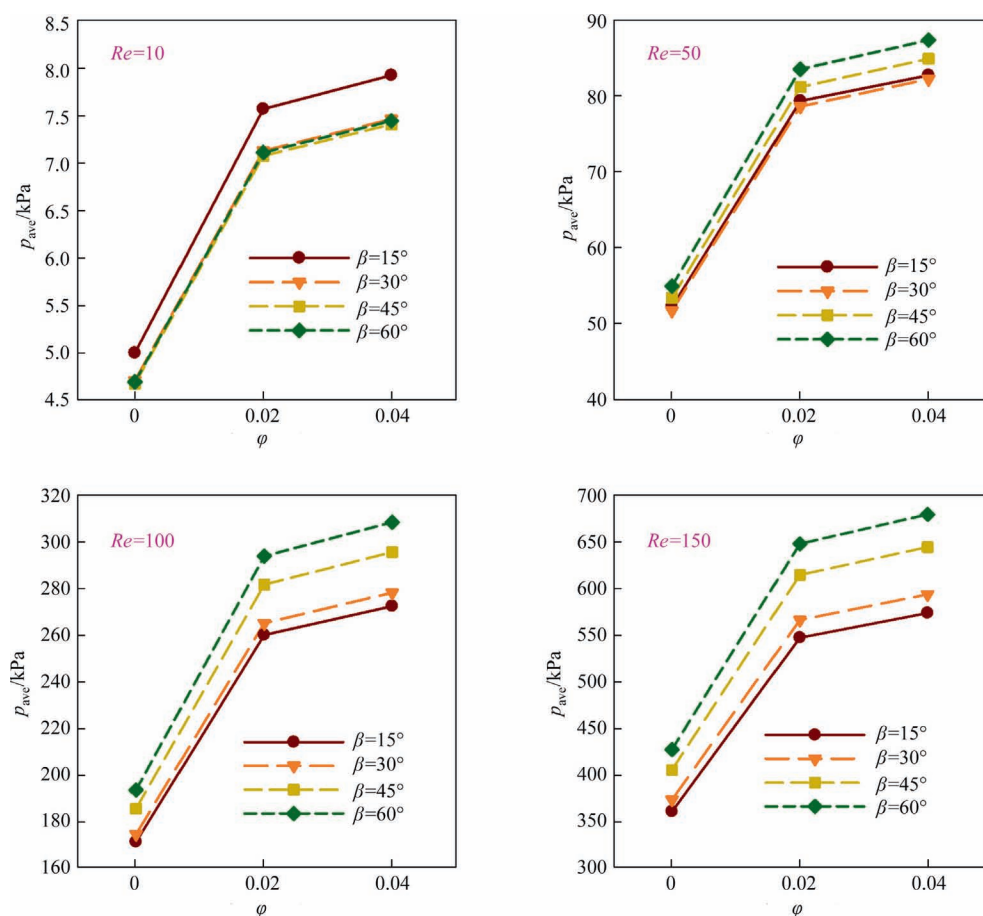


Fig. 13. Average pressure drop at various Reynolds numbers, nanoparticles mass fractions and attack angles of rib.

