# Numerical investigation of CuO nanoparticles effect on forced convective heat transfer inside a mini-channel : Comparison of different approaches

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**Abstract:** This paper proceeds numerical investigation on forced convective heat transfer of nanofluids in laminar flow inside a mini-channel with circular cross-section under constant heat flux boundary condition at walls. Nanofluid contains CuO nanoparticles with diameter of 50 nanometer in water base fluid. At the entrance of channel, profiles of uniform velocity & temperature prevail. In order to obtain fully developed profiles, geometry of problem considers as *L/D* = 100. Problem is solved by means of 4 different models, including Homogeneous and Dispersion models in both of constant and variable thermophysical properties through the finite-volume method. The temperature-dependent properties was used for the first time in nanofluids dispersion model. It was regarded in the presence of nanoparticles the heat transfer coefficient will be increased to some considerable extent and the heat transfer enhancement strongly depends on the volume concentration of nanoparticles and Peclet number. Also, comparison with experimental data and literatures' correlations is carried out which indicates the Dispersion model in both cases is more precise and Homogeneous model (single phase) underestimates the Nusselt number in constant thermo physical properties.
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## 1. Introduction

For over a century since Maxwell **[1,2]** attempts have been made to increase the thermal properties of fluids by dispersing the particles in the millimeter and micrometer scales. This issue has been carried major problems such as wall abrasion, channel clogging, poor suspension stability and high pressure drop that using them never ended up with an appropriate practical form. Along with the appearance of nanotechnology and production of particles in nanoscales, a new category of fluids has been introduced as nanofluids that their advent was directly related to the reduction of dimensions of systems while they did not have a portion in rheological problems associated with the old suspensions. In fact the innovative concept of nanofluids is taken from old Maxwell's idea that by decreasing size of particles and having a stable fluid with considerable thermal properties, has realized as a new fluid classification **[3]**.

For the first time, term of nanofluid was introduced at American Argon Institute as suspension of the base fluid and nanoscale particles that these particles are usually 1 to 100 nm. Study on the behavior of nanofluids has started since the beginning of the twenty first century and annual publication of nanofluids has substantially increased from 1999 to 2005 that has grown to more than 70% **[3]**. The middle of the last decade (since 2005) most studies were carried out on heat transfer of nanofluids and determination of coefficients in both forced and natural convection. However, due to the higher use of forced convective heat transfer in the industry, it's portion was more than natural convection.

Herris et al. **[4]** had an experimental study on nanofluids heat transfer containing copper oxide (CuO) and aluminum oxide ($Al_2O_3$) nanoparticles in water based fluid which was under laminar flow to turbulence. The results showed that by using $Al_2O_3$ particles heat transfer rate increased by 40% while increasing the thermal conductivity coefficient was less than 15%. Also Wen and Ding **[5]** did an experimental study on nanofluids convective heat transfer containing γ- $Al_2O_3$ particles and water based fluid in laminar flow inside the tube and their study was limited to the entrance region. They considered that the development of nanofluid convective heat transfer depends on more factors than improved thermal conductivity such as particles motion that made non-uniform distribution of viscosity field and thermal conductivity, and the reduction of boundary layer thickness.

Gradually theoretical and numerical analysis (CFD) on nanofluids heat transfer became popular and today many articles are about numerical solutions and comparison of their results with experimental data.

Maiga et al. **[6-8]** carried out comprehensive studies on the thermal properties of nanofluids and developed correlations in terms of volume concentration to calculate the thermal conductivity and viscosity of water-alumina and ethylene glycol-alumina nanofluids in either flow regimes. Furthermore, Equations were presented for Nusselt number in constant temperature and constant wall heat flux boundary conditions, in terms of Reynolds (*Re*) and Prandtl (*Pr*) Numbers. Heris et al. **[9-11]** conducted numerical researches on convective heat transfer of nanofluids through different circumstances. They also, validated their numerical results with their experimental data, which showed good agreement.

In order to have a definite picture of nanofluids applications in heat transfer processes, it is necessary to examine this class of fluids under different convective conditions. In this numerical investigation, forced convective heat transfer of CuO-water nanofluids is studied by means of 4 different models that includes Homogeneous and Dispersion models in two different modes of constant and variable thermophysical properties with temperature. The effect of temperature-dependent thermophysical properties on dispersion model has been used for the first time. The computational fluid dynamic code (CFD*) FLUENT 6.3* **[12]** is used for the numerical solution of the problem. Also, meshing of the problem conducted by *Gambit 2.2.3* software and discretized equations are solved by employing finite volume method in *FLUENT*.

