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# Slip velocity and temperature jump of a non-Newtonian nanofluid, aqueous solution of carboxy-methyl cellulose/ aluminum oxide nanoparticles, through a microtube

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## Abstract

**Purpose** – With respect to two new subjects, i.e. nanofluids and microchannels, in heat transfer systems and modern techniques used for building them, this paper aims to study on effect of using aluminum oxide nanoparticles in non-Newtonian fluid of aqueous solution of carboxy-methyl cellulose in microtube and through application of different slip coefficients to achieve various qualities on surface of microtube.

**Design/methodology/approach** – Simultaneously, the effect of presence of nanoparticles and phenomenon of slip and temperature jump has been explored in non-Newtonian nanofluid in this essay. The assumption of homogeneity of nanofluid and fixed temperature of wall in microtube has been used in modeling processes.

**Findings** – The results have been presented as diagrams of velocity, temperature and Nusselt Number and the investigations have indicated that addition of nanoparticles to the base fluid and increase in microtube slip coefficient might improve rate of heat transfer in microtube.

**Originality/value** – The flow of non-Newtonian nanofluid of aqueous solution of carboxy methyl cellulose-aluminum oxide has been determined in a microtube for the first time.

**Keywords** Nanofluid, Non-Newtonian fluid, Microtube, Slip velocity, Temperature jump

**Paper type** Research paper

## Nomenclature

$\beta^*$ = Non-dimensional slip coefficient ($=L_S/D$);
$L_S$ = slip length (m);
$c_p$ = Specific heat (J/kgK);
D = tube diameter (m);
$h$ = convection heat transfer coefficient ($W/m^2k$);
k = Thermal conductivity (W/mK);
$Nu_x$ = Local Nusselt number;
$Nu_t$ = Total Nusselt number;
p = Pressure (Pa);
Re = Reynolds number ($=\rho u^{2-n}{}_{in} D^n/\kappa$);
r = radial coordinate (m);
R = Non-dimensional radial coordinate (=r/D);

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Pr = Prandtl number (= $\left(C_p\left(\frac{u_{in}}{D}\right)^{n-1}k\right)$/k);
T = Temperature (K);
$T_{in}$ = Temperature of inlet nanofluid (K);
U = Non-dimensional horizontal velocity;
$U_s$ = Non-dimensional slip velocity;
v = Vertical velocity ($ms^{-1}$);
V = Non-dimensional vertical velocity;
x = Horizontal Cartesian coordinate (m);
X = Non-dimensional horizontal Cartesian coordinate;
y = Vertical Cartesian coordinate (m);
Y = Non-dimensional vertical Cartesian coordinate;
n = Power Law index (dimensionless); and
K = consistency index (Pa $s^n$).

*Greek symbols*
$\alpha$ = Thermal diffusivity (=k/$\rho c_p m^2 s^{-1}$);
$\beta$ = Slip coefficient (m);
$\phi$ = Volume fraction of nanoparticles;
$\theta$ = Dynamic viscosity ($Nsm^{-2}$) $\mu$ Non-dimensional temperature =((T− $T_w$)/($T_{in}$ − $T_w$))));
$\rho$ = Density ($kgm^{-3}$);
$\upsilon$ = Kinematic viscosity ($m^2 s^{-1}$); and
$\gamma^{\cdot}$ = Shear rate ($s^{-1}$).

*Subscripts*
f = Fluid;
nf = Nanofluid;
s = Solid;
x = Local value in X-direction;
eff = Effective; and
w = Wall.

## 1. Introduction

Energy has been assumed as the factor for advancement of industry from long time ago and following to advancement of industry, employing heat transfer techniques with high thermal efficiency and potential for transfer of high quantity of energy along with small dimensions are deemed as one of the essential needs in many modern industries and equipment. This issue is crucially important in various industrial tools and processes such as cooling and heating of thermal sources, production processes and industries, e.g. transportation, pharmacology, electronics, automotive and micro electromechanical and nano electromechanical systems. Improvement of heat transfer by means of modern techniques in general uses also leads to noticeable saving in the related costs and energy resources and environmental protection. Some methods including use of suspensions instead of active fluid in heat transfer equipment and utilization from surfaces finishing and adjustment are new techniques which are highly addressed today. Overall, heat transfer increasing techniques are divided into two general classes of active and passive techniques (Bergles, 2001).

The active techniques are called to those methods in which conservation of mechanism for improved heat transfer depends on presence of an external force while there is no need to such a force in passive techniques. Table I has shown some examples of the existing

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methods at any category. Use of each of these techniques depends on operational conditions of equipment and user's requirements. The weak point of active techniques lies in use of a power supply permanently that leads to higher costs for them compared to passive techniques. Therefore, the passive techniques play pioneering role in various industry fields and power generation. Following to advancement of industry during recent years and taking step into small dimensions at nano level and smaller than them, manufacturing of various equipment in these small dimension using of them has noticed and this course the researches have drawn attention of many researchers regarding fluid flow and heat transfer at micro scale and on the other hand this progress was led to production of materials and or their correction at nanometer dimensions and it has exposed two new practices for heat transfer equipment including utilization from nanoparticles as additives to fluids to improve their thermal properties and also adjustment of surfaces on heat transfer equipment at nano dimensions and creating special properties such as hydrophobicity for these surfaces. In the path toward advancement of industry and along the mentioned issues, the active heat transfer fluid has been also noticed, and in this regard, some items have been explored and built that they are identified as non-Newtonian fluids and one of their characteristics is behavior dependent on rate of flow shear. The most well-known one of these non- Newtonian fluids their behavior is expressed by Power Law. Many studies have been carried out to explore behavior of flow and heat transfer in channels and microchannels, method of production and use of nanoparticles, production and adjustment of microchannels and effects of their application. Jung *et al.* (2009) have empirically analyzed compulsory heat transfer displacement of nanofluids in microchannels using water- aluminum oxide nanofluid and they found that nanofluid displacement coefficient with volumetric ratio of 1.8 per cent of nanoparticles was 32 per cent higher than pure water displacement coefficient and heat transfer coefficient is smaller in Reynolds numbers in microchannels with smaller dimensions and or greater than heat transfer coefficients in larger microchannels under higher Reynolds numbers where this indicates properties of heat transfer in microchannel.

