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Numerical investigation of Al_2O_3/water nanofluid forced convection in horizontal circular tube

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***Abstract*—Laminar forced convection of Al_2O_3/water nanofluid in a circular cross-section horizontal tube under constant surface heat flux has been studied numerically by employing single-phase model. The particle volume concentrations considered for analysis are 1%, 1.5% and 2% while the nano-particle size is 100nm. Effect of some parameters i.e. nano-particle concentration, surface heat flux and Reynolds number on the heat transfer characteristics has been analyzed. Selected range of Reynolds number is 200-1000. When compared with the previous published numerical and experimental result, it has been concluded that by applying a suitable correlation for the calculation of nanofluid effective thermo-physical properties, nanofluid heat transfer characteristics can be predicted accurately using the single-phase model.**

Keywords—Al_2O_3/water, single-phase model, nanofluid thermos-physical properties, Nusselt number, isotherm profiles

I. Introduction

To enhance the heat transfer characteristics of an organic or non-organic fluid, a uniform dispersion of chemically stable metallic or nonmetallic nanoparticles with high thermal conductivity in it is known as nanofluid. Since the invention of nanoparticles by Choi and Eastman [1], a number of studies by Y. Xuan *et al*. [2], Koo and Kleinstreuer [3], Kakac and Pramuanjaroenkij [4] and Godson *et al.* [5] reported that suspension of nano-particles significantly altercates the thermo-physical properties of the base fluid. Because of the high thermal performance and energy efficiency, nanofluids have replaced various conventional fluids in multiple engineering applications including engines, solar collectors, instrumentations and microsystems.

In previous two decades, despite of numerous experimental and numerical investigations on several nano-fluids under multiple operation conditions, there are significant discrepancies in the published results as well as their performance in particular installations remained unreported. One such aspect under debate is the appropriate method for modelling nanofluids in numerical studies.

A number of researchers modelled nanofluids as homogeneous or single-phase fluid with enhanced thermo--physical properties including density, specific heat, thermal conductivity and viscosity based on the mixture of both phases (Abu-Nada et al. [6], Ben Mansour *et al*. [8], Akbarinia and Behzadmehr [7], Maiga *et al*. [9]). It is assumed that both nanoparticles and base fluid are mutually in thermal, chemical and hydrodynamic equilibrium and the relatively velocity between phases is also zero (Y. Xuan *et al*. [2], Namburu *et al*. [10], Corcione [11]). A number of researcher, based on their experimentations suggested multiple correlations for prediction of thermo-physical properties for nanofluids.

Along with single-phase model, a few researchers employed two-phase model to simulate the nanofluids and compared the results with experimental data but the reported results are inconsistent in these investigations i.e. A. Behzadmehr *et al.* [12], Lofti *et al*. [13], Bianco *et al*. [14] and Hejazian *et al.* [15] reported that two-phase model predict more accurate results while the results of Akbari *et al.* [16] are in contradiction with this statement. Bianco *et al.* [17] reported that both two-phase Lagrangian-Eulerian model and single-phase model predict identical results for a mixture in turbulent flows. Akbari *et al.* [16] stated that the two-phase models provide excessively high heat transfer coefficient at moderate to high nanoparticle concentrations. Salman *et al.* [18] stated that single-phase model predict more precise results for modeling of SiO_2-EG nanofluid when compared with the Eulerian and mixture two-phase models.

As the contradictions among the reported results in literature, have made it complicated to select more accurate model to simulate nanofluids, present research is aimed at stimulating 3D laminar flow ($100 \leq Re \leq 1000$) of Al_2O_3/water through a circular tube by employing single-phase model and a comparison has made between previously published experimental results and two-phase model numerical results. The particle volume concentrations considered for analysis are 1%, 1.5% and 2% while the nano-particle size is 100nm. Since the accurate prediction of the nano-fluid, accurate thermo-physical properties is the key rule for obtaining appropriate results for single-phase flow, thermo-physical properties have been calculated by two sets of correlations.

II. Numerical Methodology

A. *Physical and Mathematical Model*

Flow is defined by employing Cartesian coordinates (r, θ, z) as shown in Fig. 1, where z lies in flow direction.

