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Numerical Study of Laminar Mixed Convection Heat Transfer of a Nanofluid in a Concentric Annular Tube Using Two-Phase Mixture Model

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***Abstract*—**Laminar mixed Convection heat transfer of a nanofluid with prescribed constant heat flux on the inner wall of horizontal annular tube has been studied numerically based on two-phase mixture model in different Rayleigh Numbers and Azimuth angles. Effects of applying of different volume fractions of Al_2O_3 nanoparticles in water as a base fluid on hydrodynamic and thermal behaviors of the fluid flow such as axial velocity, secondary flow, temperature, heat transfer coefficient and friction coefficient at the inner and outer wall region, has been investigated. Conservation equations in elliptical form has been utilized and solved in three dimensions for a steady flow. It is observed that, there is a good agreement between results in this work and previously published experimental and numerical works on mixed convection in horizontal annulus. These particles cause to increase convection heat transfer coefficient of the fluid, meanwhile there is no considerable effect on friction coefficient.

***Keywords*—**Buoyancy force, Laminar mixed convection, Mixture model, Nanofluid, Two-phase.

I. Introduction

IN recent decades, heat transfer is one of the vital processes in all industrials all over the world. For more than a century since Maxwell 1873 [1], scientists and engineers have made great effort to increase heat transfer characteristics of conventional fluids such as Water, Ethylene-Glycol, and Oil due to poor thermal conductivity for transferring the heat.

One of the main ways to overcome this defect is to utilize advanced fluids instead of conventional ones with higher thermal conductivity. They dispersed millimeter- or micrometer-sized solid particles in liquids. However the major problem with the use of such large particles was the rapid settling of these particles in fluids. Also increasing volume fraction of solid particles caused to several other problems such as abrasion and pressure drop.

Nowadays, new strategies are used in order to improve the effective heat transfer behaviors of such fluids. Using particles in nano-meter dimensions in liquids is one of these strategies which caused to produce nanofluids. The term '*nanofluid*' refers to a two-phase mixture with continues phase being generally a liquid and the dispersed phase constituted of 'nanoparticles' i.e. extremely fine metallic particles of size below 100nm [2].

Experimental work in a growing number of nanofluid research groups has discovered that nanofluids exhibit thermal properties superior to those of base fluids or conventional solid-liquid suspensions. Some of these works [3]-[5] have shown that, effective thermal conductivity of the suspension has increased by almost 20% compared to that of the base fluid by dispersing a relatively low volume fraction of particles. Lee et al. [5] showed that Oxide Ceramic nanofluids consisting of CuO or Al_2O_3 nanoparticles in ethylene-glycol and water as a base fluid exhibit higher thermal conductivity. For instance, by using Al_2O_3 nanoparticles with mean diameter of 13nm at 4.3% volume fraction, increasing of the thermal conductivity of water by 30% has been observed [3]. Although there is a substantial number of mechanisms proposed and modeling work related to enhanced conductivity. Wang et al. [6] were first to propose new mechanisms behind enhanced thermal transport in nanofluids, such as particle motion, surface action and electro kinetic effects. Also Xuan and Li. [7], suggested other possible mechanisms such as the increased surface area of nanofluids, particle-particle collision and the dispersion of nanoparticles. Moreover Keblinski et al. [8] proposed four microscopic mechanisms for the anomalous increase in the thermal conductivity of nanofluids, which include Brownian motion of the particles, molecular-level layering of the liquid at the liquid-particle interface, the effect of nanoparticle clustering and the ballistic rather than diffusive nature of heat conduction in the nanoparticles. Other investigations and researches have been done on different aspect related to nanofluids. Wang et al. [6], were first to study the effect of particle clusters and cluster distribution. Xie et al. [9] reported the effects of shape (spherical and cylindrical) of nanoparticles on the enhancement of thermal conductivity of SiC nanofluids. Yu and Choi, [10] were first to model the effective thermal conductivity of nanofluids with a cubic arrangement of spherical nanoparticles with shells and to show a nonlinear dependence on the particle volume concentration of the effective thermal conductivity of nanofluids containing spherical nanoparticles.

