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Single-phase models for improved estimation of friction factor for laminar nanofluid flow in pipes

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ABSTRACT

Hydrodynamic and thermal modeling of nanofluid flow in a uniformly heated circular pipe is considered using single-phase models. Various single-phase models relying on Brownian and dispersion viscosity models are evaluated by comparing heat transfer coefficient, Nusselt number and friction factor with experimental results from literature. Single-phase models are capable of predicting heat transfer of nanofluids better when dispersion models are used. However, they fail to accurately predict surface shear stress when used with standard viscosity models. A new viscosity model based on dispersion viscosity is proposed to improve prediction accuracy of single-phase models for estimating the surface shear stress of laminar nanofluid flow. Results suggest that proposed single-phase dispersion model is capable of accurately predicting heat transfer coefficient and friction factor.

1. Introduction

Nanofluids are colloidal suspensions of nanoparticles and they have been attracting increasing research interest due to their improved thermal characteristics since their invention almost two decades ago [1]. The most commonly used particles are CuO, Al_2O_3, or TiO_2, with diameters smaller than 100 nm, and conventional heat transfer fluids such as water and ethylene glycol (EG) are used as base fluids. Suspended nanoparticles increase the effective thermal conductivity of the fluid and consequently improve the heat transfer performance [2,3]. Therefore, nanofluids can be considered in many heat transfer applications such as, thermal management of opto/electronic systems, internal combustion engine cooling and lubrication, and solar energy systems [4–7]. While experimental methods are considered mostly to characterize the thermal and rheological behavior, modeling methods or tools that are capable of accurately predicting the hydrodynamic and thermal behavior are required to investigate their potential use for these applications.

There are many experimental studies investigating the heat transfer enhancement using nanofluids for laminar and turbulent flow conditions [1,8–13]. However, there are only few studies on hydrodynamic characterization of nanofluids despite the fact that increase in heat transfer coefficient and Nusselt number is also accompanied by increase in friction factor and pressure drop.

Accurate modeling of nanofluid flow using macroscopic models is a necessity to design equipment that operates with nanofluids. Numerical studies mainly focus on single and two-phase macroscopic models. The homogeneous single-phase model assumes that relative velocities of nanoparticles and base fluid are negligible and therefore, nanofluid can be considered as a single continuum represented by its effective properties. Maiga et al. [14] used a homogeneous single-phase model to investigate forced convection of Al_2O_3–water and Al_2O_3–EG nanofluids in a uniformly heated tube at fully developed laminar and turbulent flow regimes. Palm et al. [15] used temperature dependent properties to model nanofluids convection and they found that temperature dependent modeling predicts higher heat transfer enhancement than considering constant properties for nanofluids. The accuracy of homogeneous single-phase model can be improved by considering the random movement of solid particles. Xuan and Roetzel [16] proposed the dispersion approach for nanofluids which takes into account the Brownian motion of the nanoparticles to modify the single-phase approach. Heris et al. [17] used dispersion model to simulate laminar convection of nanofluid in a circular tube and they showed that dispersion model results are in good agreement with their experimental data [11]. Mokmeli and Saffar-Avval [18] used both homogenous single-phase and dispersion models to study convective heat transfer of nanofluids. The comparison of numerical results with experimental values showed that dispersion model is more accurate. Özerinç et al. [19] studied fully developed laminar forced convection of Al_2O_3–water nanofluid by using

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Nomenclature

c_p	Specific heat [J/kg-K]
C'	Dispersion coefficient
d_{bf}	Diameter of base fluid molecules [m]
d_p	Particle diameter [m]
D	Pipe diameter [m]
f	Darcy friction coefficient for fully developed flow
f_x	Local Darcy friction coefficient
h	Heat transfer coefficient [W/m^2-K]
$\overline{h}$	Mean heat transfer coefficient [W/m^2-K]
k	Thermal conductivity [W/m-K]
k_B	Boltzmann constant [J/K]
L	Pipe length [m]
Nu	Nusselt number
$\overline{Nu}$	Mean Nusselt number
P	Pressure [Pa]
Pr	Prandtl number
q''	Heat flux [W/m^2]
r	Radial direction
R	Pipe radius [m]
R_f	Thermal interfacial resistance [K-m^2/W]
Re	Reynolds number
T	Absolute temperature [K]
$\overline{T}$	Average temperature [K]
u, v	Axial and radial velocity components [m/s]
U	Mean flow velocity [m/s]
$\vec{V}$	Velocity vector
V_B	Brownian velocity
x	Axial direction