## 2. Mathematical Modeling

### *2.1. Geometry & Boundary condition*

Fig.1 illustrates the geometry of problem under consideration which contains copper tube with length of 1.0 m and circular cross-section with diameter of 0.01 m. Laminar flow with axial velocity of $v_0$ and temperature of $T_0$ ($T_o$=293 *k*) enters and considers as a steady-state and 2D-Symmetric.

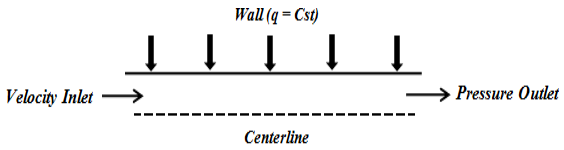


Fig1. Geometrical configuration

In order to obtain fully developed profiles, geometry of problem considers as *L/D* = 100. The fluid flow and thermal field are assumed to be symmetrical, so in order to save computational time, the half of tube is considered without compromising accuracy. At the inlet of tube, profiles of uniform axial velocity and temperature enter at atmospheric pressure. The channel wall, is under constant heat flux *q* (*q*=5000 w/m$^2$) and non-slip condition is imposed. Also, boundary condition at the exit section is pressure outlet where, fully developed condition is considered, i.e., axial derivatives are zero ($\partial/\partial x = 0$).

### *2.2. Thermophysical properties*

As results depend strongly on thermophysical properties, properties determination is a substantial part of a CFD problem. using the classical models for nanofluids seems to be a subject of debate. However, Due to the lack of experimental data for thermophysical properties calculation, it is satisfying. In this study, the most appropriate correlations were employed in order to obtain more precise results. For constant thermophysical properties, the following equations are used for density, specific heat, viscosity and thermal conductivity, respectively: [**13, 14**]

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\,\rho_p \quad (1)$$

$$C_{p_{nf}} = (1-\varphi)C_{p_{bf}} + \varphi\,C_{p_p} \quad (2)$$

$$\mu_{nf} = \mu_f(1+2.5\varphi) \quad (3)$$

$$k_r = \frac{k_{nf}}{k_{bf}} = \frac{k_p + 2k_f + 2\varphi\,(k_p - k_f)(1+\beta)^3}{k_p + 2k_f - \varphi\,(k_p - k_f)(1+\beta)^3} \quad (4)$$

In the case of temperature-dependent properties, model based on the Bianco et al. **[15]** correlations was used for determining viscosity and thermal conductivity of base fluid:

$$\mu_{bf} = -6.37\times10^{-4}\,T + 1.80\times10^{-6}\,T^2 - 1.73\times10^{-9}\,T^3 + 7.57\times10^{-2} \quad (5)$$

$$k_{bf} = 9.71\times10^{-3}\,T - 1.31\times10^{-5}\,T^2 - 1.13 \quad (6)$$

Lee and Peterson **[16]** proposed a model for CuO-water nanofluid's conductivity with T in C$^o$ :

$$\frac{k_{nf}-k_{bf}}{k_{bf}} = 3.76108\varphi + 0.017924\,T - 0.30734 \quad (7)$$

If T is calculated in *k* , eq.(7) turns :

$$\frac{k_{nf}-k_{bf}}{k_{bf}} = 3.76108\varphi + 0.017924\,T - 5.20059 \quad (8)$$

By using curve-fitting data for CuO-water nanofluids, Nguyen et al. **[17]** introduced following equation for temperature-dependent viscosity of nanofluids including water and CuO nanoparticles:

$$\frac{\mu_{nf}}{\mu_{bf}} = (1.475 - 0.319\varphi_p + 0.051{\varphi_p}^2 + 0.009{\varphi_p}^3) \quad (9)$$

For obtaining variable viscosity in different concentrations, following equations as a function of local temperature, are deriving by using eq. (9) in eq. (5) :

$$\varphi = 1\% \;:\; \mu_{nf} = -2.5465\times10^{-9}\,T^3 + 2.6496\times10^{-6}\,T^2 - 9.3766\times10^{-4}\,T + 0.1114 \quad (10)$$

$$\varphi = 3\% \quad : \quad \mu_{nf} = -2.5352 \times 10^{-9}\, T^3 + 2.6378 \times 10^{-6}\, T^2 - 9.3335 \times 10^{-4}\, T + 0.1109 \tag{11}$$