Experimentalists have shown that nanofluids have not only better heat conductivity but also greater convective heat transfer capability than that of base fluids. Experiments show

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unexpectedly that the heat transfer coefficients of nanofluids are much better than expected from enhanced thermal conductivity alone in both laminar and turbulent flow. Such enhancement of convective heat transfer has inspired several investigators to propose new mechanisms of enhanced convection heat transfer coefficient. In the flow of a nanofluid, thermal dispersion, particle migration, and Brownian diffusion may be some mechanisms of enhanced convection in nanofluids. Xuan and Roetzel [11] were first to employ the concept of thermal dispersion for modeling enhanced convection in nanofluids. This concept adds a fictitious conductivity called the thermal dispersion coefficie*nt* to the effective thermal conductivity of nanofluids by assuming that there is velocity slip between nanoparticle and liquid and that the nanoparticle induces a velocity and temperature perturbation.

Khaled and Vafai [12] investigated the effect of thermal dispersion on heat transfer enhancement of nanofluids. Ding and Wen [13] were first to develop a theoretical model to predict particle migration in pressure-driven laminar pipe flows of relatively dilute nanofluids. They showed that shear-induced, viscosity gradient-induced, and concentration gradient-induced particle migration results in the large radial variation of particle distribution, viscosity, and thermal conductivity.

There are two different approaches for modeling convective heat transfer consists of nanofluids as single phase and two-phase approach. In first approach, it is assumed that relative velocity is zero. It means that fluid phase and nanoparticles move with the same velocity. Thermal equilibrium of nanofluid is another assumption in this approach [14], [15]. Two-phase approach is define as a mixture the phase of liquid and solid. This approach provides the possibility of understanding the functions of both the fluid phase and the solid particles in the heat transfer process [16]. Compared to the two-phase approach, first approach is simpler and requires less computational time. Thus first approach has been utilized in several investigations of convective heat transfer with nanofluids [2], [17]-[20]. But there is not good agreement between numerical predictions and experimental results because of the fact that the effective properties of nanofluids are not known accurately. It is stated that some important factors such as gravity, friction between fluid and solid particles, Brownian forces, the phenomena of Brownian diffusion, sedimentation and dispersion may coexist in the main flow of a nanofluid. This means that the slip velocity between the fluid and particles may not be zero [7]. Recently Behzadmehr et al. [21] studied mixed convection of a nanofluid by using two-phase approach. They showed that two-phase approach is more precious than the single phase approach.

Mixed convection in concentric annular tube is often encountered in engineering applications such as heat exchangers, gas-cooled nuclear reactors and gas turbines. Moreover study on mixed convection heat transfer, provides insight into the distinctive feature of the thermal field such as buoyancy force and its effects on hydrodynamic and thermal behaviors of a fluid flow throughout the tubes. Buoyancy force acts in vertical direction and create a secondary lateral flow inside the tube which enhance heat transfer [22]-[28].

In the present study, laminar mixed convection of a nanofluid in a concentric horizontal annular tube is investigated with using two-phase mixture model. This study has focused on different volume fraction of nanoparticles and their concentration and related thermal and hydro dynamical effects on fully developed flow through the annuli. Also various Ra-Re numbers have been utilized and results have been compared and discussed in terms of velocity and temperature profiles, convective heat transfer coefficient and inner and outer skin friction coefficients.

II. Mathematical Formulation

Mixed convection of a nanofluid consist of water as a base fluid and Aluminum Oxide (Al_2O_3) as nanoparticles, in horizontal concentric annular tube with a prescribed constant and uniform heat flux on the inner wall and an adiabatic outside wall is analyzed. The physical properties of the fluid are assumed constant except for the density in the body force, which change linearly with the temperature changes (Boussinesq's hypothesis). Dissipation term and pressure work are neglected in this study. Dimensional conservation equations for steady state condition are as follows:

Continuity equation:

$$\nabla.\left(\rho_m \vec{v}_m\right) = 0 \tag{1}$$

Momentum equation:

$$\nabla.\left(\rho_{m,0} v_m v_m\right) = -\nabla P + \nabla.[\tau] - \rho_{m,0}\beta_m\left(\mathrm{T}-\mathrm{T}_0\right)g + \nabla.\left(\sum_{k=1}^{n}\Phi_k\rho_k V_{dr,k}V_{dr,k}\right) \tag{2}$$

Energy Equation:

$$\nabla.\sum_{k=1}^{n}\left(\alpha_k \vec{v}_k\left(\rho_k E_k + P\right)\right) = \nabla.\left(K_{eff}\nabla \mathrm{T}\right) \tag{3}$$

Volume fraction:

$$\nabla.\left(\phi_p\rho_p\vec{v}_m\right) = -\nabla.\left(\phi_p\rho_p\vec{v}_{dr,p}\right) \tag{4}$$

Effective density:

$$\rho_m = \sum_{k=1}^{n}\phi_k\rho_k \tag{5}$$

where ϕ_k is volume fraction of phase k.