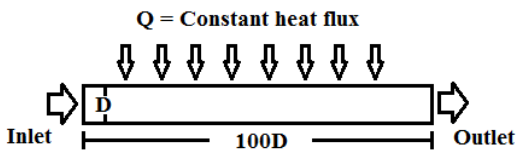

Figure 1. Flow Configuration

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With standardized notation of polar tensors, the flow governing equations are given in (1-5);

$$\frac{1}{R}\frac{\partial}{\partial\theta}(\rho_e U)+\frac{1}{R}\frac{\partial}{\partial R}(\rho_e RV)+\frac{\partial}{\partial Z}(\rho_e W)=0 \tag{1}$$

$$\frac{1}{R}\frac{\partial}{\partial\theta}(\rho_e UU)+\frac{1}{R}\frac{\partial}{\partial R}(\rho_e RVU)+\frac{\partial}{\partial Z}(\rho_e WU)+\frac{1}{R}(\rho_e UV)= -\frac{1}{R^2}\frac{\partial P}{\partial\theta}+\frac{1}{R^2}\frac{\partial}{\partial\theta}(\mu_e\frac{\partial U}{\partial\theta})+\frac{\partial}{\partial R}(\frac{\mu_e}{R}\frac{\partial(RU)}{\partial\theta})+\frac{2\mu_e}{R^2}\frac{\partial V}{\partial\theta} \tag{2}$$

$$\frac{1}{R}\frac{\partial}{\partial\theta}(\rho_e UV)+\frac{1}{R}\frac{\partial}{\partial R}(\rho_e RVV)+\frac{\partial}{\partial Z}(\rho_e WV)+\frac{1}{R}(\rho_e UU) = -\frac{1}{R}\frac{\partial P}{\partial\theta}+\frac{1}{R^2}\frac{\partial}{\partial\theta}(\mu_e\frac{\partial V}{\partial\theta})+\frac{\partial}{\partial R}(\frac{\mu_e}{R}\frac{\partial(RV)}{\partial R})-\frac{2\mu_e}{R^2}\frac{\partial V}{\partial\theta} \tag{3}$$

$$\frac{1}{R}\frac{\partial}{\partial\theta}(\rho_e UW)+\frac{1}{R}\frac{\partial}{\partial R}(\rho_e RVW)+\frac{\partial}{\partial Z}(\rho_e WW) = -\frac{\partial P}{\partial Z}+\frac{1}{R^2}\frac{\partial}{\partial\theta}(\mu_e\frac{\partial W}{\partial\theta})+\frac{1}{R}\frac{\partial}{\partial R}(R\mu_e\frac{\partial W}{\partial\theta}) \tag{4}$$

$$\frac{1}{R}\frac{\partial}{\partial\theta}(\rho_e U s)+\frac{1}{R}\frac{\partial}{\partial R}(\rho_e RV s)+\frac{\partial}{\partial Z}(\rho_e W s) = \frac{1}{R^2}\frac{\partial}{\partial\theta}(\frac{k_e}{(C_P)_e}\frac{\partial s}{\partial\theta})+\frac{1}{R}\frac{\partial}{\partial R}(R\frac{k_e}{(C_P)_e}\frac{\partial s}{\partial R}) \tag{5}$$

where, ρ_e, μ_e, $(C_p)_e$, k_e are the effective density, viscosity, heat capacity and thermal conductivity of nanofluid and non-dimensional variables in equations are;

$$R=\frac{r}{D}, Z=\frac{z}{D}, U=\frac{u}{\mathring{u}}, V=\frac{v}{\mathring{u}}, W=\frac{w}{\mathring{u}}, s=\frac{T-\bar{T}}{T_w-\bar{T}},$$

$$P=\frac{p}{\rho\mathring{u}^2}$$

B. *Effective Thermo-physical Properties*

The effective density and specific heat are calculated by using Wen and Ding [19] and Xuan and Roetzel [20] correlation as in (6) and (7). To obtain accurate numerical results to model, two sets of correlations have been employed to calculate the effective viscosity and thermal conductivity of the nanofluids. For the first case viscosity and thermal conductivity are determined by employing Corcione [11] and Maiga *et al*. [21] correlations (8) and (10) respectively while for the second case, Wang et al. [22] and Koo and Kleinstreuer [3] correlations have been used as shown in (11) and (12).