*2.3. Governing equations*

Mathematical modeling for homogeneous (single-phase) and dispersion models, are introduced separately which contains conservation, momentum and energy equations. The following equations represent governing formulations of present study:

2.3.1 Homogeneous model (Single phase):

In homogeneous model it was assumed that there exists no motion slip between phases and it can be considered host fluid and ultrafine particles are in thermal equilibrium. In this case, nanofluids with acceptable approximation can be treated as a pure fluid and all of the classical equations can be adopted for them just by using effective properties instead of pure fluids' properties:

- Conservation of mass:

$$div\ (\rho\vec{u}) = 0 \tag{12}$$

- Momentum equation

$$div\ (\rho\vec{u}\vec{u}) = -grad\ P + \nabla.(\mu\nabla^2\vec{u}) \tag{13}$$

- Energy equation:

$$div\ \left(\rho\vec{u}C_p T\right) = div\ (k\ grad\ T) \tag{14}$$

*2.3.2. Dispersion Model :*

Although the nanofluid behaves more like a fluid than the conventional solid-fluid mixtures in which relatively larger particles with micrometer or millimeter orders are suspended, it is a two-phase fluid in nature and has some common features of the solid-fluid mixtures. Because of the effects of several factors such as gravity, Brownian force and friction force between the fluid and ultrafine particles, the phenomena of Brownian diffusion, sedimentation, dispersion may co-exist in the main flow **[18]**.Under this hypothesis it can be said that motion slip will not be zero. As it mentioned in **[18]**, irregular and random movement of the particles in base fluid increases the energy exchange rate, i.e, thermal dispersion take place in the flow and it will flatten the temperature distribution and make the temperature gradient between the wall and fluid steeper, which enhances the heat transfer rate.

Xuan and Roetzel **[18]** for the first time , formulated this effect for the nanofluids (following correlations). They postulated irregular and random movements of nanoparticles, would lead to designate the temperature ($T'$) and velocity ($u'$) ( due to perturbation) in nanofluid's energy equation. Thus, it reads :

$$T = < T >^f + T', \vec{u} = < \vec{u} >^f + \vec{u}' \tag{15}$$

Which through the flow is defined as :

$$< T >^f = \frac{1}{v_f}\int_v T\ dV \tag{16}$$

$$< \vec{u} >^f = \frac{1}{v_f}\int_v \vec{u}\ dV \tag{17}$$

$$\frac{1}{v_f}\int_v T\ dV = 0 \tag{18}$$

The heat flux induced by thermal dispersion in flow can be given as :

$$q_d = (\rho C_p)_{nf} < \vec{u'}\mathrm{T}' >^f = -\boldsymbol{k}_d\ .\nabla < T >^f \tag{19}$$

Where $\boldsymbol{k}_d$ is the tensor of thermal conductivity (due to dispersion). Under these assumptions and by postulating that boundary layer between the fluid and ultrafine particles are negligible, equation (14) can be expressed as :

$$< \vec{u} >^f .\nabla < T >^f = \nabla.\left[\left(\alpha_{nf}\mathbf{I} + \frac{k_d}{(\rho C_p)_{nf}}\right).\nabla < T >^f\right] \tag{20}$$

By considering both effect of thermal conductivity tensor which includes both the molecular and dispersion effects. Thus it may take the following form :

$$k_{eff} = k_{nf} + k_d \tag{21}$$

It seems thermal dispersion tensor to be function of flow, thermophysical properties of nanofluid, size and shape of particles and volume concentration. Neither definite experimental nor theoretical correlation for calculating $k_d$ is proposed so far. Khaled and Vafai **[19]** in their literature, developed the following form by using porous media theory :

$$k_{\mathrm{d}} = c^*\ (\rho c_p)_{nf}\ \varphi\ h\ u_m \tag{22}$$

Where $h$ and $u_m$ are the half of channel and average bulk velocity, repectively. They proposed range of 0-0.4 for the unknown constant ($C^*$). In the present study, the value of 0.01 is used for $C^*$ by considering the mentioned range and comparing with experimental data.