Through conducting empirical analysis on slow flow of water-aluminum oxide nanofluid, Heris *et al.* (2006) concluded that the coefficient of head transfer displacement is increased 40 per cent compared to water while thermal conductance coefficients has maximally improved 15 per cent. Park and Cho (1998) carried out empirical studies to explain friction in the turbulent flow and behavior of heat transfer in the formed nanofluid by $Al_2O_3$ and $TiO_2$ suspended in water in a circular tube and they concluded that rising density of nanoparticles might increase Nusselt number there was useful relationship among Nusselt number and Reynolds number in fully developed turbulent flow. Shen *et al.* (2006) empirically analyzed flow and heat transfer in microchannel and with coarse wall and water as active fluid and they came to the result that normal coarse surface might impact on

| Active techniques | Passive techniques |
|---|---|
| Finished surfaces | Surface vibration |
| Coarse surfaces | Fluid vibration |
| Expanded surfaces | Suction or aeration |
| Flow torsion tools | Jet collision |
| Spiral tubes | |
| Additives to fluids | |
| Surface tension tools | |

**Source:** Bergles (2001)

**Table I.**
Classification of heat transfer techniques

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heart transfer from microchannel in slow flow to great extent and friction coefficient and Nusselt number were remarkably distant from classic theories so this was probably because of the existing coarseness and rising temperature of input flow and thermal power that enhances thermal performance of the flow. The flow is classified in small dimensions for gases based on ratio of free gas molecular distance and characteristic length of flow. This ratio is called Knudsen number and accordingly if Knudsen number is smaller than 0.001, there is continuous flow and Navier–Stokes equation applies to them. If Knudsen number ranges among 0.001 and 0.1, it is called slip flow. At this mode, Navier–Stokes equation still applies to the given flow but boundary conditions of flow has varied and they are expressed as flow slip at this temperature and also temperature jump in energy. If Knudsen number is placed within range (0.1-10) as transitional flow and if it exceeds from 10 it expresses free molecular flow and classic Navier–Stokes equations no longer apply to them (Xuan *et al.*, 2007; Ho and Tia, 1998). However, there is no such type of classification in other liquids since intermolecular forces is much stronger in liquids than in gases and it is led to conserve continuity between them while based on interaction among liquid and solid including rate of wetting on surface, fluid properties, ratio of flow shear force and surface coarseness there is possibility for slip and temperature jump at the boundary of fluid (Samaha *et al.*, 2012) therefore by means of engineering on surface and the given coverage one can achieve hydrophobic or ultrahydrophobic surfaces on which the flow is exposed to high slip (Neto *et al.*, 2005). For example, Lv and Zhang (2016) compared empirically pressure drop and heat transfer in water flow inside simple and ultrahydrophobic tubes and showed that the rate of pressure drop and heat transfer was lesser in ultrahydrophobic tubes than in simple state.

Hao *et al.* (2009) have empirically compared the rate of pressure drop in slow water flow through simple and hydrophobic microchannels and indicated that the rate of flow slip was higher for hydrophobic channel on surface of channel and the given pressure drop was smaller. Raisi *et al.* (2012) studied the compulsory numerical displacement in slow flow of water- copper nanofluid in a microchannel based on boundary condition with and without slip. They have examined the cooling potential of pure water and nanofluid. Keshavarz *et al.* (2012) have explored numerically compulsory heat transfer displacement in non-Newtonian nanofluid of Xanthan-aluminum oxide through a horizontal tube under constant heat flux. They expressed that density and diameter of nanoparticles might impact on displacement heat transfer and at the same they implied the increase in Reynolds and Prandtl numbers might increase the heat transfer coefficient and rate.

Hojati *et al.* (2011) have empirically surveyed the compulsory displacement of non-Newtonian nanofluid in a microtube under boundary conditions of the fixed temperature and observed that heat transfer coefficient and Nusselt number of nanofluid has been increased in comparison to base fluid. Kamali and Binesh (2010) showed empirically increase in heat transfer coefficient in non-Newtonian nanofluid including carbon nanotubes and at the same time they have compared results of their study by a numerical model and shown the precision of numerical model.

In this study, properties of the aforesaid modern technologies have been noticed along with each other and the effect of using aluminum oxide nanoparticles and correction of surface on parameters of flow and heat transfer has been examined in a non-Newtonian fluid in a microtube for the first time (Shamshirband *et al.*, 2015; Karimipour *et al.*, 2012; Karimipour, 2015a; Esfe *et al.*, 2015b; Afrand *et al.*, 2017; Karimipour, 2015b; Esfandiary *et al.*, 2016; Karimipour *et al.*, 2016; Mahmoodi *et al.*, 2015; Bahrami *et al.*, 2016; Afrand *et al.*, 2015; Esfe *et al.*, 2014b; Afrand *et al.*, 2016; Akbari *et al.*, 2017; Esfe *et al.*, 2015e; Harandi *et al.*, 2016; Esfe *et al.*, 2015c, 2015a; Zadkhast *et al.*, 2017; Karimipour *et al.*, 2011; Afrand, 2017a, 2017b; Soltanimehr and Afrand, 2016; Eshgarf and Afrand, 2016; Sadeghi *et al.*, 2018;

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Hadjadj *et al.*, 2015; Rashidi *et al.*, 2017). Modeling process has been done numerically and by means of finite volume method for a microtube with the fixed temperature wall and also effects of surface correction has been considered using condition of slip and temperature jump in the wall.

## 2. Problem statement

Figure 1 displays the given geometry in the current study including a microtube that is two-dimensional using cylindrical coordinates and based on condition of axial symmetry in respective of central line at microtube. The length of microtube is (L = 5 mm) with diameter of (D = 200 $\mu$m) and temperature of fixed wall is ($T_W$=308 k) with nanofluid input temperature ($T_{in}$=298k) and it is assumed that based fluid and aluminum oxide nanofluid nanoparticles include fully homogeneous suspension and this model will totally remain as homogeneous. The aluminum oxide nanofluid nanoparticles have uniform and spherical shape with diameter of 25 $\mu$m and the flow in this microtube is slow and non-contractible while the effects of radiation and changes in properties of fluid by temperature may be ignored. The base fluid is the aqueous solution of carboxy methyl cellulose with weight percentage of 0.5 per cent. Thermophysical properties of the used nanofluid in numerical model are shown in Table II.

