Abstract—This research aimed to analyse numerically the heat transfer enhancement in a turbulent flow circular conduit with respect to different nanoparticle concentration and Reynolds number including the effect of drag and lift forces, respectively. Single-phase model and two-phase (Mixture and Eulerian) models were employed to simulate the nanofluid flow behaviour in 3-D geometry. It was found that heat transfer of nanofluids is greater than that of the base liquid, and it increases with increasing particle volume concentration and Reynolds number, respectively. There was a good agreement between the present study results with the experimental correlations, especially for single-phase model (<9% difference). Among two-phase models, mixture model (<14% difference) showed better prediction compared to Eulerian-dispersed model (<18% difference).

Keywords— Nanofluid, heat transfer, turbulent, forced convection, Computational Fluid Dynamics (CFD).

1. Introduction

During the past few decades, many investigations have been made to enhance the heat transfer. Based on the studies, solid metallic materials suspended in fluid increases the thermal conductivity, however large sized particles (millimeter- and micrometer-sized particles) causes abrasion, channel clogging and additional flow resistance due to poor suspension ability [1]. Nanofluid is the suspension of nanoparticles in base fluid. Nanoparticles are fine metallic particles of sizes less than 100nm such as Al2O3, CuO, TiO2, Cu, Fe and carbon-based material such as carbon nanotubes (CNTs). Nanofluids exhibit great potentials to enhance heat transfer compared to conventional heat transfer fluids [2]. With small quantity of high thermal conductivity solid nanoparticles added in the base fluid, the overall thermal conductivity increases, thus increasing the heat transfer rate.

2. Governing Equations

The governing equations are described as follow [4]:

Mass Continuity equation:

\[ \frac{\partial u_i}{\partial x_i} = 0 \]  

Momentum equation:

\[ F = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_{ij}} \right) \frac{\partial u_i}{\partial x_j} + \frac{\partial \rho u_i}{\partial t} + \rho_f u_i \Phi + \mathbf{S}_i \]  

Energy equation:

\[ \frac{\partial \rho e}{\partial t} + \frac{\partial}{\partial x_j} \left( u_j \rho e + \frac{\mu_t}{\sigma_{ij}} S_{ij} \right) = \frac{\partial}{\partial x_j} \left[ \kappa \frac{\partial T}{\partial x_j} \right] - \rho_f c_p \frac{\partial T}{\partial t} + \mathbf{S}_e \]  

2.1. Turbulence Modeling

In present study, the Launder and Spalding (1972) k-ε model (standard k-ε model) is used to simulate turbulence flow for nanofluids. The turbulence kinetic energy, k, and its rate of dissipation, e are as follow [4]:

\[ \frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho \epsilon u_j) = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_{ij}} \right) \frac{\partial u_i}{\partial x_j} + G_k - \rho \epsilon + S_k \]  

\[ \frac{\partial}{\partial t} (\rho e) + \frac{\partial}{\partial x_j} (\rho e u_j) = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_t}{\sigma_{ij}} \right] \frac{\partial u_i}{\partial x_j} + C_{1k} \frac{\epsilon}{k} G_k - C_{2k} \rho e^2 + S_e \]  

2.2. Boundary Conditions

Uniform axial velocity and temperature are assumed at velocity inlet. At pressure outlet, the static (gauge) pressure is set to zero. The wall boundary is assigned with no-slip wall boundary conditions with uniform wall temperature.

2.3. Physical Properties of Fluids

The properties of water and nanofluid are obtained from the benchmark research paper Bianco et al. [3]. The nanofluid used is water suspended with Al2O3 nanoparticles with particle diameter of 38nm. For single-phase model, the properties of nanofluid are calculated as effective properties calculated using equations provided in Bianco et al. [3]. For two-phase model, the respective properties for the water phase and nanoparticle phase are input accordingly.

2.4. Numerical Method and Validation

The finite-volume solver FLUENT is used to solve the governing equations, appropriate boundary conditions and constitutive relations. The semi-implicit method for the pressure linked equations (SIMPLE) scheme is used to solve the pressure-velocity decoupling. The numerical results are validated with correlations and benchmark paper. Reynolds number and Nusselt number defined respectively as follow:

\[ Re = \frac{\rho D}{\mu} \]  

\[ Nu = \frac{h D}{k} \]
3. Results

In Fig. 2, the average Nusselt numbers for each particle concentration are reported with benchmark paper Bianco et al. [3] and correlation by Gnielinski [5] and Petukhov [6] for base fluid and Pak and Cho [7] for nanofluid. Nusselt number for Pak and Cho [7] correlation is a function of Reynolds number and Prandtl number. It is observed that heat transfer of nanofluid is higher than that of base fluid. The heat transfer increases with the increase in Reynolds number and particle volume concentration of nanoparticles.

For base fluid, there is strong agreement between the present study and the correlations and the benchmark. For nanofluids, single phase model has close agreement with Pak and Cho [7] at low concentrations, however it slightly overestimates the Nusselt number at $\phi = 6\%$. Therefore, it can possibly over predict the Nusselt number at particle concentration higher than 6%. This may be due to the assumption of single-phase model to treat nanofluid as homogeneous fluid with effective properties.

For two-phase models, mixture and Eulerian models are studied. Mixture model includes the drag force, while Eulerian model include both drag and lift forces. Overall, mixture model gives close agreement to both the correlation and benchmark, however it slightly underestimates the Nusselt number as particle concentration increases. The same pattern was observed between the correlation and benchmark. The percentage difference could be reduced by using temperature-dependent nanofluid properties. In the case of Eulerian model, although it includes the lift force in the simulation process, it further underestimates the Nusselt number as compared to mixture model, with higher percentage difference.

4. Conclusion

The results showed that nanofluid heat transfer increases as Reynolds number and particles volume concentration increases. There is a good agreement between the present study results and experiment correlation by Pak and Cho [7] and the benchmark paper Bianco et al. [3]. Single-phase model has strong agreement with Pak and Cho [7]. As for two-phase models, mixture model is satisfactory, while Eulerian model gives higher percentage difference when compared to Pak and Cho [7]. Temperature-dependent nanofluid properties could be used to improve the results. Moreover, heat transfer of nanofluid particle volume concentration of more than 6% could be further studied.

References