Mean velocity:

$$\vec{v}_m = \frac{\sum_{k=1}^{n}\phi_k\rho_k\vec{v}_k}{\rho_m} \tag{6}$$

Shear stress:

$$\tau = \mu_m \nabla V_m \tag{7}$$

In (2), $V_{dr,k}$ is the drift velocity for the nanoparticle phase:

$$V_{dr,k} = V_k - V_m \tag{8}$$

The slip velocity (relative velocity) is defined as the velocity of a secondary phase (p) relative to the velocity of the primary phase (f):

$$V_{pf} = V_p - V_f \tag{9}$$

The drift velocity is related to the relative velocity:

$$V_{dr,p} = V_{pf} - \sum_{k=1}^{n} \frac{\Phi_k \rho_k}{\rho_m} V_{fk} \tag{10}$$

Manninen et al. [29] proposed (11) for determining the relative velocity:

$$V_{pf} = \frac{\rho_p d_p^{\ 2}}{18 \mu_f f_{drag}} \frac{(\rho_p - \rho_m)}{\rho_p} a \tag{11}$$

Equation (12) by Schiller and Naumann [30] is used for calculating the drag function when Re_p is very low and the flow regime is laminar:

$$f_{drag} = \begin{cases} 1 + 0.15 \mathrm{Re}_p^{\ 0.687} & \mathrm{Re}_p \le 1000 \\ 0.0183 \mathrm{Re}_p & \mathrm{Re}_p \succ 1000 \end{cases} \tag{12}$$

where acceleration (a) in (11) is:

$$\vec{a} = g - (V_m \cdot \vec{\nabla}) \vec{V} \tag{13}$$

and

$$\mathrm{Re}_p = \frac{u_m d_p}{\upsilon_{nf}} \tag{14}$$

Effective viscosity:

$$\mu_{nf} = (123\phi^2 + 7.3\phi + 1)\mu_f \tag{15}$$

Effective thermal conductivity is determined by Chon et al. [31] correlation which considers the Brownian motion and nanoparticles mean diameter:

$$\frac{K_{eff}}{K_{BF}} = 1 + 64.7 \times \phi^{0.7460} \left(\frac{d_{BF}}{d_p} \right)^{0.3690} \left(\frac{K_p}{K_{BF}} \right)^{0.7476} \times \mathrm{Pr}^{0.9955} \times \mathrm{Re}^{1.2321} \tag{16}$$

where

$$\mathrm{Pr} = \frac{\mu}{\rho_{BF} \alpha} \tag{17}$$

$$\mathrm{Re} = \frac{\rho_{BF} K_b T}{3\pi \mu^2 l_{BF}} \tag{18}$$

$K_b = 1.3807 \times 10^{-23}$ J/K is the Boltzman constant, l_{BF} is the mean free path of water as base fluid and μ is defined as following equation:

$$\mu = A \times 10^{\frac{B}{T-C}}, \; C = 140, \; B = 247, \; A = 2.414 \times 10^{-5} \tag{19}$$

Thermal expansion coefficient:

$$\beta_{nf} = \left[\frac{1}{1 + \frac{(1-\phi)\rho_f}{\phi \rho_s}} \frac{\beta_s}{\beta_f} + \frac{1}{1 + \frac{\phi}{1-\phi} \frac{\rho_s}{\rho_f}} \right] . \beta_f \tag{20}$$

III. Boundary Condition

This set of nonlinear elliptical equations has been solved using following boundary conditions:

At the *tube inlet* ($z = 0$)

$$V_z = V_0, \; V_\theta = V_r = 0, \; T = T_0 \tag{21}$$

At the *wall of inner tube* ($r = r_i$)

$$q_w = K \frac{\partial T}{\partial r}, \; V_r = V_\theta = V_z = 0 \tag{22}$$

At the *wall of outer tube* ($r = r_o$)

$$q_w = 0, \; V_r = V_\theta = V_z = 0 \tag{23}$$

At the *tube outlet* ($z = L$)

$$q''_w = k \frac{\partial T}{\partial r} = 0, \; \frac{\partial V_z}{\partial r} = 0, \; V_r = V_\theta = 0 \tag{24}$$

The diffusion flux in the direction normal to the exit plane is assumed to be zero for all variables and an overall mass balance correction is also applied.