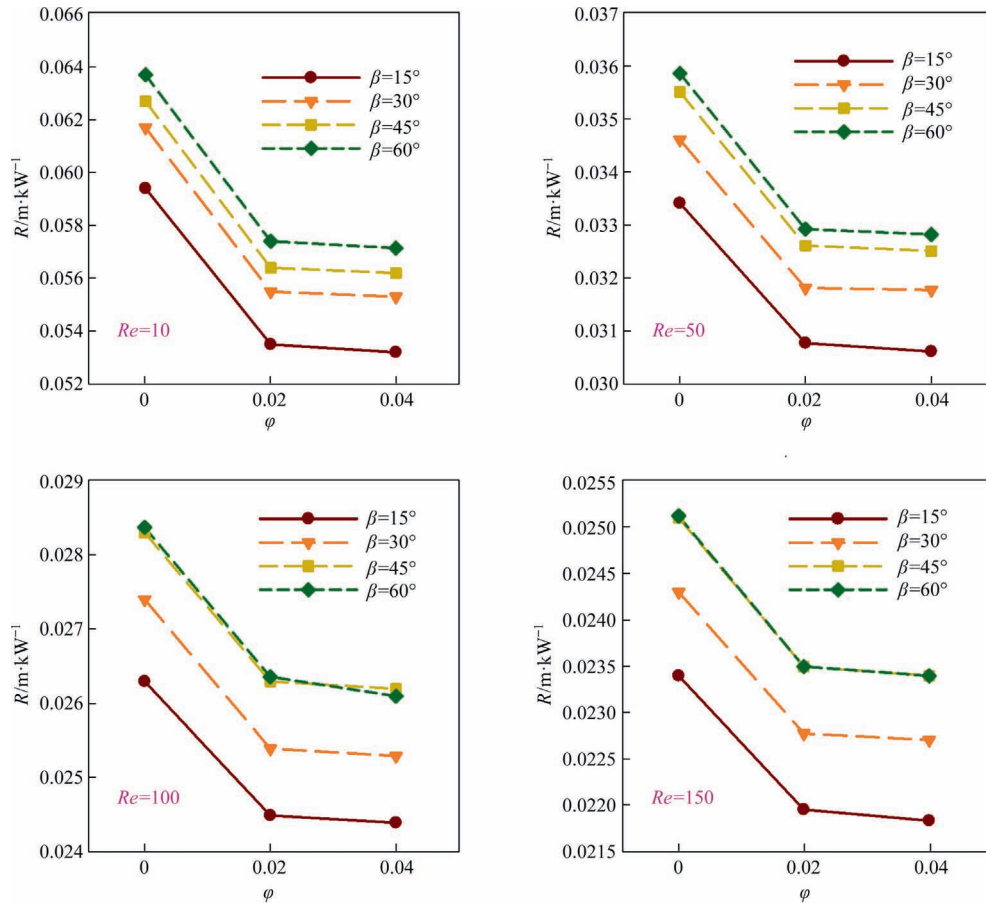


Fig. 14. Thermal resistance figures on ribbed wall of microchannel at different Reynolds numbers, nanoparticles mass fractions and attack angles of ribs.

angle, especially attack angles of 30° , 45° and 60° are almost similar. By increasing fluid velocity, the effect of attack angle variations on pressure drop becomes significant and pressure drop figures act differently.

5.8. Variations of thermal resistance

Fig. 14 indicates thermal resistance figures on ribbed wall of microchannel at different Reynolds numbers, nanoparticles mass fraction and attack angles of rib. Quantitative value of thermal resistance of ribbed surfaces depends on different factors including maximum temperature of surface, inlet fluid temperature, microchannel length and applied heat flux to bottom surface of microchannel. Reduction of thermal resistance of heated surface is an effective factor on increase of PEC of heat generation equipment. As it is seen, increase of fluid velocity is the most effective factor on reduction of thermal resistance, hence, by increasing Reynolds number, the level of these figures is significantly reduced. On the other hand, variations of attack angle of rib are another effective factor resulting in reduction of thermal resistance of nanoparticles mass fraction.

Compared to other factors, by increasing mass fraction of nanoparticles, the distinction of reduction of thermal resistance is insignificant.

5.9. Entropy generation

In Fig. 15 variations of entropy generation on ribbed wall at different Reynolds numbers, mass fractions and attack angles of rib are shown. Quantitative value of entropy generation depends on used methods in this numerical investigation. Therefore, the effect of some factors such as friction factor enhancement caused by adding solid nanoparticles and presence of ribbed surface with different attack angles on entropy generation caused by friction factor is inevitable. Affectability of different factors on studied parameters is compared in this figure. As it is seen, by decreasing attack angle of rib and increasing Reynolds number and nanoparticles mass fraction, entropy generation caused by flow irreversibility can be reduced. Also, by increasing fluid velocity, behavior of entropy generation for different attack angles of rib becomes similar and differences of figures in each studied attack angle tend to a small value.