## 3. Formulation

### *3.1 Governing equations*

The governing equations over this problem comprise of continuity, momentum and energy equations which are solved for permanent and slow state in cylindrical coordinates with axial symmetry. These equations are listed in below:continuity equation:

$$\frac{\partial}{\partial x}(u_x) + \frac{\partial}{\partial r}(u_r) + \frac{u_r}{r} = 0 \tag{1}$$

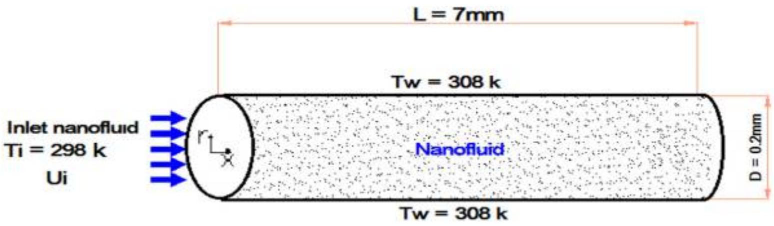

**Figure 1.** Schemata of microtube design

**Table II.** Thermophysical properties of base fluid and nanofluid

| Property | Base fluid | Nanofluid 1(%) | Nanofluid 2(%) |
|---|---|---|---|
| $\rho$ (Kg/m$^3$) | 997.1 | 1026.8 | 1056.8 |
| k(W/m-k) | 0.613 | 0.631 | 0.649 |
| $C_p$ (J/kg) | 4179 | 4047 | 3922.4 |
| n | 0.54 | 0.52 | 0.49 |
| K | 0.15 | 0.18 | 0.25 |

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momentum equation in X direction:

$$\frac{1}{r}\frac{\partial}{\partial x}(r\rho u_x u_x)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho u_r u_x)=-\frac{\partial P}{\partial x}+\frac{2}{r}\frac{\partial}{\partial x}\left(r\mu\frac{\partial u_x}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(\frac{\partial u_r}{\partial x}+\frac{\partial u_x}{\partial r}\right)\right] \tag{2}$$

momentum equation in R direction:

$$\begin{aligned}&\frac{1}{r}\frac{\partial}{\partial x}(r\rho u_r u_x)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho u_r u_r)\\&=-\frac{\partial P}{\partial r}+\frac{2}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial u_r}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial x}\left[r\mu\left(\frac{\partial u_r}{\partial x}+\frac{\partial u_x}{\partial r}\right)\right]-2\mu\frac{u_r}{r^2}\end{aligned} \tag{3}$$

energy equation:

$$\frac{\partial(u_x T)}{\partial x}+\frac{\partial(u_r T)}{\partial r}+\frac{u_r T}{r}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right) \tag{4}$$

The value of efficient viscosity in momentum equation is calculated for non-Newtonian fluid with respect to exponential viscosity law as follows (Kamali and Binesh, 2010):

$$\mu=K\dot{\gamma}^{n-1} \tag{5}$$

The following equations have been employed for calculation of properties of nanofluid. Density of nanofluid (Brinkman, 1952):

$$\rho_{nf}=(1-\phi)\rho_f+\phi\rho_s \tag{6}$$

Specific heat capacity of nanofluid:

$$(\rho Cp)_{nf}=(1-\phi)(\rho Cp)_f+\phi(\rho Cp)_s \tag{7}$$

The efficient thermal conductivity coefficient of nanofluid (Chon *et al.*, 2005):

$$\frac{k_{eff}}{k_f}=1+64.7\left(\phi\frac{d_f k_s}{d_s k_f}\right)^{0.7476}Pr_f^{0.9955}Re_b^{1.2321} \tag{8}$$

Also Reynolds and Prandtl numbers have been calculated for non-Newtonian nanofluid as follows (Shayam and Chhabra, 2013):

$$Re=\frac{\rho u_{in}^{2-n}D^n}{k} \tag{9}$$

$$Pr=\frac{Cp\left(\frac{u_{in}}{D}\right)^{n-1}K}{k} \tag{10}$$

The following non-dimensionalization processes have been utilized to propose the results better:

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$$R = \frac{r}{D}, \theta = \frac{T - T_w}{T_{in} - T_w}, X = \frac{x}{D}, U = \frac{u}{u_{in}} \tag{11}$$

The value of local Nusselt number has been computed as follows:

$$Nu(x) = \frac{q^{'}(x)D}{k_f(T_b(x) - T_w)} \tag{12}$$

$$T_b(x) = \frac{\int \rho u(x,r)T(x,r) \ dA}{\dot{m}} \tag{13}$$

In addition, total Nusselt number has been also calculated as follows:

$$Nu_T = \frac{qD}{k_f(T_w - T_{in})} \tag{14}$$

### *3.2 Hydrodynamic boundary conditions*

As usual, no-slip condition is satisfied in the boundary among fluid and solid state namely it denotes the same velocity in layer of fluid in contact with solid surface but under various modes such as diluted fluid in gaseous form, very high pressure gradient through the path, and/or in small dimensions in which the flow scale is adjacent to molecular dimension of fluid it has been observed that the fluid layer has greater velocity on solid surface. On the other hand, following to scientific advancement in engineering of surface and creating surfaces with coarseness lower than nanometer and generating hydro phobicity and ultrahydro phobicity properties in them some tubes have been built in them that included greater velocity of fluid layer on solid layer under normal conditions as well. These conditions are expressed as slip in flow of fluid and show temperature jump at this energy level and implied as follows (Samaha *et al.*, 2012):

$$u_s = Ls\frac{\partial u_x}{\partial r}\bigg|_{r\to r_w} \tag{15}$$

$$T_j = T_w - T_f\bigg|_{r\to r_w} = \frac{Ls}{Pr}\frac{\partial T}{\partial r}\bigg|_{r\to r_w} \tag{16}$$

In these equations, $L_s$ is called slip length and it denotes the amount of distance among a point if no-slip condition satisfies in that point and flow velocity becomes equal to slip velocity in the wall. This number becomes dimensionless as $\beta^* = \frac{Ls}{D}$. In this investigation, Reynolds number Re = 50,100,500 and volume fraction of solid nanoparticles are $\phi = 0$, 1 per cent, 2 per cent as well as slip coefficient $\beta^* = 0.0$, 005, 0.05 have been examined.