$$\rho_e = \varphi\rho_p + (1-\varphi)\rho_f \tag{6}$$

$$(C_p\rho)_e = \varphi(C_p\rho)_p + (1-\varphi)(C_p\rho)_f \tag{7}$$

$$\mu_e = \frac{1}{1-34.87\left(\frac{d_p}{d_f}\right)^{-0.3}\varphi^{1.03}} * \mu_f \tag{8}$$

Where;

$$d_f = 0.1\left(\frac{6M}{N\pi\rho_f}\right)^{\left(\frac{1}{3}\right)} \tag{9}$$

$$k_e = (4.97\varphi^2 + 2.72\varphi + 1)k_f \tag{10}$$

$$\mu_e = (123\varphi^2 + 7.3\varphi + 1)\mu_e \tag{11}$$

$$k_e = \frac{(k_p + 2k_f + 2(k_p - k_f)\varphi)}{(k_p + 2k_f + 2(k_p - k_f)\varphi)} + 5 * 10^4\beta\varphi\rho_f (C_p)_f\sqrt{\left(\frac{K_B T}{\rho_p d_p}\right) f} \tag{12}$$

where;

$$f = (-134.63 + 1722.3\varphi) + (0.4705 - 6.04\varphi)T \tag{13}$$

C. *Boundary Conditions and Numerical method*

Inlet velocity is defined at the tube inlet based on the Reynolds range selected for the study. The inlet fluid temperature was specified as 293K while no slip and constant heat flux boundary conditions were specified at the tube wall. Flow was assumed fully developed at the tube outlet.

The present problem has been computed by using CFD code Fluent 16.0 and control volume approach has been used to solve the governing (1-5). To attain higher order precision, second order upwind scheme is implemented to solve convective terms in momentum and energy equations while diffusive terms are discretized by central difference method. The non-dimensional time step size of the order of Δt = 0.001 has been specified. The absolute convergence criteria of 10^{-7} has been used for (1-4) while convergence criteria of 10^{-8} has been implemented for (5).

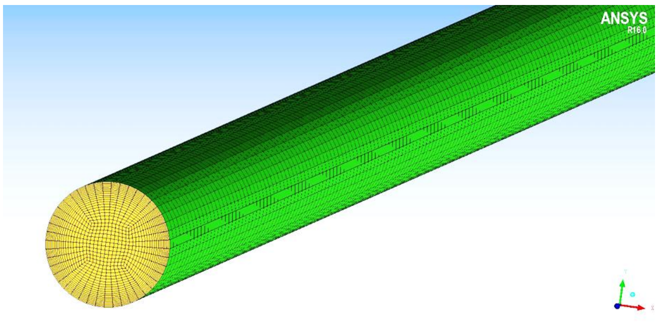

Figure 2. Close up view of Grid

Fig. 2 show the close up view of the shows the close up view discredited computational gird used in the study. Variable density grid is used to accurately capture the flow physics near the wall. To ensure the accuracy of the numerical results, three variable density grids G1, G2 and G3 of size 12x14x400, 22x24x600, 30x34x700 have been tested for each case and compared in terms of Average Nusselt number with the experimental findings of Maiga *et al.* [21]. G2 and G3 showed identical results up to third decimal places thus to save the computation time, results were computed by using Grid G2.

III. Results and Discussion

Results has been computed by applying single-phase CDF model for the nanoparticle volume concentration φ= 1%, 1.5% and 2% at Reynolds number 200-1000 with constant wall temperature of 10000, 20000 and 30000 W/m^2. The diameter of nano-particles is 100nm. Heat transfer characteristics dependence on nano-particle volume concentration, surface heat flux and Reynolds number has been analyzed.

A. *Validation*

To assess the accuracy of numerical methodology and selected correlations, results of Averaged Nusselt Number has been compared with the experimental and two-phase (discrete phase model) computational results of Maiga *et al.* [21] and Bianco *et al.* [17] respectively. It was observed that present results for case 1 showed more accurate results in comparison to the experimental results of Maiga *et al*. [21] at Re>200 with the maximum percentage difference of 1.74%. At low Reynolds number (Re = 200), case 2 results showed more precise results with the percentage difference of 3.33% while for case 1 the percentage difference of the result was 8.8%. The percentage difference of the results calculated by Bianco at Re = 500 by implementing the two-phase model, with respect to the Maiga *et al*. [21] is 8.5%. As the case two provided more accurate results, it has been used for further simulations.

