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Comparison of single and two-phase models for nanofluid convection at the entrance of a uniformly heated tube

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ABSTRACT

Macroscopic modeling of hydrodynamic and thermal behavior of nanofluid flows at the entry region of uniformly heated pipe is studied. Single-phase models with and without thermal dispersion effect, Eulerian–Eulerian, and Eulerian–Mixture two-phase models are evaluated by comparing predicted convective heat transfer coefficients and friction factors with experimental results from literature. Solutions with two different velocity–pressure coupling algorithms, Full Multiphase Coupled, and Phase Coupled Semi-Implicit Method for Pressure Linked Equations are also compared in terms of accuracy and computational cost. Dispersion model that uses velocity gradient to define dispersion conductivity is found to be more effective at entry region compared to other single-phase models. However, two-phase models predict convective heat transfer coefficient and friction factor more accurately at the entry region. Moreover, computational cost of Eulerian–Eulerian two-phase model can be reduced up to 50% by implementing Full Multiphase Coupled scheme.

1. Introduction

Engineered fluids made of a base fluid and nano sized particles such as CuO, Al_2O_3, or TiO_2 [1] that form colloidal suspensions are referred as nanofluids [2]. The most commonly used base fluids are water and ethylene glycol due to their use in conventional thermal systems. Measured thermal conductivities of nanofluids are found to be exceeding predictions based on the Maxwell's effective medium theory that led many researchers to consider nanofluids as next generation heat transfer fluids [3]. Therefore, nanofluids are considered for many engineering applications such as, cooling of electronics [4,5], vehicle thermal management [6], and solar energy systems [7,8]. Design and analysis of such systems necessitate accurate estimation of hydrodynamic and thermal characteristics of nanofluids.

Many experimental studies were carried out to quantify thermal and flow characteristics of nanofluids for laminar and turbulent flow conditions [2,9–13]. However, it is important to be able to model nanofluid flow accurately in order to design equipment that operates with nanofluids. It was observed that addition of nanoparticles to a base fluid, augments convective heat transfer together with an increase in pressure drop due to increased thermal conductivity and viscosity [1,2,9–13]. Therefore, modeling tools should estimate both of these behaviors accurately.

Macroscopic models for nanofluid flow and heat transfer can be classified as single-phase and two-phase models [1–3,7,9–15]. Single-phase approaches consider nanoparticles and base fluid as a single homogeneous fluid with respect to its effective properties [14]. Two-phase approaches handle continuity, momentum and energy equations for particles and base fluid using three different methods. One of these methods used in this study is Eulerian–Mixture model (EMM) where momentum and energy equations are solved for mixture phase coupled with continuity equation for each phase, then phase velocities are related by empirical correlations [16,17]. The other method that is used in this study is the Eulerian–Eulerian model (EEM) where separate continuity, momentum, and energy equations for each phase are solved. This approach is suggested for flows where interactions between phases are not well defined [17,18]. Although two-phase models provide a better understanding of both phases, single-phase models are computationally more efficient, however provide less detail about each phase [18].

Forced convection of Al_2O_3–water/EG nanofluids in a uniformly heated tube at fully developed laminar and turbulent flow regimes using a homogeneous single-phase model is studied by Maiga et al.

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[14]. While their predictions underestimate measured heat transfer coefficients, results indicate that addition of nanoparticles enhances convective heat transfer coefficient of Al_2O_3–water nanofluid with 10% particle concentration by 60% at a Reynolds number of 250 [14]. Experimental studies such as [19] reported that the increase in convective heat transfer coefficient exceeds that of effective thermal conductivity. This indicates that there are different mechanisms in heat transfer enhancement for forced convection other than the enhancement in thermal conductivity. Single-phase thermal dispersion models are introduced in Refs. [20] and [21] to account for energy transport by random movement of nanoparticles, that is also known as thermal dispersion effects. Using thermal dispersion model presented in Ref. [20], Ozerinc et al. [22] studied fully developed laminar forced convection of Al_2O_3–water nanofluid by considering temperature dependent properties. The reported increase in convective heat transfer coefficient of 2.5% Al_2O_3–water nanofluid is 36% at a Peclet number of 6500. The results are in good agreement with the experimental data in the literature, suggesting that single-phase models considering thermal dispersion and temperature dependent properties are capable of predicting heat transfer behavior more accurately. Moraveji et al. [23] showed that convective heat transfer increases as particle size decreases for developing Al_2O_3–water nanofluid flow using single phase models.