IV. Numerical Method and Validation

This set of coupled nonlinear differential equations was discretized with the control volume technique. A second order upwind method was used for the convective and diffusive terms, and the SIMPLEC procedure was introduced for the velocity-pressure coupling. The discretization grid is uniform in the circumferential direction and non-uniform in the radial and axial directions. Fig. 1 shows the geometry of considered problem and grid distribution. It is finer near the tube entrance

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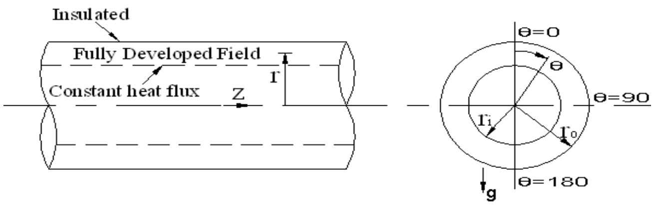
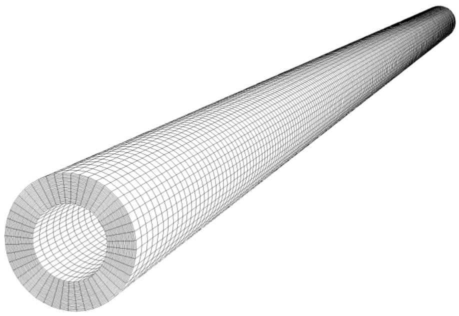
and near the wall where the temperature and velocity gradients are large. Several different grid distributions have been tested for ensuring of grid independency of calculated result. The selected grid for the present calculation consisted of 36, 36 and 160 nodes, respectively in the radial, circumferential and axial directions.



(a)



(b)

Fig. 1 (a) Schematic of the considered problem, (b) Grid distributions

Fig. 2 shows that increasing in the grid numbers does not significantly changes velocity and temperature profile at developing and fully developed regions. Other axial and radial profiles have also been verified to be sure the results are grid independent. Comparison with the previously published experimental simulations has been done in order to demonstrate the validity and also precision of the model and the numerical procedure. Fig. 3 shows the comparison of the calculated results with the experimental results of Nazrul Islam et al. [32] in horizontal annuli. Axial evolution of the circumferentially averaged Nusselt number was compared. Good agreement between the results is seen. Therefore the numerical procedure is reliable and it can predict developed mixed convection flow in horizontal annuli.

