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SINGLE-PHASE AND MULTI-PHASE SIMULATION OF LAMINAR FLOWS OF ISOPROPANOL/ Al_2O_3 IN A TUBE OF CIRCULAR CROSS SECTION

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Abstract. Nanofluids have emerged in the past few decades as a very promising and modern technique for heat transfer enhancement. The main reason is the increase of the thermal conductivity compared to the base fluid. A lot of experiments and computational work has been done to better understand the behaviour of nanofluids and verify their theory. Numerically, single-phase and multi-phase approaches can be used to study nanofluids. The multi-phase approach seems to be most accurate method for numerical simulations, although requiring greater computational cost. Three different multi-phase models have been used for nanofluid flows modelling, namely Eulerian-Mixture, Eulerian-Eulerian and Eulerian-Lagrangian. In this study, these three models are analyzed for an Al_2O_3 / isopropanol flow in a tube of circular cross-section. Experimental data are used to assess the accuracy of the results. In addition, results from a previous work using a single-phase model are included in the analysis to evaluate the two approaches. The heat transfer coefficient was computed for various inlet temperatures (15°C and 25°C), Reynolds numbers (laminar flow) and nanoparticle concentrations (0.387 to 4.71% on a mass basis). The main purpose of the work is focused on the accuracy of the three multi-phase models. It was found that two-phase models yield better results than the single-phase model for all studied cases. The three models closely match the experimental values for low particle mass fraction, while some discrepancies are observed for the Eulerian-Eulerian model in the case of high particle mass fraction. So, in general, the Eulerian-Mixture and the Eulerian-Lagrangian models were found to be more precise for the heat transfer simulations performed in the present work. As far as the computational cost is concerned, the Eulerian-mixture model requires less computational time while yielding very reliable results.

Keywords: nanofluids, numerical simulation, multiphase approach

1. INTRODUCTION

The ever-increasing energy demand has led researchers to search multiple ways to enhance energy efficiency. A promising technique to enhance the heat transfer rate, which has been attracting more and more attention, especially with the development of nanotechnology, is the colloidal suspension of solid nanoparticles into common heat transfer fluids, such as water, ethylene glycol, oil, etc. These particles are usually oxides with particle size smaller than 100nm and in small quantities. This new type of fluid made of the base fluid and the dispersed nanoparticles was called “nanofluid” by Choi and Eastman (1995). Since then, nanofluids have found a lot of applications, such as coolants in electronic devices, in automobile industry, in mechanical lubrication, in biomedical area and in space station equipment. Moreover, they improve the heat transfer performance in reactors and heat exchangers, solar thermal collectors and heat pipes (Said *et al.* 2021, Wong and de Leon, 2010).

Nanofluids are gaining more and more interest because of their capability to alter the properties of the working fluid as needed. The nanoparticles have a higher thermal conductivity than the base fluid and that may lead to better heat transfer rate. Moreover, Xuan and Li (2000) and Keblinski *et al.* (2002) presented a few other mechanisms that may play a role, namely the increase of the heat transfer area and the heat capacity of the fluid, the Brownian motion, the interaction and the collision among the particles and the fluid, the intensification of the mixing fluctuations and turbulence, the molecular-level layering of the liquid/particles interface, etc.

Apart from experimental works, a lot of studies have focused on the computational investigation and modelling of nanofluid flows. They use either a single-phase or a multi-phase approach. The former assumes that the two phases are in thermal equilibrium and no slip velocity exists between them. So, the nanofluid is modelled as a single fluid but the thermophysical properties are different from those of the base fluid. This approach has gain popularity due to its simplicity and computational economy in comparison with other methods. On the other hand, several factors such as gravity, friction between the fluid and solid particles, Brownian diffusion, sedimentation, and dispersion may affect a nanofluid flow. Consequently, the slip velocity between the fluid and particles should be considered for simulating nanofluid flows (Xuan and Li, 2000) and multiphase models may be more appropriate.

There are several different multiphase models, namely the Eulerian-Mixture, the Eulerian-Eulerian and the Eulerian-Lagrangian models. The Eulerian-Mixture model is based on a single fluid two-phase approach and assumes that the coupling between phases is strong, and the particles closely follow the flow (Mirmasoumi and Behzadmehr, 2008). Each phase has its own velocity vector field, but the thermal equilibrium between the phases is preserved. The Eulerian-Eulerian model treats the different phases as interpenetrating continua. It is more complex than the Eulerian-mixture model because it requires the solution of the mass, momentum, and energy equations for the fluid and solid phases separately. Thus, every phase has its own velocity and temperature fields. The Eulerian-Lagrangian methods relies on the solution of the Navier-Stokes equations for the fluid phase and traces the particles separately by solving the differential equations governing the dynamics of each particle. The phases interact and exchange mass, momentum, and energy with each other.