### *3.3 Convergence criterion*

Simple numerical technique has been utilized to solve the equations and to determine the convergence between two groups. Initially, the remainder of governing equations has been solved as weighted by the coefficients and normalized by the value of residue from fifth iteration. The weighted form of remainder of parameter-X is defined according to numerical discretization of that equation:

$$R^X = \frac{\sum_{cells\ \ P} \left| \sum_{nb} a_{nb} X_{nb} + b - a_p X_p \right|}{\sum_{cells\ \ P} \left| a_p X_p \right|} \tag{17}$$

In addition, this value is normalized according to fifth iteration as follows:

$$\overline{R}^{\mathrm{X}} = \frac{R^{\mathrm{X}}}{R^{\mathrm{X}}{}_5} \tag{18}$$

The first convergence criterion in these equations was smaller value of this remainder than $10^{-6}$ and the second criterion was the lesser variances of physical parameters such as temperature of bulk wall, maximum and minimum of slip velocity and temperature jump in wall, and quantities of velocity and temperature at several points within solution range from quantity of $10^{-6}$ along with five iterations.

## 4. Results and discussion

### *4.1 Independence of results from the grid*

To determine the effect of a grid on numerical results and their independence from grid size, flow with Reynolds number 500 modeled in various grids then the temperature and dimensionless velocity were examined in a point called 1 with dimensionless coordinates (12.5, 0.0). The results of this study are given in Table III. No other change was observed in grid (1,000 × 40) following to smaller size of grid in the results and consequently this grid has been utilized for all of calculations.

### *4.2 Validation of numerical solution*

The method of operational slip condition (Raisi *et al.*, 2012) was employed for validation of numerical solution and profiles of developed velocity in water-copper nanofluid were compared inside a microchannel for different values of velocity slip coefficient in Re= 50, $\varphi$ = 0.03 per cent. Figure 2 compares the calculated velocity profiles in the current study with the reference work and indicates full compliance with the results. The method of modeling non-Newtonian fluid has been also used for validation in study of Keshavarz *et al.* (2012). The comparison of averaged heat transfer coefficient for non-Newtonian nanofluid of Xanthan-aluminum oxide in a tube was given for two different weight percentage and Reynolds number $Re = 1510$ in Figure 3. The rate of calculated heat transfer is totally consistent with the values acquired by Keshavarz *et al.* based on model in the current study and it indicates correctness of modeling trend for non-Newtonian fluid. The main subject of research was modeled after ensuring from method of solution of problems under various

**Table III.** Temperature and dimensionless velocity in various grids

| Grid | $U_1$ | $\theta_1$ |
|---|---|---|
| 500 × 20 | 1.4570 | 0.6760 |
| 750 × 30 | 1.4580 | 0.6760 |
| 1000 × 40 | 1.4580 | 0.6770 |
| 1250 × 50 | 1.4580 | 0.6770 |
| 1500 × 60 | 1.4580 | 0.6770 |

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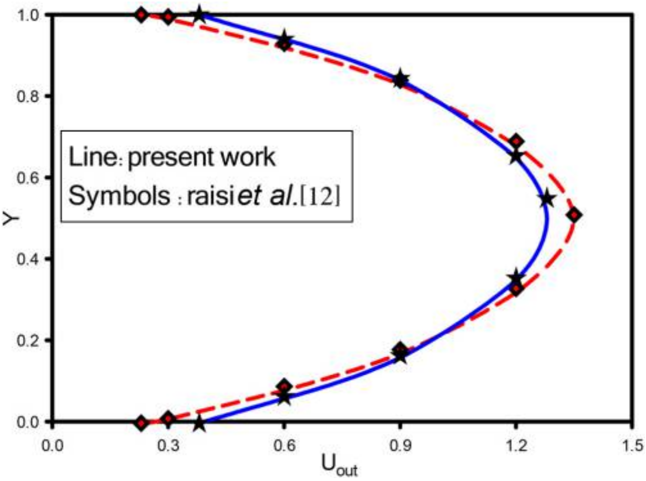

**Figure 2.** Comparison of velocity profile for validation of solution at various slip coefficients versus Raisi *et al.* (2012)

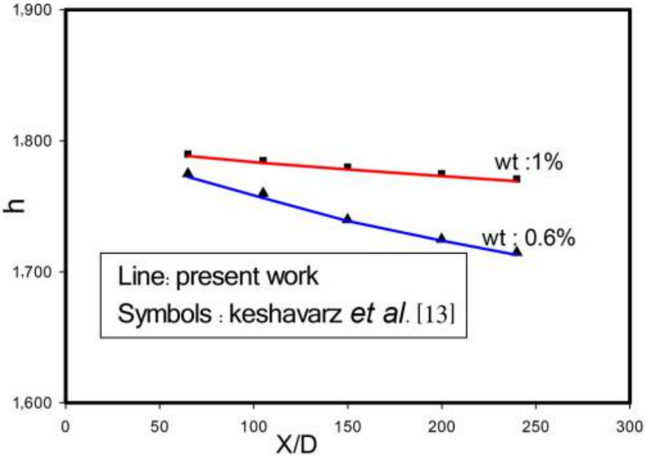

**Figure 3.** Comparison of heat transfer coefficient for validation of non-Newtonian fluid solution has been also used for validation in study of Keshavarz *et al.* (2012)

conditions. The results came from these modeling processes are given as diagrams of dimensionless velocity and dimensionless temperature through the channel and along with radial axis with total and local numbers along with the channel and discussed in the followings.

### *4.3 Effects of Reynolds number and volume fraction of nanoparticles*

The effect of Reynolds number for flow and volume fraction of nanoparticles to velocity at central line of channel is given in Figure 4. The value of dimensionless velocity is proved for the flow with Reynolds number 50 after point (X = 9) that indicates that the flow has been developed in terms of hydrodynamics after this distance but no development occurs in flow with Reynolds number 500 through this channel. The other point is reduction in velocity because of rising number of nanoparticles at central line and this is because of effect of nanoparticles on non-Newtonian parameters in the fluid and it has caused increase in flow strength and reduction in its velocity.

Figure 5 shows radial velocity at the middle of microtube for various volume fraction of nanoparticles and the aforesaid point is well visible in this figure. The velocity profile is given in Figure 6 for different Reynolds numbers at dimensionless length 18.75 and for volume fraction of 2 per cent and slip coefficient of zero. The velocity profile for flows at Reynolds numbers 50 and 100 which are developed at this length adjusted together and this indicates the velocity profile is independent from Reynolds at this region.