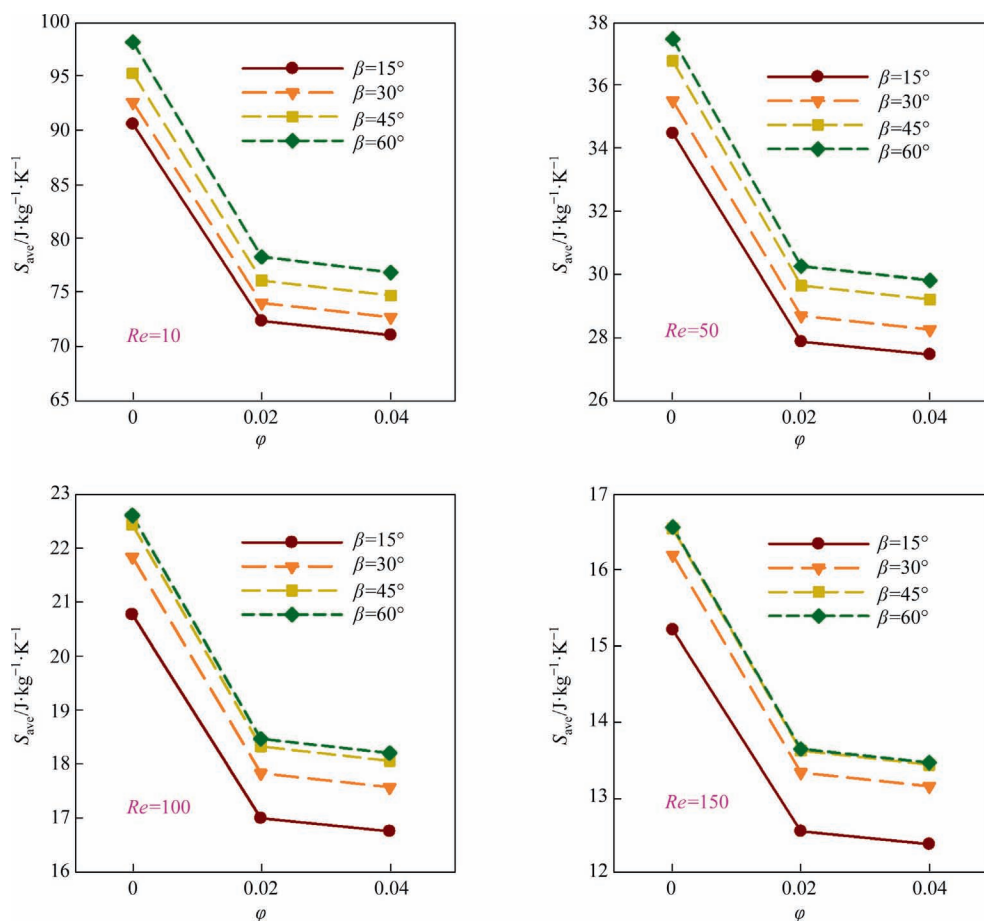


Fig. 15. Variations of entropy generation on ribbed wall at different Reynolds numbers, nanoparticles mass fractions and attack angles of ribs.

6. Conclusions

In present research, laminar flow of water/NDG nanofluid in a 2D rectangular microchannel with the length of $L = 1.4$ mm and the height of $H = 50$ μm with triangular ribs in attack angles of 15° , 30° , 45° and 60° at NDG nanoparticles mass fractions of 0, 2% and 4% is numerically simulated. Studied microchannel is under the influence of sinusoidal oscillating heat flux. Obtained results are compared for different parameters including Nusselt number, friction factor, PEC, thermal resistance, streamlines and temperature distribution contours. Results reveal that, fluid motion on inclined ribbed surface with variations of attack angles is different. Attack angle of rib and fluid velocity are main factors resulting in fluid coincidence on surface. By increasing Reynolds number, fluid coincidence to frontal surface of rib, due to the improvement of fluid momentum, enhances, however, behind the rib, due to the creation of wake area, this behavior is insignificant and fluid is separated. Fluid motion along microchannel under the influence of fluid jet injection leads to the creation of axial and vertical velocity parameters. When fluid velocity is minimum ($Re = 10$), rib with attack angle of 60° creates insignificant changes in fluid direction. According to these contours, by processing fluid to the outlet section of channel, the effect of temperature gradients reduces which is due to the mixture of inlet cold fluid along its direction. By processing and entrance of cold fluid at constant cross section of microchannel, for establishing continuity law fluid velocity should be enhanced. The increase of nanoparticles mass fraction has an insignificant effect on quantitative value of average friction factor in all studied Reynolds numbers. In fact, the reason of this behavior

is due to the reduction of nanofluid density with the increase of mass fraction of nanoparticles. Heat transfer along fluid direction depends on temperature difference between fluid and surface. Some factors including solid nanoparticles, fluid mixture due to the presence of ribs with less attack angle and increase of fluid velocity lead to 15% enhancement in Nusselt number.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

C_f	friction factor
C_p	heat capacity, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
h	local heat transfer coefficient, $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$
k	thermal conductivity, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
Nu	Nusselt number
P	pressure, Pa
S	entropy generation, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
T	temperature, K
u, v	velocity components in x, y directions, $\text{m}\cdot\text{s}^{-1}$
U_s	dimensionless slip velocity
X, Y	Cartesian dimensionless coordinates
α	thermal diffusivity, $\text{m}^2\cdot\text{s}^{-1}$
θ	dimensionless temperature
μ	dynamic viscosity, $\text{Pa}\cdot\text{s}^{-1}$

ρ	density, $\text{kg}\cdot\text{m}^{-3}$
ν	kinematics viscosity, $\text{m}^2\cdot\text{s}^{-1}$
ϕ	nanoparticles mass fraction

Subscripts

c	cold
eff	effective
f	base fluid (pure water)
h	hot
in	inlet
nf	nanofluid
p	solid nanoparticles

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