B. *Nusselt number*

Fig. 4 shows the Averaged Nusselt No. variation with respect to Reynolds number at φ = 1, 1.5%, 2%.Results shows that by increasing the nano-particle concentration, the average Nusselt number increases. This is because the thermal conductivity increases with the increment of particle volume concentration and heat transfer mainly depends on the thermal conductivity of the fluid. For nano-particle concentration of 1.5% and 2% the average Nusselt number has increased 5.2% and 11.3% as compared to φ=1%.

Fig. 5 shows the Heat transfer coefficient variation along tube axis at Re = 1000 with φ = 1, 1.5%, 2%. The figure indicates that with the increase of nanoparticle concentration, the convective heat transfer coefficient also increases and this increment is more predominant at the exit portion of the tube where the fully developed flow exist. Convective heat transfer coefficient is larger at the tube inlet where the flow is in developing phase and thermal boundary layer is thin.

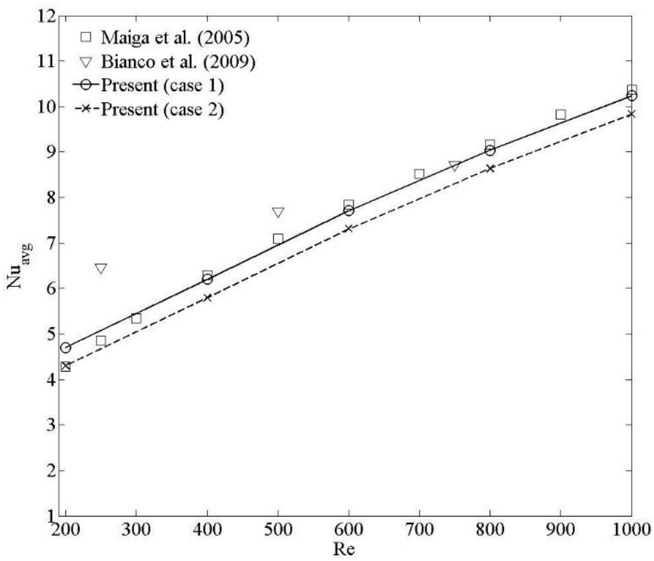

Figure 3. Averaged Nusselt No. variation with respect to Reynolds number for φ=1%

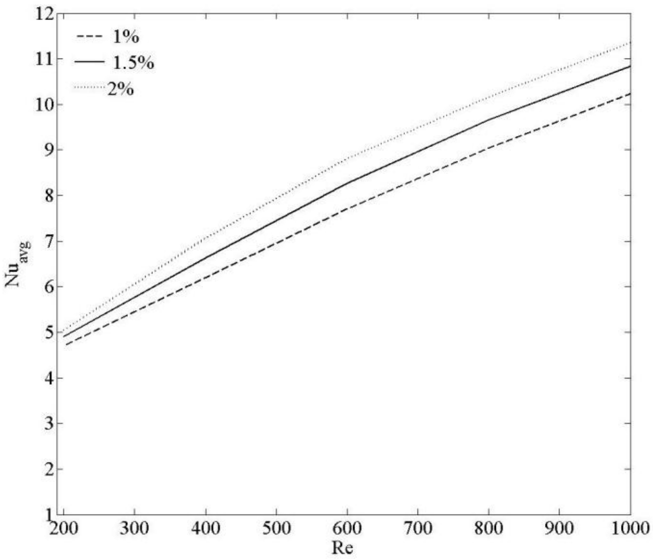

Figure 4. Averaged Nusselt No. variation with respect to Reynolds number for φ = 1, 1.5%, 2%