### *4.4 The effect of slip coefficient*

The effect of slip coefficient on form of velocity profile is shown in Figure 7 for Reynolds number 500 with volumetric percentage of 2 per cent in nanofluid and at length X = 18.75. Following to rise of slip coefficient, rate of velocity increases at the common boundary

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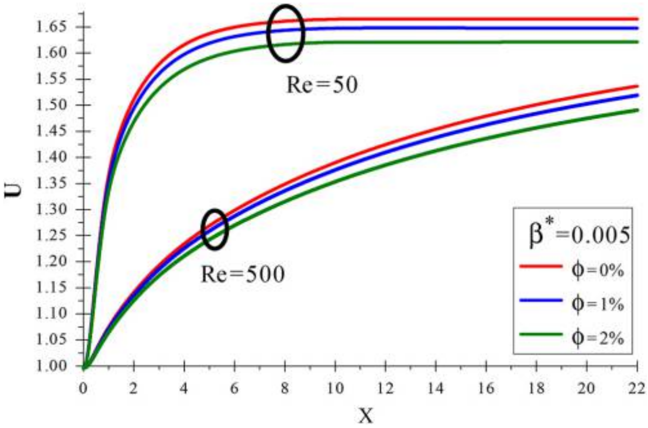

**Figure 4.** The velocity at central line of microtube at Reynolds numbers 50 and 500 and volume fraction of nanoparticles with slip coefficient of 0.005

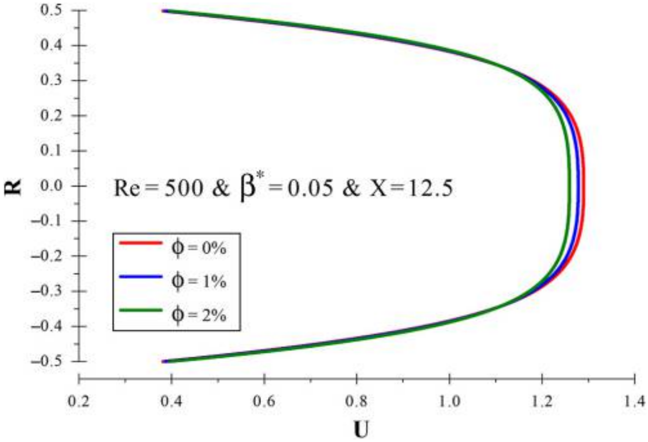

**Figure 5.** Velocity profile at the center of microtube for Reynolds number 500 and slip coefficient 0.005 at different volume fraction of nanoparticles

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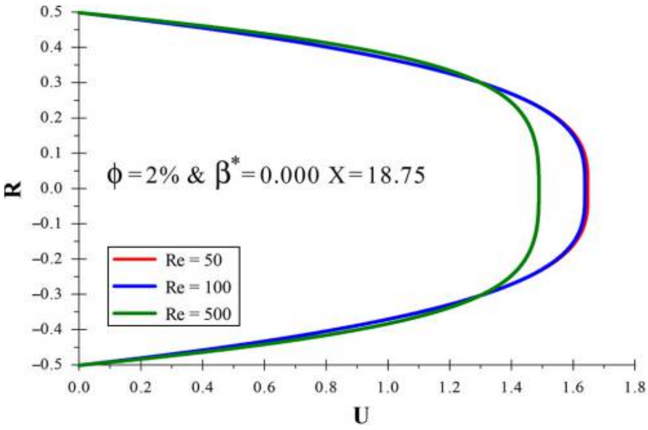

**Figure 6.**
Velocity profile in X = 18.75 for 2 per cent volume fraction and slip coefficient of zero with various Reynolds numbers

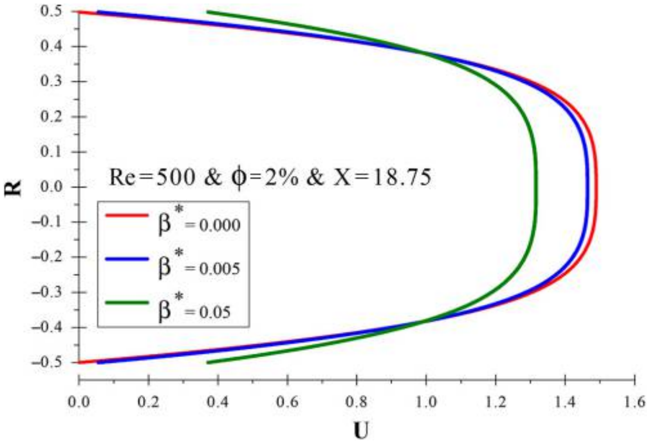

**Figure 7.**
Velocity profile at the center of microtube for Reynolds number 500 and volume fraction of (2%) at different slip coefficients

among fluid and solid and on the other hand maximum velocity indicates reduction at the given section i.e. more uniformity of velocity at radial axis.

The velocity profile is given in Figure 8 for Reynolds number 500 with volumetric percentage of 2 per cent and slip coefficient of 0.05 at two lengths (X = 6.25 and X = 18.75). It is observed in this figure that the slip velocity is not constant on the wall and it varies through the microtube. The other point is related to change in uniformity of velocity along microtube where this quantity is reduced by advancement through microtube. To determine effect of slip coefficient on velocity at central line of microtube, the quantity of this velocity has been drawn in Figure 9 at Reynolds numbers of 50 and 100 and slip coefficients of zero and 0.05 for volume fraction of 1 per cent. This figure indicates that rise of slip coefficient only influences in value of velocity and it has no effect on length of input region and at the same time, flow Reynolds number is only directly related to length of input region without any effect on the developed region.

The variance of slip velocity along wall of microtube is drawn in Figure 10 for flow with Reynolds number 100 and slip coefficient of 0.05 and for different volume fractions and it indicates that rise of nanoparticles leads to increase in slip velocity at wall.

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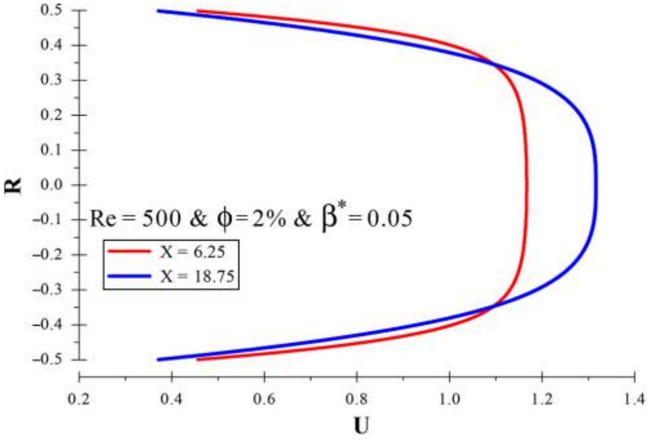