Many researchers have compared the different computational approaches for nanofluid modelling (see, e.g., the review by Sidik *et al.*, 2016). Bianco *et al.* (2009) concluded that the Eulerian-Lagrangian model performed better than the single-phase model for laminar flows and found a maximum 11% difference between these two models. Similar conclusions on the performance of these two models were reported by Mojarrad *et al.* (2013). Moraveji and Ardehali (2013) confirmed that the multiphase models yield better results than the single-phase approach and claimed that the difference between the results of different two-phase models was marginal. Bég *et al.* (2015) also found that multiphase models yield similar results, being more accurate than the single-phase approximation. Madhavi *et al.* (2015) compared the Eulerian-Lagrangian and the Eulerian-Eulerian models and concluded that the former is more reliable. In another work, Lotfi *et al.* (2009) showed that the Eulerian-Mixture model was more precise in comparison with the Eulerian-Eulerian and the single-phase models.

In the present study, the three multiphase models are compared for Al₂O₃/isopropanol laminar flow in a tube of circular cross-section subjected to a uniform heat flux. Experimental data available in Nikulin *et al.* (2019) is used to assess the accuracy of the results. Moreover, numerical simulations performed by Romão and Coelho (2021) using a single-phase model are also shown for comparison purposes.

2. GOVERNING EQUATIONS

2.1 Eulerian-Mixture model

The Eulerian-Mixture model uses a single-fluid approach. The Navier-Stokes equations are solved, along with a volume fraction equation for the secondary (solid) phase. The governing equations for steady-state conditions are written as follows:

- Continuity equation:

$$\nabla \cdot (\rho_m \mathbf{V}_m) = 0 \quad (1)$$

- Momentum equation:

$$\nabla \cdot (\rho_m \mathbf{V}_m \mathbf{V}_m) = -\nabla p + \nabla \cdot (\mu_m (\nabla \mathbf{V}_m + \nabla \mathbf{V}_m^T)) + \rho_m \mathbf{g} - \nabla \cdot \left(\sum_{k=1}^n \varphi_k \rho_k \mathbf{V}_{dr,k} \mathbf{V}_{dr,k} \right) \quad (2)$$

- Energy equation:

$$\nabla \cdot \left(\sum_{k=1}^n \varphi_k \mathbf{V}_k (\rho_k E_k + p) \right) = \nabla \cdot (k_m \nabla T) \quad (3)$$

The volume fraction equation for the solid phase is given by:

$$\nabla \cdot (\varphi_p \rho_p \mathbf{V}_m) = -\nabla \cdot (\varphi_p \rho_p \mathbf{V}_{dr,k}) \quad (4)$$

In the above equations, ρ , k and μ are the density, thermal conductivity and dynamic viscosity, respectively, \mathbf{V} the velocity vector, p the pressure, \mathbf{g} the gravity vector, E the internal energy, T the temperature, φ_k the volumetric fraction of k th phase, and n the number of phases (two in the present case). Subscripts m and p stand for mixture and particles, respectively. The thermophysical properties of the mixture may be determined as a weighted average of the properties of the fluid and solid phases. The mass-averaged velocity is given by:

$$\mathbf{V}_m = \frac{\sum_{k=1}^n \varphi_k \rho_k \mathbf{V}_k}{\rho_m} \quad (5)$$

and the drift velocity for phase k , $\mathbf{V}_{dr,k}$, is defined as:

$$\mathbf{V}_{dr,k} = \mathbf{V}_k - \mathbf{V}_m \quad (6)$$

The relative (slip) velocity was determined using the correlation proposed by Manninen *et al.* (1996) and the drag function was calculated using the correlation given by Schiller and Naumann (1935).