Greek letters

α	Thermal diffusivity [m/s^2]
δ	Nanoparticle spacing [m]
λ	Mean free path [m]
μ	Dynamic viscosity [Pa-s]
ρ	Density [kg/m^3]
τ	Shear stress [Pa]
φ	Particle volume fraction

Subscripts and superscripts

app	Apparent
bf	Base fluid
br	Brownian
disp	Dispersion
eff	Effective property
i	Inner diameter
in	Inlet
m	Mean
nf	Nanofluid
o	Outer diameter
out	Outlet
p	Particle
theo	Theoretical
w	Wall
x	Local

thermal dispersion model and their results indicated that dispersion model can accurately predict nanofluid heat transfer.

Another class of macroscopic models is the two-phase models where the effect of relative velocities of nanoparticles and base fluid are taken into account by considering nanoparticles and base fluid as different phases. In these models interactions between phases are related by interphase exchange coefficients. Lotfi et al. [20] used homogeneous single-phase and two-phase models to study forced convective flow of nanofluid inside a tube and they showed that the mixture model results have better agreement with experimental values. Akbari et al. [21] compared homogeneous single-phase model and two-phase models for forced convection heat transfer of Al_2O_3–water nanofluid. Their results indicated that two-phase models are more accurate in prediction of nanofluid heat transfer compared to that of homogeneous single-phase model.

More recently, Göktepe et al. [22] studied laminar nanofluid flow in the entrance region of a circular pipe considering various single and two-phase models. It was observed that thermal behavior in forced convection of nanofluids can be accurately modeled by using two-phase models and advanced single-phase models such as thermal dispersion model. Although single-phase models are computationally more efficient, they are not accurate in predicting the change in friction factor, while two-phase Eulerian-Eulerian model (EEM) estimates better the increase for Al_2O_3–water nanofluid laminar flow. As a result, single-phase models need improvement for predicting hydrodynamic effects to increase their overall accuracy.

Rheological studies [23–34] in regards to nanofluids suggest that viscosity of nanofluids, μ_{nf}, is a function of particle volume fraction, φ, particle size, d_p, and nanofluid temperature, T. In general, nanofluid viscosity decreases as temperature rises [23–26] while the augmentation of particle volume fraction increases nanofluid viscosity [23,27,28]. There are conflicting views in regards to the effect of particle size; for larger particle size nanofluid viscosity can either increase or decrease [23,29,30]. The uncertainty is due to agglomeration and the effective particle size and its effect on changes in viscosity accordingly.

Based on rheological studies, nanofluids exhibit either non-Newtonian or Newtonian behavior depending on their base fluid, particle material and concentration. Das et al. [31] reported that Al_2O_3–water nanofluids for particle volume fractions up to 4% exhibit Newtonian behavior. However, non-Newtonian behavior is observed between shear rates of 0.1 and 1000 1/s for TiO_2–water nanofluid with particle volume fraction of 1.2% [29]. Tseng and Wu [32] studied Al_2O_3–water nanofluid for volume fractions between 1% and 16% at different pH values. Non-Newtonian behavior was observed for volume fractions of 3–16% for shear rates between 1 and 1000 1/s. In their review, Ding et al. [33] concluded that while viscosities of dilute nanofluids are independent of shear rate, nanofluids with high particle volume fractions are more likely to exhibit shear thinning behavior. The review also revealed that nanofluids with low-viscosity base fluids are more likely to behave non-Newtonian compared to nanofluids with high-viscosity base fluids.

Since nanoparticles in a nanofluid tend to agglomerate, they require electrostatic stabilization by adjusting pH value for prolonged stability. Anoop et al. [34] investigated influence of electroviscous effects on effective nanofluid viscosity considering water and EG based nanofluids with Al_2O_3 and CuO particles. The results suggested that viscosity of water based nanofluids is more sensitive to changes in particle volume fraction compared to that of EG based nanofluids, while temperature sensitivity is opposite. Both nanofluids exhibit Newtonian behavior at shear rates of 10–1000 1/s for volume fractions between 0.5% and 6%.

Researchers have suggested various models as a function of volume fraction and base fluid viscosity to estimate the effective viscosity of nanofluids. Einstein [35] suggested a formula for dilute