Mirmasoumi et al. [24] investigated mixed convection of Al_2O_3–water nanofluid in a horizontal tube using a two-phase EMM. They have shown that particle concentration is higher near the wall and bottom of the tube, hence uniform particle distribution is not valid for all cases. Nanofluid forced convection in developing flow in a tube subjected to constant heat flux and temperature was studied by Bianco et al. [25] by using single and two-phase models including volume of fluid (VOF), EMM, EEM considering both constant and temperature dependent properties. According to their results difference between homogeneous single-phase and two-phase mixture model becomes significant at 11% volume concentration. Moreover, consideration of temperature dependent properties gives a better estimation of convective heat transfer coefficient. They observed that convective heat transfer coefficient for 2.5% Al_2O_3–water nanofluid at a Reynolds number of 250 increases up to 17%.

Kalteh et al. [18] numerically studied CuO–water nanofluid laminar forced convection in a micro-channel by two-phase EEM. Although velocity and temperature differences between phases are negligible, EEM estimates convective heat transfer coefficient more accurately with respect to single-phase models. They also showed that particle–particle interactions have negligible effect on Nusselt number for laminar flow. Lotfi et al. [16] evaluated homogeneous single-phase model, EMM, and EEM for Al_2O_3–water nanofluid. The study neglected temperature dependency of properties and did not include thermal dispersion models. They reported that two-phase models overestimate fully developed heat transfer coefficients and EMM is the most accurate model among three two-phase models (EEM, EMM, VOF). Akbari et al. [26] compared single and two-phase models for mixed convection heat transfer of Al_2O_3–water nanofluid. Their study covers homogeneous single-phase and two phase models (VOF, EMM, EEM) with temperature dependent properties. It is reported that estimated convective heat transfer coefficients by two-phase models are similar. Two-phase models provide more accurate prediction of convective heat transfer coefficient with an overestimation, whereas single-phase model underpredicts convective heat transfer coefficient. Although single-phase models are found to be less accurate, it should be noted that the study did not include thermal dispersion models. Single and two-phase models for Al_2O_3–water nanofluid are also studied by Frad et al. [15]. They showed that two-phase models provide more accurate prediction of heat transfer of nanofluids for fully developed flow.

Although they are more accurate in predicting heat transfer, two-phase models are computationally more expensive than single-phase models due to the increased number of equations to be solved. Despite being expensive, the Phase Coupled Semi Implicit Method for Pressure Linked Equations (PC-SIMPLE) algorithm is widely used in literature due to its robustness [16,18,24,26] for EEM. Computational cost of two-phase EEM can be reduced by using Full Multiphase Coupled (FMC) algorithm for velocity and pressure coupling where equations are solved simultaneously rather than in a segregated manner like PC-SIMPLE.

Considering the literature, there is no complete study that considers recent state-of-the art single and two-phase models for laminar forced convection of nanofluids. This study aims at evaluating single-phase and two-phase models by considering the effect of temperature dependent properties, and dispersion effects for single-phase models, together with the first time use of FMC for two-phase EEM of nanofluid forced convection. Results are compared with experimental data available in literature in terms of error and required CPU time. Al_2O_3–water nanofluid with 42 nm nanoparticles is considered throughout the study due to availability of experimental data in the literature.

2. Mathematical models

2.1. Single-phase model

Single-phase models assume that base fluid and nanoparticles have the same temperature and velocity field. Therefore, continuity, momentum and energy equations can be solved as if the fluid were a classical Newtonian fluid by using effective properties of nanofluid. Effective properties are functions of particle size (d_p), type, shape, and particle volume concentration (ϕ_p) and temperature [2,14,27].

In this study, for the homogeneous single-phase (SPM) Al_2O_3–water nanofluid model with constant properties, nanofluid thermal conductivity (k_{nf}) is determined by the correlation reported by Hamilton–Crosser [28] to take a simpler thermal conductivity model into account together with other advanced models. The formulation can be given as;

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p + (n-1)k_{bf} - (n-1)\left(k_{bf} - k_p\right)\phi_p}{k_p + (n-1)k_{bf} + \left(k_{bf} - k_p\right)\phi_p} \tag{1}$$

where, k_{bf} and k_p are the base fluid and nanoparticle thermal conductivities, respectively and $n = 3$ is the shape factor for spherical particles. This correlation does not consider temperature and particle size dependency of thermal conductivity. To account for temperature and particle size dependency of thermal conductivity of Al_2O_3–water nanofluid, correlation suggested by Chon et al. [29] is used. This is a more advanced correlation compared to that of presented by Hamilton and Crosser [28]. The formulation can be given as;

$$\frac{k_{nf}}{k_{bf}} = 1 + 64.7\phi_p^{0.7460}\left(\frac{d_{bf}}{d_p}\right)^{0.3690}\left(\frac{k_p}{k_{bf}}\right)^{0.7476} Pr^{0.9955} Re_{disp}^{1.2321} \tag{2}$$

where, d_{bf} is molecular diameter of base fluid (0.29 nm, for water). For this study we considered Al_2O_3 particles with 42 nm diameter. The Prandtl number (Pr) and the dispersion Reynolds number (Re_{disp}) in this correlation are defined as;