2.2 Eulerian-Eulerian model

The Eulerian model is more complex, as it solves the conservation equations separately for each phase. Therefore, it requires more computational time than the Eulerian-Mixture model, but it is expected to be more accurate. The conservation equations for this model are written as follows:

- Continuity equation for the fluid, f , and the particles, p :

$$\nabla \cdot (\varphi_f \rho_f \mathbf{V}_f) = 0, \quad \nabla \cdot (\varphi_p \rho_p \mathbf{V}_p) = 0 \quad (1)$$

- Momentum equation for the fluid and the particles:

$$\nabla \cdot (\varphi_f \rho_f \mathbf{V}_f \mathbf{V}_f) = -\varphi_f \nabla p + \varphi_f \nabla \cdot (\mu_f \nabla \mathbf{V}_f) + \varphi_f \rho_f \mathbf{g} + \mathbf{F}_{D,f} + \mathbf{F}_{L,f} \quad (8)$$

$$\nabla \cdot (\varphi_p \rho_p \mathbf{V}_p \mathbf{V}_p) = -\varphi_p \nabla p + \varphi_p \nabla \cdot (\mu_p \nabla \mathbf{V}_p) + \varphi_p \rho_p \mathbf{g} - \mathbf{F}_{D,p} - \mathbf{F}_{L,p} + \mathbf{F}_{col,p} \quad (9)$$

where \mathbf{F}_D , \mathbf{F}_L and \mathbf{F}_{col} denote the interaction drag force between the fluid and the particles, the lift force and the particle-particle collision force. The latter two are only significant in the case of large particles. Details on the calculation of these forces may be found, e.g., in Sidik *et al.* (2016). Other forces, namely the virtual momentum forces play a small role and can be neglected.

- Energy equations for the fluid and the particles:

$$\nabla \cdot (\varphi_f \rho_f c_{p,f} T_f \mathbf{V}_f) = \nabla \cdot (\varphi_f k_f \nabla T_f) - h_v (T_p - T_f) \quad (2)$$

$$\nabla \cdot (\varphi_p \rho_p c_{p,p} T_p \mathbf{V}_p) = \nabla \cdot (\varphi_p k_p \nabla T_p) - h_v (T_p - T_f) \quad (11)$$

Here, c_p is the specific heat capacity and h_v the volumetric interphase heat transfer coefficient, which is calculated as

$$h_v = \frac{6k_p \varphi_f \varphi_p \text{Nu}_p}{d_p^2} \quad (3)$$

where d_p is the diameter of the particles and the Nusselt number, Nu_p can be calculated using the correlation proposed by Ranz and Marshal (1952):

$$\text{Nu}_p = 2 + 0.6\text{Re}_p^{0.5}\text{Pr}^{0.33} \quad (13)$$

where Re and Pr are the Reynolds and Prandtl numbers, respectively.

2.3 Eulerian-Lagrangian model

In this model, the base fluid is treated as a continuum phase for which the Navier-Stokes equations are solved. The particles are handled using a Lagrangian approach by tracking the nanoparticles through the fluid flow field. The solid and the fluid phases exchange momentum and energy. These exchanges are introduced as source terms in the governing equations. However, even for a small volume fraction, the number of particles in the computational domain is large, and so the computational time is typically greater than that of the models mentioned above.

The governing equations for the fluid phase are given by:

- Continuity equation:

$$\nabla \cdot (\rho_f \mathbf{V}_f) = 0 \quad (14)$$

- Momentum equation:

$$\nabla \cdot (\rho_f \mathbf{V}_f \mathbf{V}_f) = -\nabla p + \nabla \cdot (\mu_f (\nabla \mathbf{V}_f + \nabla \mathbf{V}_f^T)) + \rho_f \mathbf{g} + S_d \quad (15)$$

- Energy equation:

$$\nabla \cdot (\mathbf{V}_f (\rho_f E_f + p)) = \nabla \cdot (k_f \nabla T) + S_E \quad (16)$$

The momentum source term S_d expresses the momentum transfer between the fluid and the nanoparticles and is given by:

$$S_d = \sum \mathbf{F} \dot{m}_p \Delta t \quad (17)$$

where \dot{m}_p is the mass flow rate of the nanoparticles, Δt the time step used in the solution of the momentum equation for the nanoparticles and \mathbf{F} the total force acting on a nanoparticle. The total force includes the drag force, the gravity and the pressure gradient. Other forces (Brownian, thermophoretic, lift and virtual mass) are usually negligible.