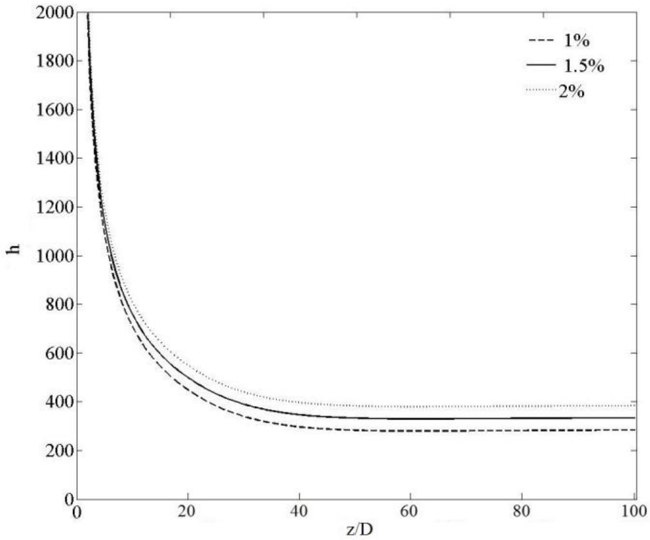

Figure 5. Heat transfer coefficient variation along tube axis at Re = 1000 with φ = 1, 1.5%, 2%

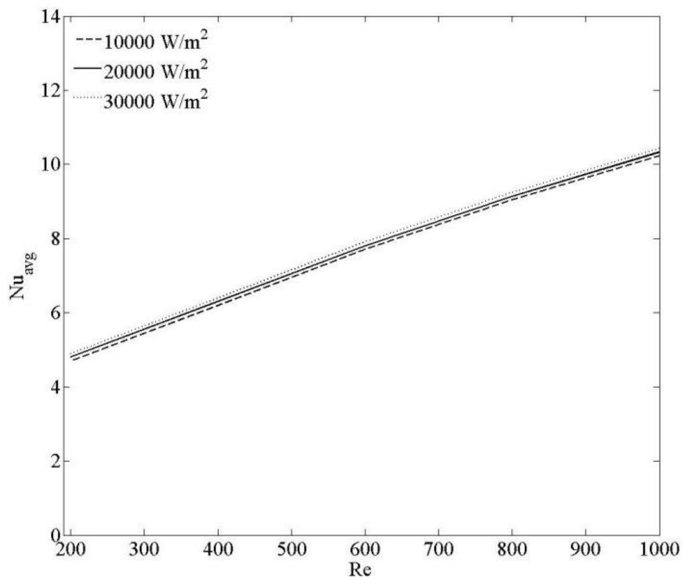

Figure 6. *Averaged Nusselt No. variation with respect to Reynolds number for φ=1% at Q = 10000, 20000 and 30000W/m²*

The local heat transfer coefficient decreases as the flow tends to develop inside the tube as well as the thermal boundary layer thickens and then becomes stable once the flow is fully developed.

Fig. 6 represents the Averaged Nusselt No. variation with respect to Reynolds number for φ=1% at Q = 10000, 20000 and 30000W/m2 . It was established that by increasing the wall flux, the average Nusselt number slightly rises. The results are in agreement as reported by Bianco *et al*. [14].

IV. Conclusion

In this manuscript, the laminar forced convection of Al_2O_3/water through a horizontal tube of circular x-section has been studied numerical by applying single-phase model. The nano-particle diameter under consideration is 100 nm. Effect of Reynolds number, particle volume concentration and surface heat flux on thermal characteristics of Al_2O_3/water has been studied. When compared with the previous experimental and numerical work, it has been concluded that single-phase CFD model can predict heat transfer characteristics accurately by selection of appropriate correlations for prediction of thermo-physical properties of the nanofluids.

Local and Average Nusselt number increases by increasing the particle volume concentration because of higher thermal conductivity. For nano-particle concentration, 1.5% and 2% the average Nusselt number has increased 5.2% and 11.3% as compared to φ=1%.

Nomenclature

C_p	Fluid specific heat [J/kgK]
D	Tube diameter [m]
d	Particles diameter [m]
h	heat transfer coefficient [W/m² K]
k	thermal conductivity of the fluid [W/mK]
L	tube length [m]
Nu	Nusselt number [-]
Q	wall heat flux [W/m²]
Re	Reynolds number [-]
T	fluid temperature [K]
T^-	Dimesnionless temperatrure [-]
φ	particle volume concentration [-]
μ	fluid dynamic viscosity kg/ms [-]
ρ	fluid density [kg/m³]
Subscript	
e	Nanofluid
f	Base fluid
p	Nano-particle

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