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Original Research Paper

# Evaluation of single-phase, discrete, mixture and combined model of discrete and mixture phases in predicting nanofluid heat transfer characteristics for laminar and turbulent flow regimes

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A B S T R A C T

It is essential to investigate the appropriate model for simulating nanofluid flow for different flow regimes because, at present, most previous studies do not agree with each other. It was, therefore, the purpose of this study to present a Computational Fluids Dynamics (CFD) investigation of heat transfer coefficients of internal forced convective flow of nanofluids in a circular tube subject to constant wall heat flux boundary conditions. A complete three-dimensional (3D) cylindrical geometry was used. Laminar and turbulent flow regimes were considered. Three two-phase models (mixture model, discrete phase model (DPM) and the combined model of discrete and mixture phases) and the single-phase homogeneous model (SPM) were considered with both constant and variable properties. For the turbulent flow regime, it was found that the DPM with variable properties closely predicted the local heat transfer coefficients with an average deviation of 9%, and the SPM deviated from the DPM model by 2%. It was also found that the mixture and the combined discrete and the mixture phase model gave unrealistic results. For laminar flow, the DPM model with variable properties predicted the heat transfer coefficients with an average deviation of 9%.

## 1. Introduction

Nanofluids are a suspension of nano-meter sized solid particles either metallic or nonmetallic dispersed in a base heat transfer fluid which could be water, ethylene glycol or some other fluids. Some common nanoparticles include alumina, silica, copper oxide (CuO), titanium oxide ($TiO_2$) [1–11]. Most recently, nanoparticles have even been synthesized from biomaterials [12,13]. The inclusion of these metallic oxides augment the thermal conductivity of the nanofluids significantly as the thermal conductivity of the particles is usually some orders higher in magnitude in comparison to the base fluid. In general, it can be concluded that nanofluids have shown great prospects and implications for a wide range of heat transfer and other applications [12,14–19] such as electronic cooling, heat exchangers, air conditioning, automotive, nuclear system cooling, heating buildings, reducing pollution, storing energy [15,17,20–22].

Some recent works have been carried out on nanofluids by researchers using various innovative methods to study the complex heat and fluid dynamic interactions in the flow. Shirvan et al. [23] numerically studied a heat exchanger filled with nanofluid. In their study, the response surface methodology and two-phase mixture model was used to carry out the sensitivity analysis of heat transfer and heat exchanger effectiveness in a double pipe heat exchanger filled with $Al_2O_3$ nanofluid. Ijaz et al. [24] presented a comprehensive study on the liquid and solid particles interaction propagating through a finite symmetric wavy channel. Bahiraei et al. [25] carried out an assessment and optimization of hydrothermal characteristics for a non-Newtonian nanofluid (Cu nanoparticles in a base solution of 0.4 wt% carboxymethyl cellulose (CMC) in water) flow within miniaturized concentric-tube heat exchanger where he considered it from the designer's viewpoint in order to find the optimal cases with maximum heat transfer and minimum pressure drop. Bahiraei et al. [26] carried out a CFD simulation of the irreversibility caused by heat transfer and friction for a power-law nanofluid in a mini-channel having chaotic perturbations. The flows were laminar and turbulent regimes were not applicable. The convective heat transfer rate was reported to be

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## Nomenclature

| | |
|---|---|
| $A_0, A_1, C_1, C_2, C_{1\epsilon}, C_{2\epsilon}$ | RANS model constants |
| $\vec{a}$ | particle acceleration |
| $Cp$ | specific heat transfer, J/kgK |
| *cst.* | constant properties |
| $D$ | tube diameter, m |
| DPM | discrete phase model |
| $d$ | nanoparticle diameter, m |
| $F$ | body force, N |
| $g$ | gravitational acceleration, $m/s^2$ |
| $G_K$ | generation of turbulent kinetic energy |
| $Gz$ | Graetz number, $VD^2/\alpha L$ |
| $H$ | total enthalpy, kJ/kg |
| $h$ | heat transfer coefficient, $\mathrm{W/m^2K}$ |
| $k$ | thermal conductivity, W/mK |
| $L$ | tube length, m |
| $m$ | mass, kg |
| $Nu$ | Nusselt number, $hD/k$ |
| $P$ | pressure, Pa |
| $Pr$ | Prandtl number, $Cp\mu/k$ |
| $q$ | wall heat flux, $\mathrm{W/m^2}$ |
| $r$ | radial coordinate, m |
| $r_0$ | tube radius, m |
| RANS | Reynolds average Navier Stokes |
| $Re$ | Reynolds number, $\rho VD/\mu$ |
| $Sm, Se$ | source and sink terms |
| SPM | single phase model |
| $T$ | fluid temperature, K |
| $T^*$ | dimensionless temperature, $(T - T_w)/(T_b - T_w)$ |
| $t$ | time, s |
| $v$ | velocity vector, m/s |
| $v_{dr}$ | drift velocity, m/s |
| $\delta V$ | cell volume, $\mathrm{m^3}$ |