The heat source term S_E expresses the heat transfer between the fluid and the nanoparticles and is expressed as:

$$S_E = \sum \dot{Q} \Delta t \quad (18)$$

where \dot{Q} is the rate of the transferred energy and can be written as:

$$\dot{Q} = Nu \pi d_p k_f (T_p - T_f) \quad (19)$$

The momentum equation for the nanoparticles in a Lagrangian frame of reference is given by:

$$\frac{d \mathbf{V}_p}{dt} = \mathbf{F} + \frac{\mathbf{g} (\rho_p - \rho_f)}{\rho_p} \quad (20)$$

The total force includes the drag force and other forces that are often negligible, namely the virtual mass force, the pressure gradient, the lift force, the Brownian force and the thermophoresis force. The hydrodynamic drag force, \mathbf{F}_D , is given by Stokes's law:

$$\mathbf{F}_D = \frac{18 \mu_f}{d_p^2 \rho_p C_c} (\mathbf{v}_f - \mathbf{v}_p) \quad (21)$$

where C_c is the Cunningham correction (Das *et al.*, 2008).

The energy equation for spherical particles is given by (Das *et al.*, 2008):

$$\rho_p c_{p,p} \frac{d T_p}{dt} = \frac{6h (T_f - T_p)}{d} \quad (22)$$

where the convective heat transfer coefficient, h , is calculated from Eq. (13).

2.4 Heat transfer coefficient

The local heat transfer coefficient for a tube subjected to uniform heat flux at the wall is computed as follows:

$$h = \frac{Q}{(T_w - T_b)} \quad (23)$$

where Q is the heat flux at the wall, T_w the wall temperature, and T_b the bulk temperature of the nanofluid. In the Eulerian-Mixture model, the two phases are in thermal equilibrium and so the bulk temperature is calculated as:

$$T_b = \frac{\int u \rho c_p T dA}{\int u \rho c_p dA} \quad (24)$$

In the Eulerian-Eulerian and Eulerian-Lagrangian models, a modified expression is used (see., e.g., Mirzaei *et al.*, 2014):

$$T_b = \frac{\iint (1 - \varphi) u_f \rho_f c_{p_f} T_f dA + \iint \varphi u_p \rho_p c_{p_p} T_p dA}{\iint (1 - \varphi) u_f \rho_f c_{p_f} dA + \iint \varphi u_p \rho_p c_{p_p} dA} \quad (25)$$

The average convective heat transfer coefficient is determined by integrating the local value along the length of the tube and then dividing by that length.

2.5 Thermophysical properties

The thermophysical properties of the base fluid and nanoparticles were taken from the experimental data and correlations reported in the works of Shimchuk and Geller (2014), Zhelezny *et al.* (2017, 2018) and Nikulin *et al.* (2019). The density was obtained by Nikulin *et al.* (2019) using a Coriolis mass flow meter and compared with Eq. (26), which was proposed by Zhelezny *et al.* (2018), and with the widely used Eq. (27):

$$\rho_m = 958 + 7.35w - 0.0341 T^{1.5} \quad (26)$$

$$\rho_m = \varphi_p \rho_p + (1 - \varphi_p) \rho_f = \varphi_p \rho_p + \varphi_f \rho_f \quad (27)$$

where w is the mass fraction of the particles. The deviation between the experimental data and the density determined either from Eq. (26) or from Eq. (27) was no more than 5 kg/m³.

The kinematic viscosity was measured by Nikulin *et al.* (2019) using a glass capillary viscometer. In the case of low particle concentration, namely up to 0.992%, the results were in good agreement with Eq. (28), which is based on data reported by Zhelezny *et al.* (2018):

$$\frac{\nu_m}{\nu_f} = 1 + (41.52 - 90.16 \cdot 10^{-3}T) w \quad (28)$$

Greater deviations were found for higher particle concentration.

The thermal conductivity was taken from the experimental work of Shimchuk *et al.* (2014) and fitted in the following equation:

$$\frac{k_m}{k_f} = 1 + (0.098 - 2.61 \cdot 10^{-3}T)w \quad (29)$$

The specific heat capacity was obtained from the measurements of Zhelezny *et al.* (2017). The data were compared with those determined from correlations given by Pak and Cho (1998) and Xuan and Roetzel (2000) and the maximum deviations were 2% and 8%, respectively.

3. NUMERICAL PROCEDURE

3.1 Computational Domain and Setup

In the present study, an Al₂O₃/isopropanol nanofluid flow in a tube of circular cross-section is investigated using the

multiphase models described above. The tube is 2.4 m long and has a diameter of 3.5 mm. The simulations were performed for laminar flow and for low and high Re numbers. The flow is hydrodynamically fully developed at the inlet (parabolic inlet velocity), and various values of uniform heat flux at the wall were considered. Gravity is enabled. Four different mass fractions of nanoparticles are considered ranging from 0.387% to 4.71%.