After solving the energy equation, calculating the heat transfer coefficient and Nusselt number will be the main subjects. Average heat transfer coefficient and Nusselt number defined as:

$$h_{av} = \frac{1}{L}\int_0^L h(x)\,dx \tag{23}$$

$$Nu_{av} = \frac{h_{av}\cdot D}{k_0} \tag{24}$$

## 3. Numerical Method

To solve the sets of algebraic dicretized equations in finite volume approach, the computational fluid dynamic code *FLUENT* **[12]** is employed. In order to obtain precise results for momentum and energy equations, second order upwind scheme is used. Moreover, by considering the steady state flow and result convergence, the Simple $C^1$ algorithm is imposed for pressure field- velocity connection. Also, residuals resulting from the integration of governing

equations are considered as convergence criterion. In order to ensure the accuracy of numerical results, grid independency for pure water in *Re*=750 was checked which can be seen in tab.1. Scant discrepancy between results shows the desirable accuracy of numerical method.

Validating the computer model is the crucial part of the CFD problem. Fig.2. illustrates Successful validation of numerical code with well-known Shah **[20]** correlation for pure water under constant heat flux boundary condition inside a circular tube.

Tab.1. Grid independency

| No. grid Cells in x-dir | No. grid Cells in r-dir | $Nu_{av}$ | $\Delta Nu_{av}$ |
|---|---|---|---|
| 540 | 42 | 6.607 | 0.021 |
| 620 | 26 | 6.554 | 0.074 |
| 700 | 20 | 6.628 | 0 |
| 780 | 32 | 6.606 | 0.022 |
| 820 | 16 | 6.544 | 0.084 |

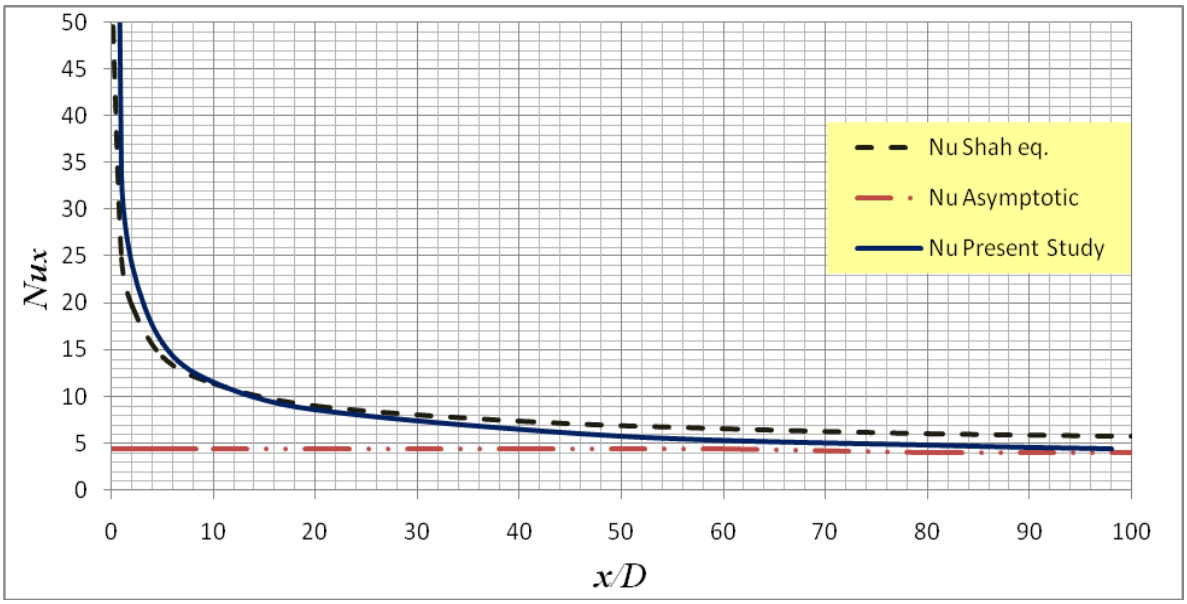


Fig.2. Grid validation (Pure water , *Re*=750)

**4. Results**

Results were carried out employing 4 different models. Fig.3. shows variation of heat transfer coefficient along tube length for nanofluid including CuO particles in *Re*=750. It's possible to observe an increase in heat transfer coefficient when volume concentration increases. This issue is more intensive in the case of temperature dependent properties which would due to the thermal conductivity dependency to temperature (increase in thermal conductivity will lead to heat transfer coefficient augmentation).Also, it can be seen, in the case of variable properties increase in the curve slope at the entrance region is more than the case of constant properties (specially in *x*=0-0.2 m).