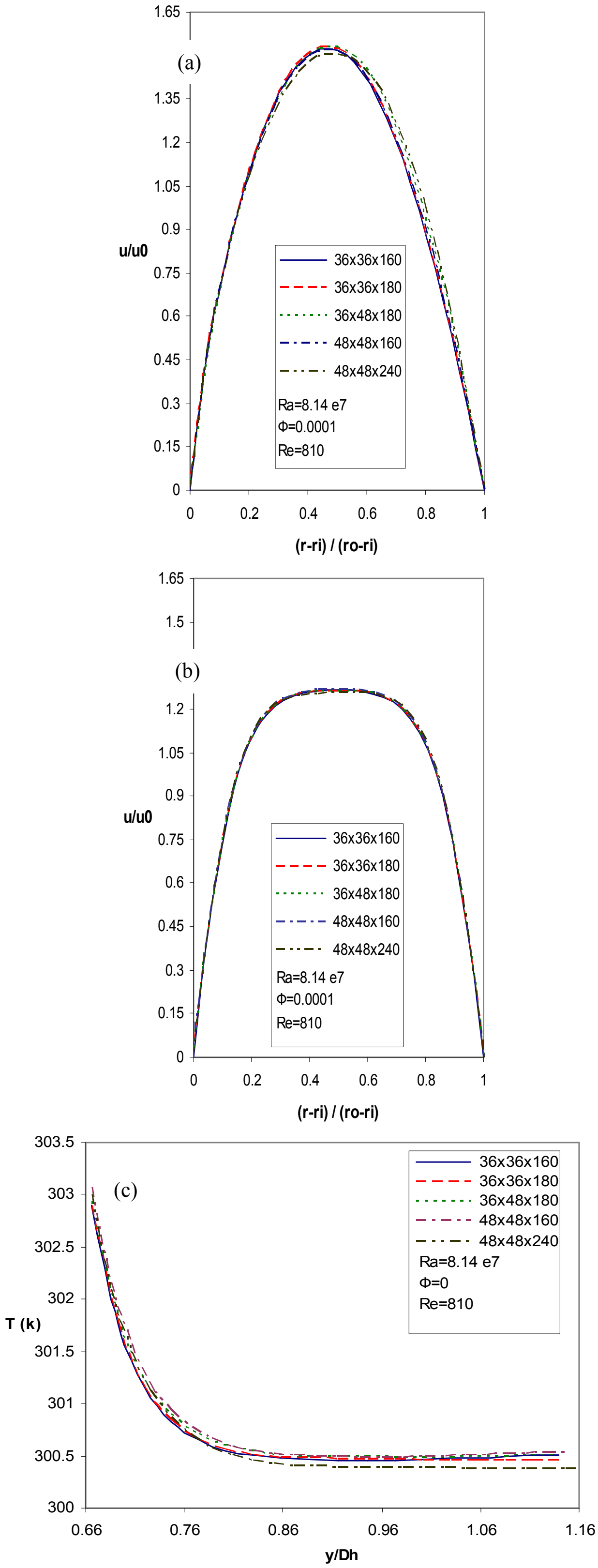


Fig. 2 (a), (b) and (c) Grid independence tests

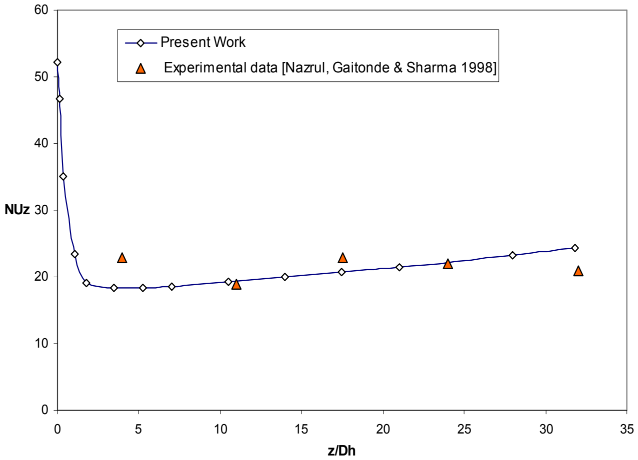


Fig. 3 Comparison of the circumferentially averaged Nu numbers in the horizontal annuli with the corresponding experimental results

V. Results and Discussion

Numerical simulations have been done on a wide range of Re and Ra numbers for four different values of particle volume fraction. However, because of similar behaviors, the results are expressed for three different Azimuth angles (0°, 90° and 180°), Re = 900, Two different heat fluxes ratios corresponding to the Ra = $8\times e6$ and $2.5\times e7$ and four particle volume fractions (0%, 1%, 3% and 5%) with spherical shape and 10nm mean diameter. Maximum Ra (or inner wall heat flux) at each Re are limited by the value of increasing bulk temperature. This value respects the suggested criteria for validation of Boussinesq approximation [16].

For a given Re and four different values of the Al_2O_3 particles volume fractions and also at three different azimuth angles, vectors of secondary flow and contours of temperature at fully developed region are shown in Figs. 4 and 5 As it is seen in Fig. 4, because of the buoyancy force, flow rises to the top of the annuli near the inner wall and descends toward the bottom at the other regions (through the vertical plane); therefore a secondary flow appears at the cross section of the annuli. Increasing the Rayleigh number, strengthen the buoyancy force; therefore a secondary flow appears at the cross section of the annuli. Increasing the Rayleigh number, strengthen the buoyancy force; consequently, stronger secondary flow is generated near the inner wall and top of the annuli. Also increasing volume fraction of nanoparticles augments the secondary flow. It is meant that for a constant heat flux, irregular motion of the nanoparticles increases the energy transport throughout the flow.