| | |
|---|---|
| *var.* | variable properties |
| $x$ | axial coordinate, (m) |

*Greek letters*

| | |
|---|---|
| $\epsilon$ | dissipation rate of turbulent kinetic energy $\left(\frac{m^2}{s^3}\right)$ |
| K | turbulent kinetic energy |
| $\kappa$ | kinematic viscosity |
| $\sigma_t$ | constant for turbulent Prandtl number |
| $\sigma_K$ | effective Prandtl number for turbulent kinetic |
| $\sigma_\epsilon$ | effective Prandtl number for the rate of dissipation |
| $\tau_D$ | time |
| $\alpha$ | thermal diffusivity, $\mathrm{m^2/s}$ |
| $\mu$ | dynamic viscosity, Pa s |
| $\rho$ | density, $\mathrm{kg/m^3}$ |
| $\phi$ | particle volume fraction |
| $\tau$ | wall shear stress, Pa |
| $k_B$ | Boltzmann constant, $1.3807 \times 10^{-23}$ J/K |
| $\mu_t$ | turbulent molecular viscosity |
| $\omega$ | angular velocity |
| $\upsilon$ | kinematic viscosity, $\mathrm{m^2/s}$ |

*Subscripts*

| | |
|---|---|
| $av$ | average |
| $b$ | bulk mean |
| $bf$ | base fluid |
| $i$ | inlet |
| $m$ | mixture |
| $n$ | total number of particles |
| $nf$ | nanofluid |
| $p$ | nanoparticle |
| $w$ | wall |
| $0$ | reference to inlet condition |

limited due to poor flow mixing. Ellahi et al. [27] devoted a study to explore the credible potential use of kerosene-alumina nanofluid for thrust chamber regenerative cooling in semi-cryogenic rocket engine due to its enhanced thermal properties. Bhatti et al. [28] studied the peristaltic transport of two-phase (fluid-particle) flow. Rashidi et al. [29] used the volume of fluid model to simulate the nanofluid flow and entropy generation in a single slope solar still. They investigated the potential of $Al_2O_3$-water nanofluid to improve the productivity of a single solar slope still. Rahmat and Ellahi [30] state that the materials that advance the state-of-art of experimental, numerical and theoretical methodologies are still insufficient. Hence the need for more studies on nanofluid.

Over the years, there have been several experimental and numerical studies on heat transfer characteristics of the flow of nanofluids in tubes carried out by researchers [2,3,6,8,10,17,31–73]. A quick review of the most relevant works is presented below.

Kim et al. [31] experimentally studied the convective heat transfer characteristics of nanofluids in a straight circular tube under laminar flow conditions with constant wall heat flux. They used alumina nanofluid containing 3 vol% of suspended particles and found a 15% increase in the heat transfer coefficient at the early entrance region.

Wen and Ding [68] carried out an experimental investigation into convective heat transfer of nanofluid made of $\Upsilon\text{-}Al_2O_3$ nanoparticle and de-ionized water flowing through a copper tube under laminar flow ($Re < 2300$) conditions and found that the enhancement was particularly significant in the entrance region.

Numerical investigation of forced convective heat transfer for water $Al_2O_3$ nanofluid inside a circular tube under constant wall heat flux has been investigated by several researchers [6,32,36,43]. Furthermore, some researchers devised new models to simulate nanofluids based on their opinions on which phenomenon contributed more to the nanofluid's behavior [33,36,37,56,74,75]. Several models have been used to simulate nanofluids. Some models used include the single-phase model and two-phase models: mixture model, discrete phase model, combined model of discrete and mixture phases but not all the models accurately predicted the heat transport properties of nanofluid with respect to the flow regimes. For example, Albojamal and Vafai [35] used a two dimensional (2D) fluid domain in his study and found that the mixture model only succeeded to accurately predict the heat transfer coefficient of the $Al_2O_3$/water nanofluid in a circular pipe under constant wall heat flux at a low volume fraction ($\phi$) < 1% and for the developing region. The converse was true in other regions. He suggested the single-phase model for modeling nanofluids, since it gave results with good agreement with experimental data for the fully developed region with a maximum discrepancy of 5%. However, the single-phase models require that the nanofluid under investigation has correlations that accurately represents its thermophysical properties before we can use the single-phase model. Additionally, the single-phase model therefore only solves but does not capture the physics of the particle-fluid interactions and does not give information of the secondary phase as a two-phase model will.

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