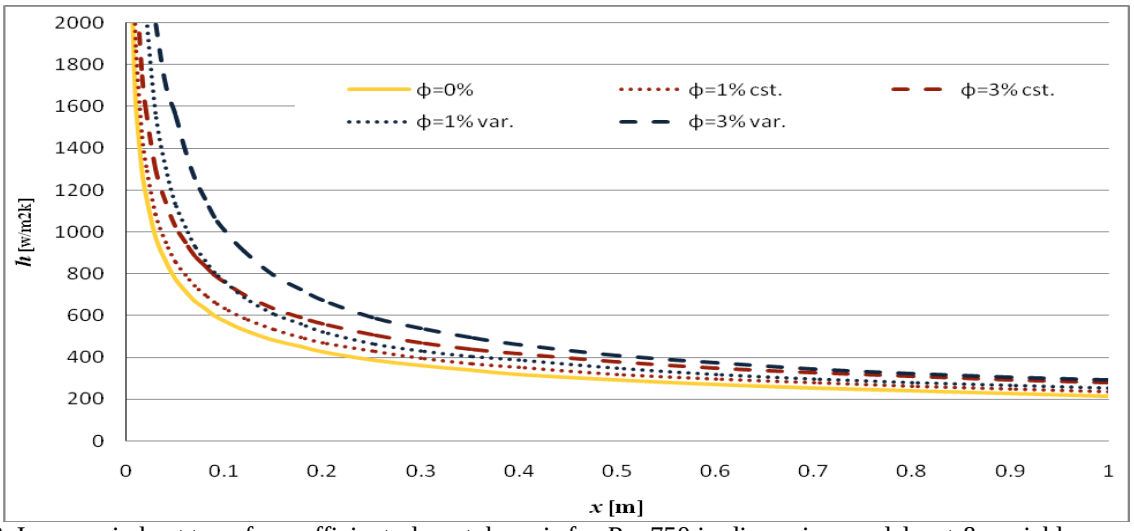


Fig. 3. Increase in heat transfer coefficient along tube axis for *Re*=750 in dispersion model: cst & variable properties

In order to compare and validate the numerical results, it's necessary to check the results with experimental data and theoretical correlations. Fig.4. and 5. display Nusselt number as a function of Peclet number and compare the results for volume concentrations of 1% and 3%.

For precise comparing of present study with Herris et al. **[4]** experimental data, Nusselt number considered as a function of Peclet number. Also, it should be noted Herris et al. **[4]** have conducted their examination under the constant temperature boundary condition while, present study has constant wall flux boundary condition which would cause of a slight error in comparison of Nusselt number. In order to obtain accurate induction and by deriving this fact that Nusselt number in developing laminar flow inside a circular tube is averagely 20% higher for constant heat flux boundary condition with respect to constant temperature **[20,15]** , results of Herris et al. **[4]** were corrected by means of 20% increase.

Clearly can be seen, for $\varphi = 1\%$ in fig.4. , dispersion model in constant properties shows a good agreement with Xuan & Li **[21]** correlation. Discrepancy between two models in constant properties is slight (lower Peclet numbers, particularly). Dispersion model in variable properties is compatible with Maiga et al. **[7]** correlation, while Nusselt numbers for constant properties in dispersion model are very close to experimental data. Homogeneous model for $\varphi = 3\%$ in constant thermophysical properties, underestimates the results. However, dispersion model in both states of properties and homogenous model in temperature-dependent model, demonstrate the good compatibility with other data. Moreover, it's possible to see by increasing the Peclet number, differences between 4 models increase, slightly.