**Figure 8.** Velocity profile at two lengths of X = 6.25 and X = 18.75

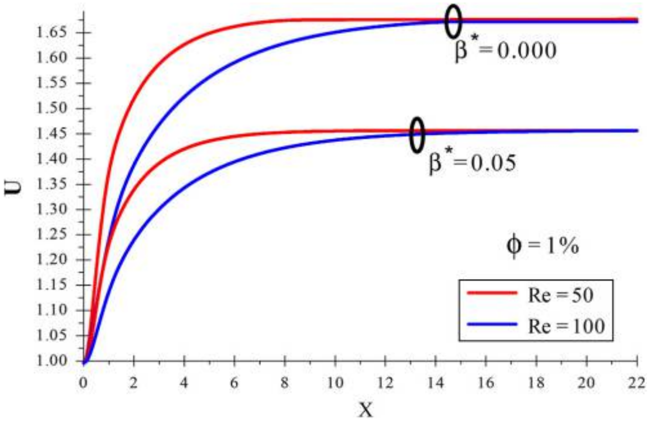

**Figure 9.** Velocity at central line of microtube at Reynolds numbers 50 and 500 and slip coefficients of zero and 0.05 for volume fraction of 1 per cent

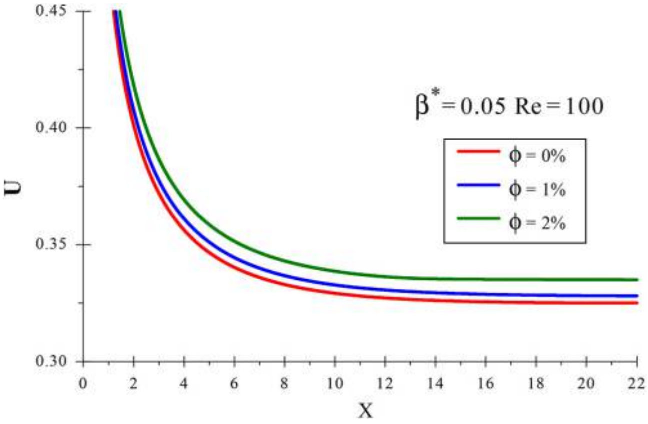

**Figure 10.** Slip velocity along with microtube wall for the flow with Reynolds number 100 and slip coefficient 0.05 and at various volume fractions

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### *4.5 Effect of Reynolds number and slip coefficient*

The effect of flow Reynolds number and value of slip coefficient on rate of slip velocity at wall is given in Figure 11. As it seen in Figure 11, the flow Reynolds number has no effect on final quantity of slip velocity similar to velocity at central line of microtube and it only approaches to this value by increase in flow Reynolds number and in fact input length increases. The slip velocity also increases following to rise of slip coefficient.

Regarding the given heat transfer in microtube, initially bulk temperature is calculated along with microtube at any section based on equation (13) and Reynolds numbers 50 and 500 and slip coefficients of zero and 0.05 have been drawn at volume fraction of 1 per cent in Figure 12. Given that temperature is constant in wall of microtube and higher than input fluid, rise of bulk temperature indicates absorption of heat from this wall by the fluid. As Reynolds number increases in flow, the gradient of this curve decreases since velocity of flow increases and therefore nanofluid has less opportunity for exchange of energy with microtube. This point does not mean reduction in total heat transfer in microtube; of course, and it only indicates that nanofluid has been less heated. On the other hand, it is observed that gradient of this curve is increased following to rise of slip at wall. Whereas discharge of

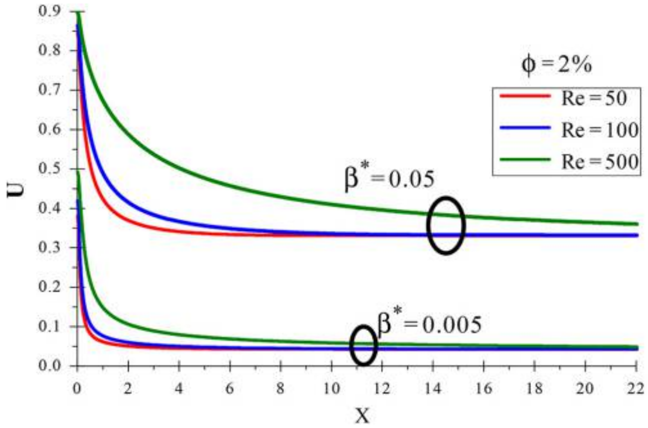

**Figure 11.**
Slip velocity along with microtube wall for the flow with volume fraction of 2 per cent and slip coefficients of 0.05 and 0.005 at different Reynolds numbers

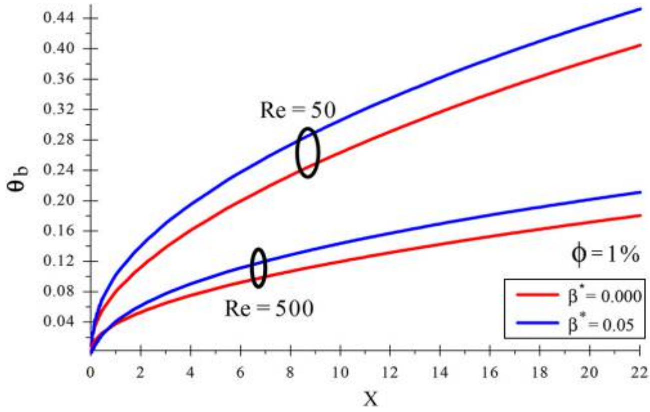

**Figure 12.**
Dimensionless bulk temperature along with microtube for Reynolds numbers 50 and 500 and slip coefficients of zero and 0.05

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flow is fixed at this mode, rising bulk temperature indicates better heat transfer in microtube.

Figure 13 indicates that gradient of bulk temperature curve for nanofluid is greater than the gradient of this curve for the base fluid and rise of volume fraction in nanoparticles also leads to increase in gradient at this curve. Temperature profile is drawn in Figure 14 at length X = 18.75 and volume fraction of 1 per cent and slip coefficient of 0.05 for different Reynolds numbers. Temperature has changed only at Reynolds number 50 at the center of this section of microtubeand in two other cases the effects of wall temperature have not yet reached to central line of microtube. The other point is related to the effect of Reynolds number on rate of temperature jump in wall where the rate of temperature jump is increased at wall as Reynolds number is added in flow.