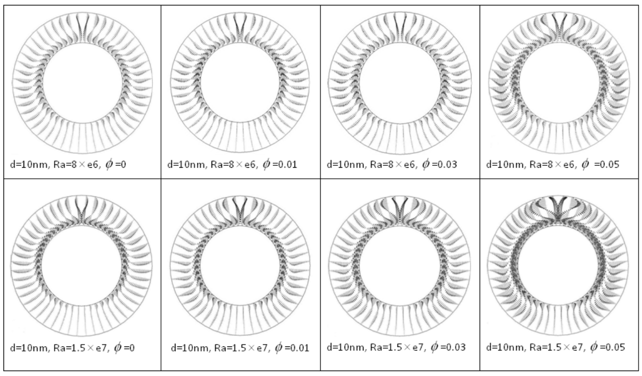


Fig. 4 Vectors of secondary flow for different Ra and ϕ at Re=900

Irregular motion of the nanoparticles increase the energy transport throughout the flow, consequently increasing the nanoparticles volume fractions also increases the secondary lateral flow. In fact the higher nanoparticles concentrations, is needed a higher heat flux to have constant Rayleigh number. Fig. 5 shows that the cross sectional temperature contours of the nanofluid flow. It is obvious that, maximum temperature appears at the top region of the annuli. Because the secondary flow transport the fluid from the bottom to the top of the annuli. Larger heat flux and also increasing the particle volume fraction create higher temperature which is directly related to the effects of the buoyancy force and secondary flow at the vertical plane.

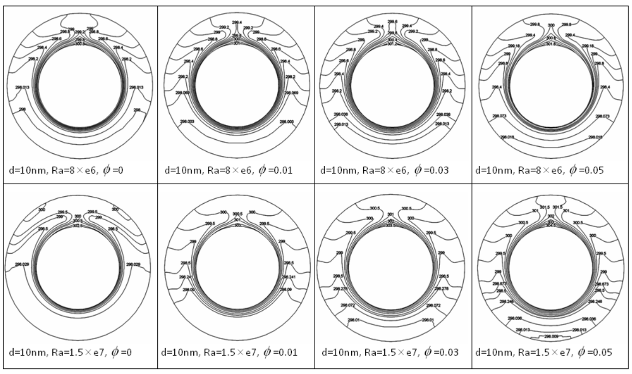


Fig. 5 Contours of temperature for different Ra and ϕ at Re=900

Fig. 6 shows dimensional axial velocity profiles at the fully developed region. As shown, dimensional axial velocity increases with nanoparticles volume fraction at different azimuth angles. This arises from the fact that, volume fraction changes the physical properties of nanofluid, therefore flow needs different mean velocity for different nanoparticles volume fraction to have Re as a constant value.

As it is seen, dimensional axial velocity profiles are various at different azimuth angles while it is uniform and strong at azimuth angle 90° and non uniform and weak at 0°. Because buoyancy force has maximum effect at the top of the annuli, therefore it displaces the position of the maximum axial velocity toward the lower portion of the annuli. Also by

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increasing the heat flux, buoyancy force creates larger secondary flow and displacement of the maximum axial velocity profile toward the lower portion is increased at all azimuth angles especially at top portion of the annuli.

Bulk temperature of the nanofluid is presented in Fig. 7 it is seen that bulk temperature increases linearly along the tube. Bulk temperature augments as volume fraction of nanoparticles increase. This may arise from the fact that, nanoparticles concentration increases the energy transport throughout the annuli.