Three different multiphase models, namely the Eulerian-Mixture, Eulerian-Eulerian and Eulerian-Lagrangian models, were used to perform the simulations. The results from a single-phase model previously reported by Romão and Coelho (2021) are also included for comparison purposes. The experimental data obtained by Nikulin *et al.* (2019) are used to assess the accuracy of the results.

The ANSYS-Fluent software was used to perform the simulations. The SIMPLE algorithm was used for the Eulerian-Mixture and Eulerian-Eulerian models, while the coupled algorithm was employed for the Eulerian-Lagrangian model for better convergence. The convergence criterion required the normalized residuals of the governing equations to be lower than 10^{-4} .

3.2 2D Axisymmetric vs 3D Modelling

Previous simulations were carried out by Romão and Coelho (2021) using a 2D axisymmetric domain and a single-phase model. Although the 2D approximation saves a lot of computational time and simplifies the complexity of the problem, it is not accurate if buoyancy effects are relevant. Accordingly, 3D numerical simulations were performed in order to find out whether the predicted temperature field is axisymmetric or not. Two cases were considered for $\text{Re}=449$ and $\text{Re}=1482$, with particle mass concentration of 0.387% and inlet temperature of 15°C . Figures 1 and 2 show the velocity field and temperature contours at a cross-section of the tube computed using the Eulerian-Mixture model. A non-uniform distribution of the temperature around the wall is observed. Moreover, a secondary flow induced by buoyancy and a non-uniform temperature distribution at the cross-section are observed. The value of the velocity is quite small, which means that the secondary flow is not strong. However, gravity plays a role in this problem, which although not being a significant one, still justifies the use of 3D simulations in the present work.

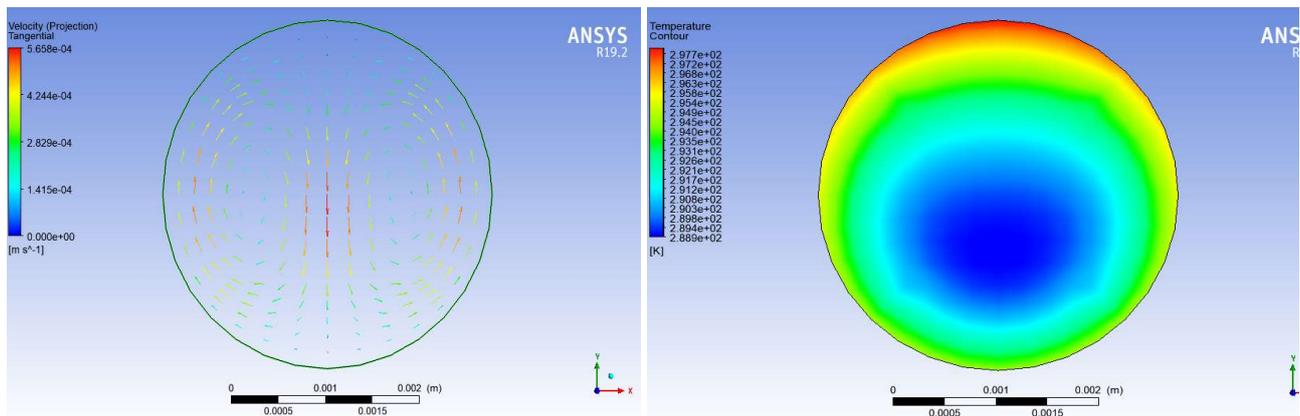


Figure 1: Velocity field and temperature contours in a cross-section for $\text{Re}=449$.