Figure 15 indicates temperature profile with volume fraction of 2 per cent and Reynolds number of flow of 100 at length X = 18.75 for different slip coefficients. Total form of temperature profile has not varied tangibly and temperature jump has slightly increased by rise of slip coefficient and effect of wall temperature is slightly better transferred near to

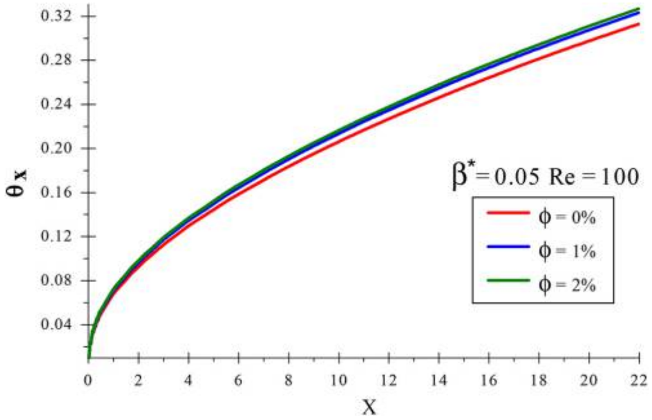

**Figure 13.**
Dimensionless bulk temperature through microtube for various volume fractions of nanofluid

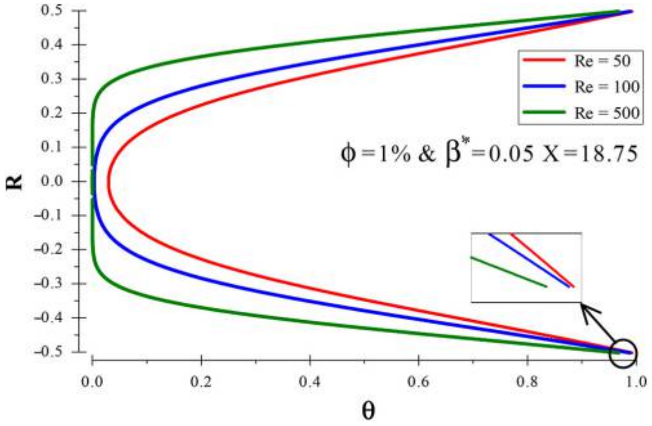

**Figure 14.**
Temperature profile at length X = 18.75 and volume fraction of 1 per cent and slip coefficient of 0.05 for different Reynolds numbers

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central line of microtube while temperature is more increased in this region, it is not too tangible. The effect of volume fraction of nanoparticles on temperature profile is given in Figure 16 for the flow with Reynolds number 50 and slip coefficient of 0.05 at length X = 18.75 for different volume fraction in nanofluid. This figure indicates that addition of nanoparticles to base non-Newtonian fluid does not tangibly influence in temperature profile.

### 4.6 Effect of Reynolds number, slip velocity and temperature jump

In case of absence of slip and temperature jump at wall, temperature of layer in nanofluid in contact with the wall will be the same as wall temperature but with the presence of slip phenomenon and temperature jump, this layer will no longer be isotherm with the given layer an as it seen in Figure 17, the temperature jump among nanofluid layer with the wall is increased as slip length is added and such a rise is directly related to Reynolds number in

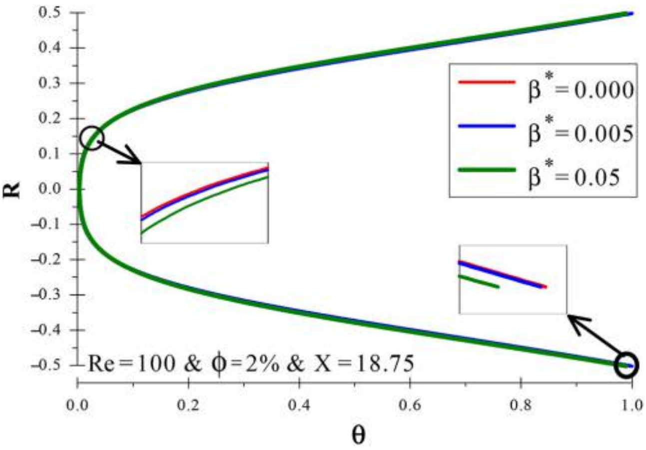

**Figure 15.** Temperature profile at length X = 18.75 and volume fraction of 2 per cent and Reynolds number 100 for various slip coefficients

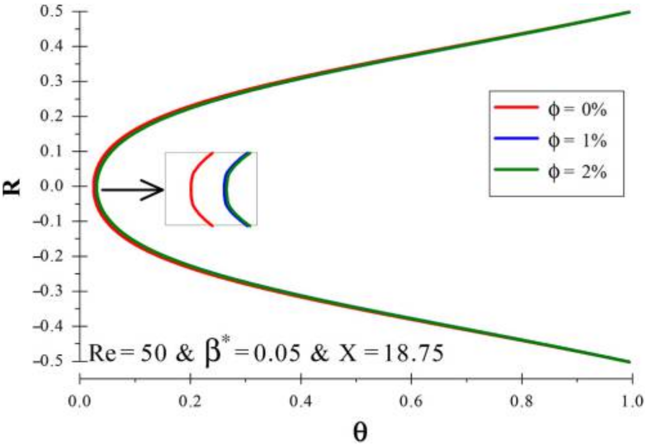

**Figure 16.** Temperature profile at length X = 18.75 and Reynolds number 50 with slip coefficient 0.05 for nanofluid

flow and as Reynolds number of flow is higher, the distance of temperature in fluid is further with temperature in wall and it needs more time to approach to temperature of wall so this is because of rise of fluid momentum energy at solid surface because of increase in Reynolds number.

Figure 18 indicates that rise of slip coefficient of flow leads to increase in rate of local Nusselt number through the channel and this rise of flow is further with higher Reynolds. The effect of volumetric percentage in nanoparticles on local Nusselt number is also given in Figure 19 and it indicates that rise of nanoparticles has led to increase in local Nusselt number at flow. It is seen in Figure 20 that rise in all three parameters of flow Reynolds number, slip coefficient, and volumetric coefficient of nanoparticles increases total Nusselt number in microtube but the impact of adding nanoparticles in flow is more efficient with lower Reynolds number and rise in slip coefficient may further impact on flow with higher Reynolds numbers.