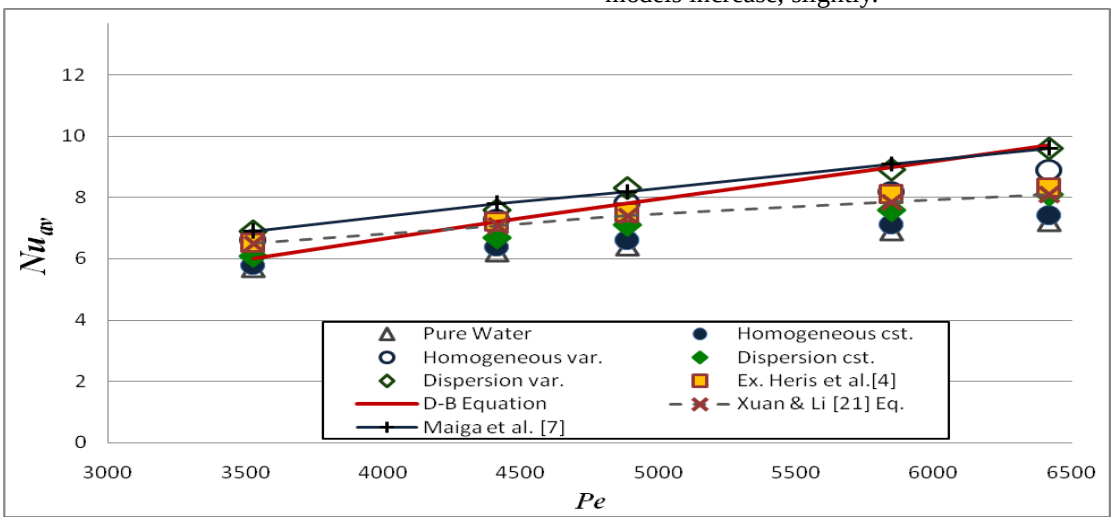


Fig.4. Nusselt number as a function of Pe for : $\varphi = 1\%$

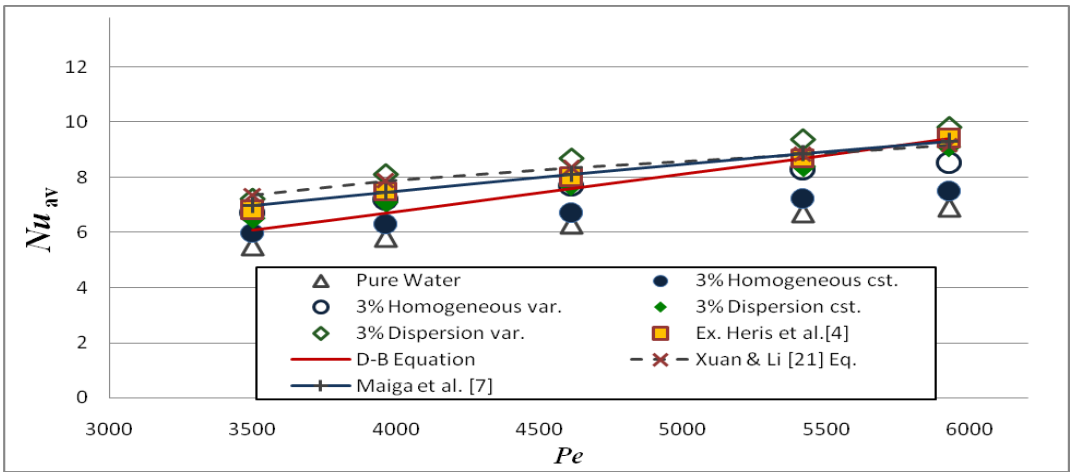


Fig.5. Nusselt number as a function of Pe for : $\varphi = 3\%$

## 5. Conclusions

In this numerical study, convective heat transfer of water-copper oxide nanofluid was evaluated by four different models. Was observed in the presence of the nanoparticles heat transfer coefficient will increase the amount and heat transfer enhancement depends strongly on the volume concentration of nanoparticles and Pecelt number.

Dispersion model in both constant and temperature-dependent thermophysical properties is shown appropriate compatibility with experimental results and the theoretical correlations. Comparing both constant and variable properties for each model, it can be said variable properties often estimates larger amounts than constant properties. The values for Nusselt number were more desirable when dispersion method was employed in comparison with the homogeneous model (single-phase), which can be due to the fact that augmentation in nanofluids heat transfer would not be attributed only to increase their thermal conductivity but the dispersion of nanoparticles, non-zero slip velocity between particles and base fluid can be reasons for improvement of nanofluids heat transfer.

At the end, for more favorable modeling, and due to the lack of empirical data and independent correlations, requirement of models which accurately predict the convective mechanisms of nanofluids is actually felt.

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