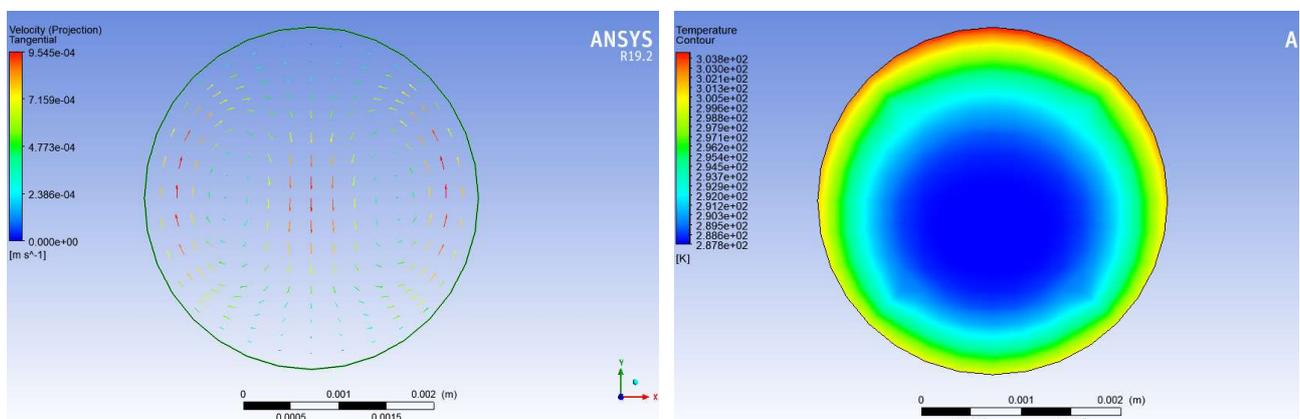


Figure 2. Velocity vectors and temperature contour in a cross-section for $\text{Re}=1482$.

3.3 Mesh Independence Study

Non-uniform meshes were employed to discretize the computational domain. The length of the tube is three orders of magnitude greater than the diameter, so the grid size in streamwise direction must be fine enough to avoid control volumes with an aspect ratio too different from unity. Four meshes with different number of control volumes, ranging from about 0.5 million to about 2 millions, were considered. The analysis was made for $Re=449$, particle mass concentration of 0.387% and inlet temperature of 15°C. The local heat transfer coefficient along the streamwise direction is plotted in Fig. 3 for every mesh and for the Eulerian-Mixture model. It can be seen that the results obtained for the 4 different grids are similar and for that reason the grid 2, with about 1 million control volumes, was chosen to perform the rest of the simulations. The difference between the values computed for grids 2 and 4 was only about 1%, so grid 2 was chosen in order to save computational time.

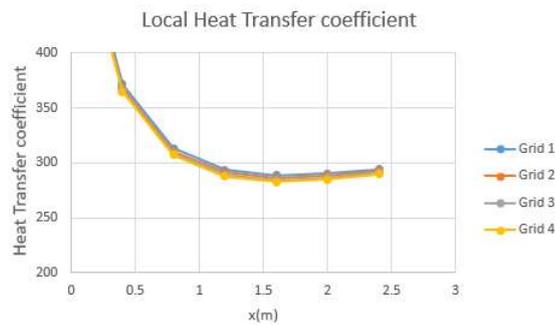


Figure 3. Mesh independence study.

4. RESULTS AND DISCUSSION

The local convective heat transfer coefficient along the streamwise direction is plotted in Figs. 4 to 7 for various Re numbers and particle loading. Four different cases were considered, which correspond to the combinations of low/high Re number and low/high particle loading, for which experimental data by Nikulin *et al.* (2019) are available. Note that high Re number in the present context means that the Re number is relatively close to the critical Re number above which transition to turbulent flow begins. It can be seen that, in general, the multiphase models yield better results in comparison with the single-phase model, as they are closer to the experimental values.

The predictions of the single-phase model and the Eulerian-Mixture model are not identical for two reasons. First, the results of the single-phase model were computed using a two-dimensional axisymmetric approximation, neglecting buoyancy. Although the latter plays a small role in the present flows, due to the relatively small heat flux and the small diameter of the tube, it still contributes to generate a secondary flow in the cross-section of the tube, as illustrated in Figs. 1 and 2. This secondary flow can only be simulated when a 3D domain is considered, as in the case of the Eulerian-Mixture model. Second, the single-phase model does not account for the drift velocity of the nanoparticles, in contrast to the Eulerian-Mixture model.

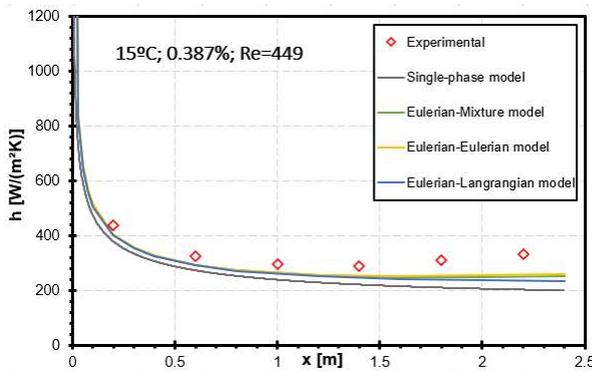


Figure 4. Local heat transfer coefficient for low Re number and low particle concentration.