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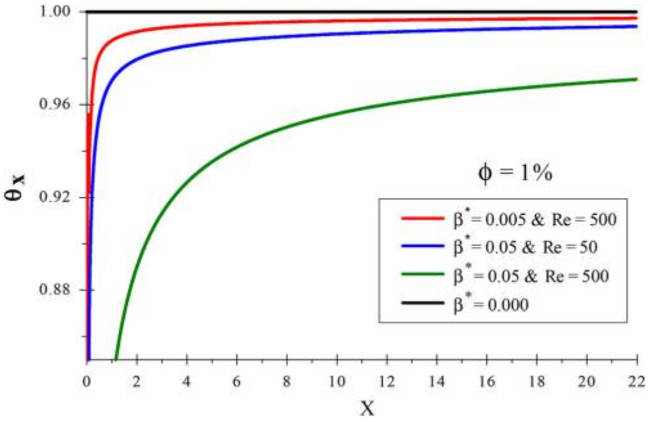

**Figure 17.**
The effect of slip coefficient and Reynolds number on temperature jump in microtube wall

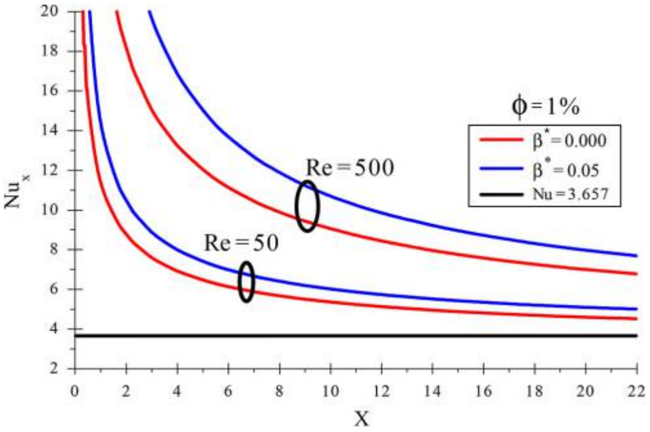

**Figure 18.**
The effect of slip coefficient and Reynolds number of flow on value of local Nusselt number for nanofluid 1 per cent

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## 5. Conclusion

The flow of non-Newtonian nanofluid of aqueous solution of carboxy methyl cellulose-aluminum oxide has been determined in a microtube for the first time (Sadeghi *et al.*, 2018; Karimipour *et al.*, 2017; Sajadifar *et al.*, 2017; Chamkha *et al.*, 2015; Chamkha and Rashad, 2012; Chamkha and Khaled, 2000; Kumar *et al.*, 2010; Umavathi *et al.*, 2005; Chamkha *et al.*, 2002; Reddy and Chamkha, 2018, 2017; Ben-Nakhi and Chamkha, 2007; Ben-Nakhi and Chamkha, 2006; Goodarzi *et al.*, 2014a; Behnampour *et al.*, 2017; Togun *et al.*, 2015; Safaei *et al.*, 2011; Nikkhah *et al.*, 2015; Esfe *et al.*, 2015d; Goodarzi *et al.*, 2014b; Alipour *et al.*, 2017; Karimipour *et al.*, 2015; Akbari *et al.*, 2016a, 2016b; Safaei *et al.*, 2014; Karimipour *et al.*, 2014; Goodarzi *et al.*, 2014c, 2015; Esfe *et al.*, 2014a; Afrand *et al.*, 2017; Karimipour *et al.*, 2013). The effect of various volume fraction of nanoparticles and different slip coefficients was explored under different conditions at surface of micro tube in Reynolds number below 500 on parameters of flow and heat transfer. The flow was modeled as single-phase by assuming homogeneity and isotherm state of nanoparticles and base fluid. However,

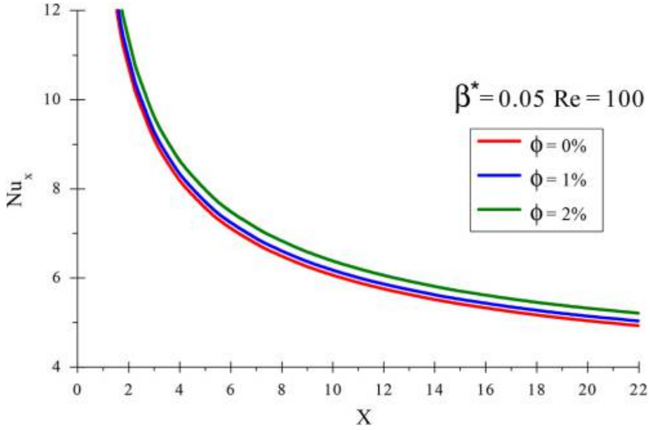

**Figure 19.**
Effect of volume fraction of nanoparticles on rate of local Nusselt for flow with Reynolds number of 100 and slip coefficient of 0.05

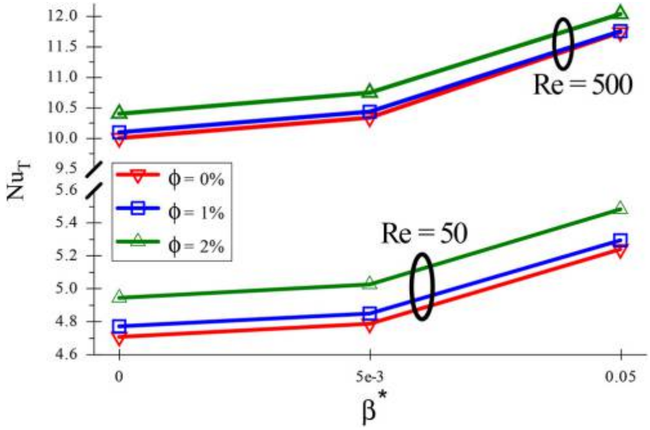

**Figure 20.**
Total Nusselt number in microtube at different modes

Brownian motion of nanoparticles has been designated in the given calculation in this model to compute thermal conductivity of nanofluid. It is seen that rise of volume fraction in nanoparticles may reduce maximum velocity of flow and make velocity profile more uniform at radial axis and similarly lead to increase in heat transfer among microtube and nanofluid and further increase in bulk temperature of nanofluid through the microtube but it has no tangible effect on temperature profile at radial axis. Similarly, addition of nanoparticles has increased total heat transfer in microtubeand this rise is more visible in fluid with lower Reynolds number.

Change on the surface of microtube and preparation of conditions for greater slip on that surface was led to rise of flow slip coefficient which may cause the velocity profile to become more uniform in flow and increase maximum velocity in microtube and at the same time because of creating stronger flow near to the wall it increases rate of heat transfer in microtube and such a rise shows the flow further by increase in Reynolds number.

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