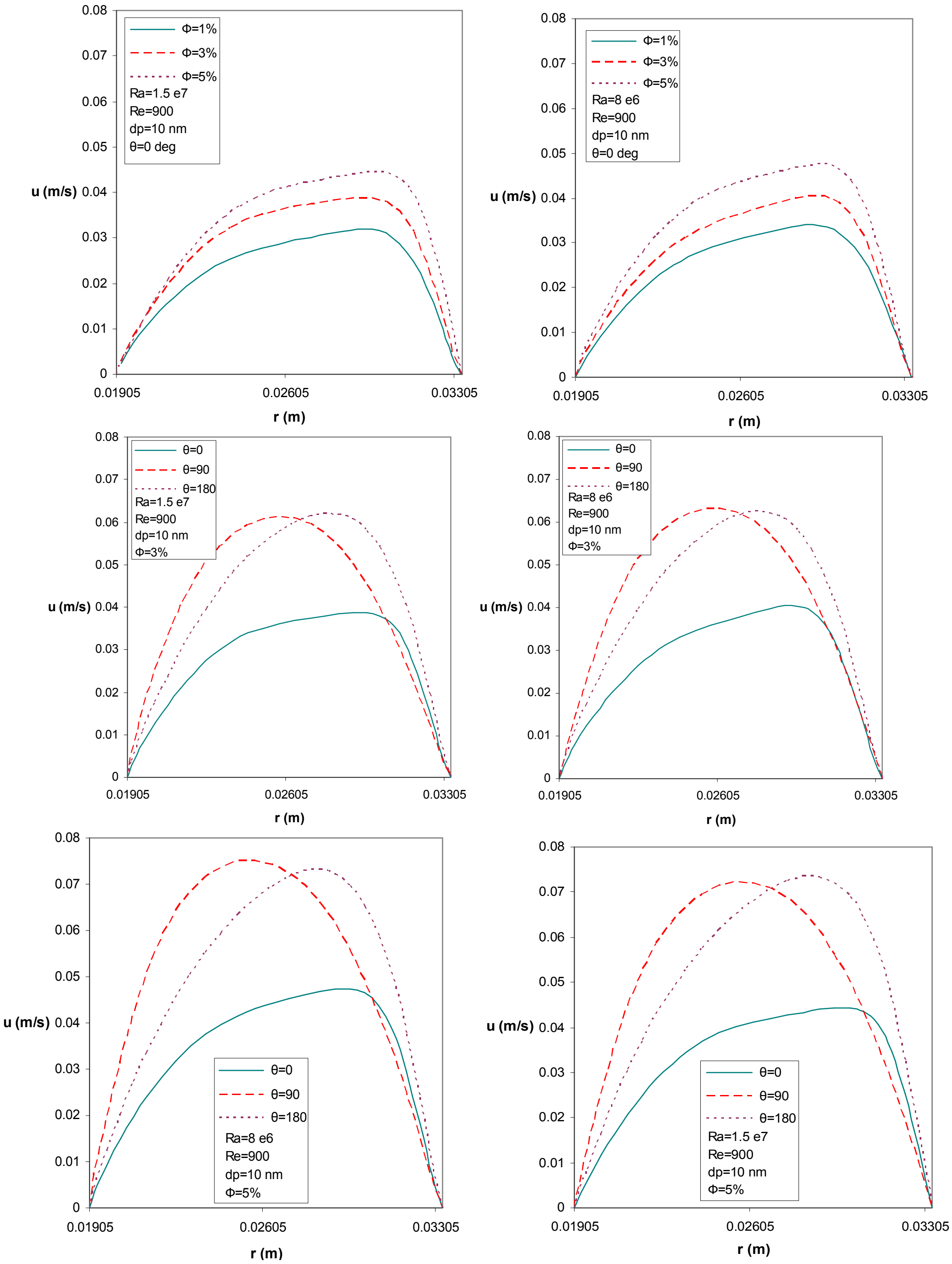


Fig. 6 Velocity profile for different Ra and ϕ at $\theta = 0$ and Re = 900

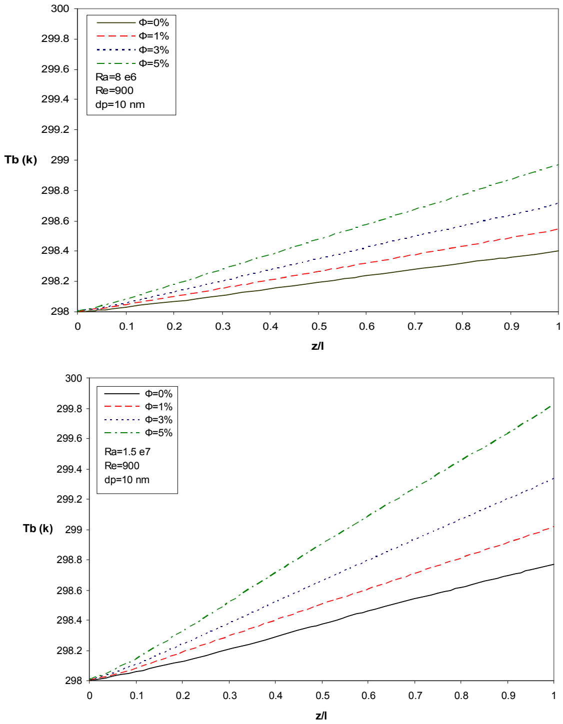
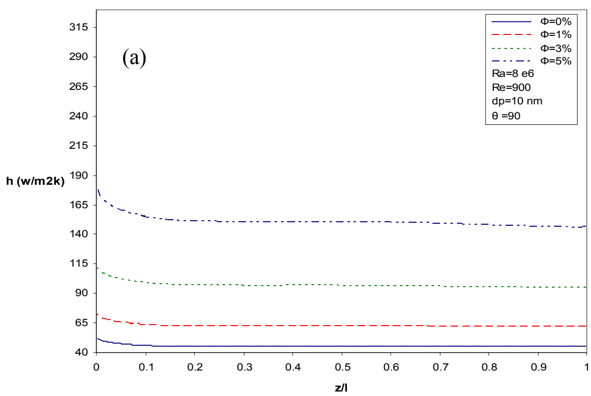