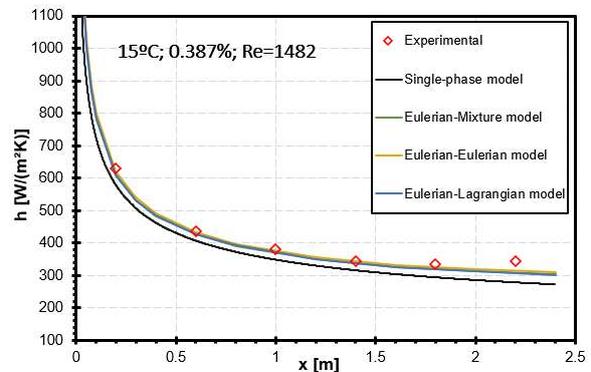


Figure 5. Local heat transfer coefficient for high Re number and low particle concentration.

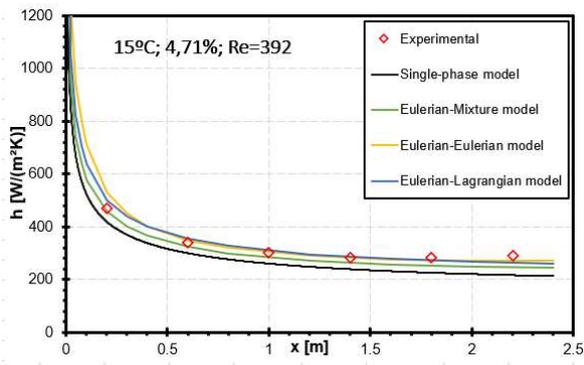


Figure 6. Local heat transfer coefficient for low Re number and high particle concentration.

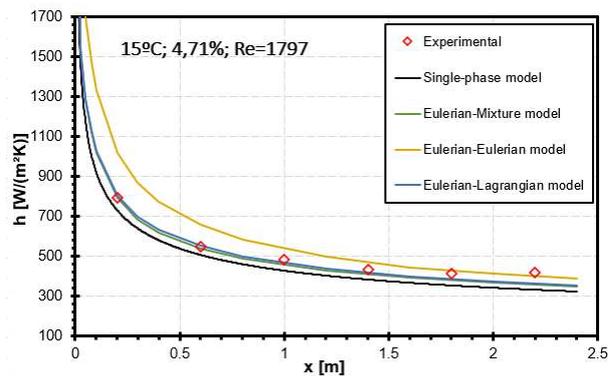


Figure 7. Local heat transfer coefficient for high Re number and high particle concentration.

In the case of low particle concentration and low particle loading (Fig. 4), the experimental data shows a slight increase of the heat transfer coefficient downstream of $x \approx 1.5$ m, in contrast to what is expected from the theory for forced convection and corroborated by the numerical results, no matter the model employed. It is important to point out that this increase is not due to the nanoparticles, since additional experiments performed for the base fluid (isopropanol) showed the same increasing trend downstream of $x \approx 1.5$ m. All the three multiphase models are efficient and yield results in good agreement with the experiments for low particle loading (Figs. 4 and 5). In case the Re number and the particle concentration are high, the Eulerian-Eulerian model significantly overestimates the heat transfer coefficient in the vicinity of the inlet section of the tube and for about 1 m alongside (Fig. 7). The reason for this behaviour is unclear. Apart from this case, the three multi-phase models yield predictions in close agreement with each other and reproduce the experimental results quite well.

It can be concluded from these results that the Eulerian-Mixture and the Eulerian-Lagrangian models are more consistent with the experimental data for all tested conditions. Between those two, the Eulerian-Mixture model is simpler and requires less computational time than the Eulerian-Lagrangian one. The latter requires up to 4 hours for a simulation while the Eulerian-Mixture model requires less than one hour in a standard laptop, the results for both models being quite similar. Accordingly, the Eulerian-Mixture model was selected to perform calculations for different heat fluxes and particle loading, as shown in Figs. 8 and 9. It can be seen that the Eulerian-Mixture model consistently outperforms the single-phase model and reproduces well the experimental values of the convective heat transfer coefficient, even though it tends to slightly underestimate them, particularly far from the inlet. However, the experimental values in the region far from the inlet are questionable, as pointed out above, since the slight rising trend is not consistent with the theory, unless buoyancy effects play a relevant role, which is not the case.