Fig. 7 Bulk temperature for different Ra and ϕ at Re=900

Axial evolution of the convective heat transfer coefficient is shown in Fig. 8. In general increasing the nanoparticles volume fraction increase the convective heat transfer coefficient at the fully developed region because of increasing temperature due to existence of nanoparticles. In all case, h decreases at the tube entrance and then goes monotonically to its value further downstream. The effect of secondary flow increases along the tube length (because of uniform heating along the tube length). The lateral enhances the heat transfer and therefore the convection heat transfer coefficient starts to increase and reach to its asymptotic value.



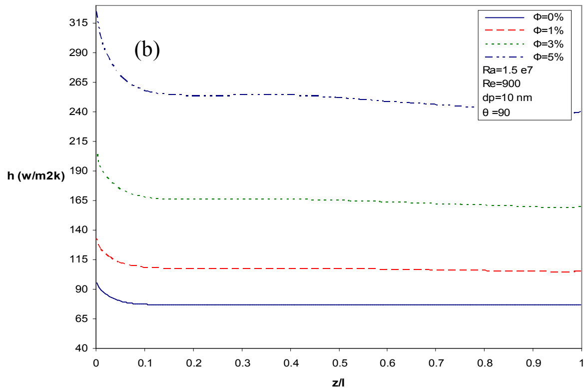


Fig. 8 (a) and (b) Convective heat transfer coefficient for different Ra and ϕ at Re = 900

Axial profile of friction coefficient at the inner wall and outer wall are presented in Fig. 9 It is seen that, skin friction coefficient does not significantly change with the nanoparticle concentration at this region. However, the effect of nanoparticle volume fractions at the entrance region is significant.

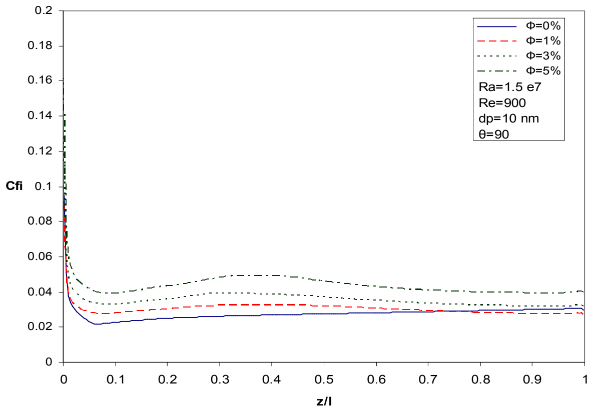


Fig. 9 Friction coefficient for different Ra and ϕ at Re = 900

VI. Conclusion

Fully developed laminar mixed convection of a nanofluid consists of water and Al_2O_3 has been considered numerically. Two-phase mixture model has been used to study numerically the effect of nanoparticles volume fraction on the hydrodynamic and thermal properties. The result showed that secondary flow strength is increased with augmentation of the nanoparticles volume fraction. Maximum temperature is appeared at the top of the annuli. With increasing nanoparticles concentration, the mean and bulk temperature of the flow is increased while the maximum axial velocity approaches to the bottom of the annuli. Significant enhancement on the convective heat transfer coefficient is observed with increasing the nanoparticles volume fraction while the skin friction coefficient at the fully developed region does not remarkably change. However, significant augmentation on the skin friction coefficient is observed at the entrance region of the annuli.

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