Figure 10 shows the average convective heat transfer coefficient for all the simulations carried out. The Eulerian-Mixture model yields rather accurate results, the errors being typically smaller than 5% in comparison with the experiments, except in one simulation, where the error is about 10%.

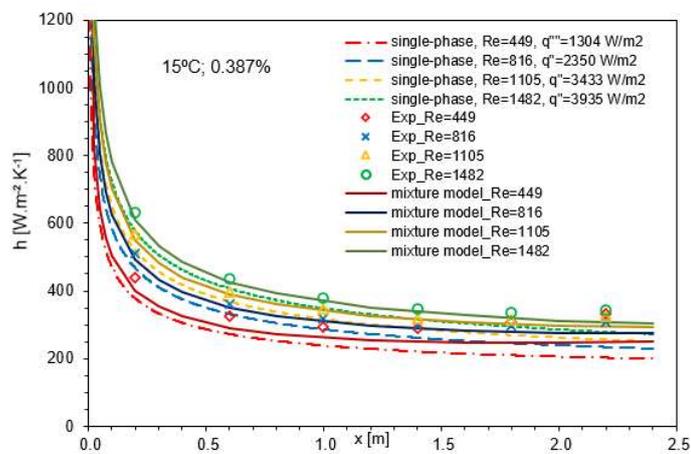


Figure 8. Local heat transfer coefficient for low particle concentration and various Re numbers.

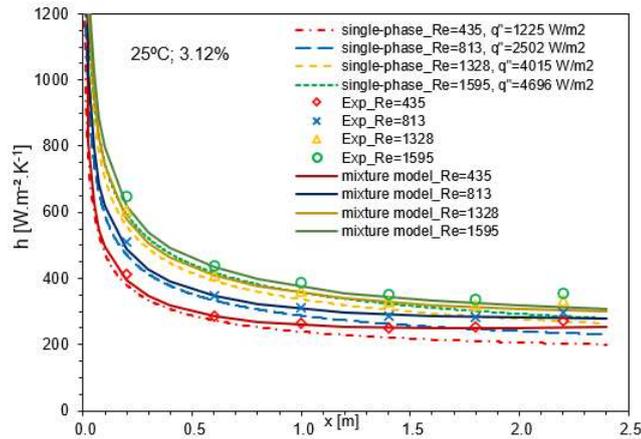


Figure 9. Local heat transfer coefficient for intermediate particle concentration and various Re numbers.

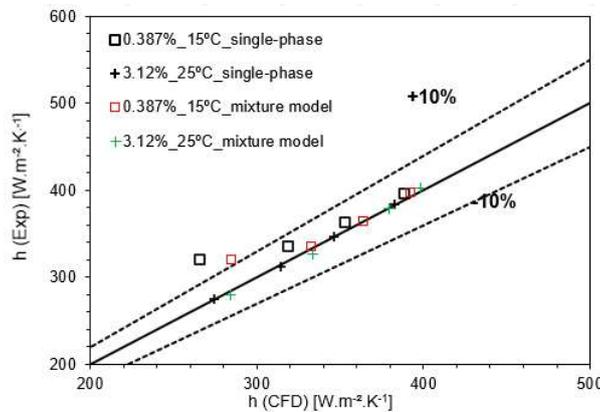


Figure 10. Average heat transfer coefficient, Experimental versus CFD.

5. CONCLUSIONS

Numerical simulations of Al_2O_3 /isopropanol laminar flows in a tube of circular cross-section subjected to a uniform heat flux were reported in this work. Three-dimensional simulations were carried out for three different multi-phase models and for different Re numbers and particle loading. The predictions were compared with the results from previous two-dimensional axisymmetric single-phase simulations and with experimental data. It can be concluded from the analysis carried out that:

- In general, the multi-phase models are more accurate for nanofluid simulations than the single-phase model, as expected.
- The Eulerian-Eulerian model yields very good results for low particle concentration, but it overpredicted the experimental data in the vicinity of the inlet section for high particle loading and high Re number.
- The Eulerian-Mixture and Eulerian-Lagrangian models yielded results in good agreement with the experiments for low and high particle concentration and for low and high Re number. The difference in the predictions of these two models was marginal for the studied conditions. Hence, if there is no particular interest in the investigation of the trajectory of the nanoparticles, the Eulerian-Mixture model is preferable because of its numerical simplicity and computational efficiency.
- The Eulerian-Mixture model predicted the average heat transfer coefficient for all but one of the simulations carried out with an error below 5%.

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