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Numerical simulations of forced convection heat transfer and flow characteristics of nanofluids in small tubes using two-phase models

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ABSTRACT

Laminar and turbulent forced convection heat transfer and flow characteristics of nanofluids in small smooth tubes are numerically simulated using two kinds of multiphase-flow models. The simulated results are compared with the experimental results from the published papers and the traditional predicting correlations to investigate the applicability of these models for nanofluids. The multiphase-flow models including mixture model and Eulerian model, and both of them belong to the well-known Euler–Euler model. The effects of various parameters such as Reynolds number and nanoparticles concentration on the heat transfer and flow characteristics are investigated and discussed in each model. The study results show that little deviation exists between the simulated results and the traditional predicting correlations for low concentration nanofluid, which indicates that low concentration nanofluid has no meaningful nano-effect on forced convection heat transfer. While, non-traditional fluid characteristics occur and increase with increasing the nanoparticles concentration, and the simulated results using special models of multiphase flow are closer to the experimental data than that of the traditional correlations, which means the multiphase flow models are more accurate than traditional correlations for high concentration nanofluid. Moreover, the numerical results also indicate that the drag coefficients of simulated results have only little difference less than 0.4% with that of experimental results for nanofluids in the laminar flow region. However, the drag coefficients of simulated results have a increase by about 60–22% compared with the experimental results in the turbulent flow region. As conclusion, the present study indicates that the two-phase models, including mixture model and Eulerian model, can predict the forced convection heat transfer and flow characteristics of nanofluid well, and have important implications for the application of nanofluid.

1. Introduction

In 1993, Masuda [1] added the nanoparticles (Al_2O_3, TiO_2) into the water firstly, and prepared colloids with different concentration. The measurement results of colloids showed that their thermal conductivity could be enhanced by adding the nanoparticles. For instance, the thermal conductivity of nanoparticles colloid with volume concentration of 4.3% is increased by 32% compared with that of water. However, the viscosity of nanoparticles colloid did not increase evidently. Choi [2] proposed the concept of nanofluid for the first time, which is a kind of new heat transfer working fluid with nanoparticles in the base fluid.

Lee and Choi [3] applied nanofluid into cooling system, which was used for cooling the crystal silicon lenses in a high intensity X-ray source. Water, liquid nitrogen and nanofluids were used for testing, and the nanofluids contained the nanoparticles of CuO and γ-Al_2O_3. The experimental results indicate that the heat transfer coefficients of nanofluids are three times higher than that of water, and the heat flux could reach up to 1500 W/cm^2. Besides, the heat resistance of nanofluids is about half of water with the lowest value of 0.04 °C/W/cm^2. Therefore, nanofluids have important implications for the application as a cooling fluid. Later on, many researchers focus on the study of forced convection heat transfer characteristics of nanofluids. Among the published literatures, the nanoparticles contain TiO_2, Al_2O_3, CuO, Cu, graphite, carbon nanotubes and etc., and the base fluids include water, alcohols and oils.

Although there are abundant of studies about the forced convection heat transfer characteristics of nanofluid in small tubes, the literature with detailed experiment conditions description is less. Liao and Liu [4] experimentally studied the forced convection heat transfer and flow characteristics of CuO water-based nanofluid in a horizontal small stainless tube with 1 mm inner diameter. The results showed that the thermal conductivity

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Nomenclature

HTC	heat transfer coefficient
r	radial direction (m)
x	distance from entrance in the flow direction (m)
Q	heat power (W)
q	heat flux (W/m^2)
L	length of tube (m)
d	diameter of tube (m)
K	fluid-solid exchange coefficient (–)
F	force (N)
v	velocity (m/s)
h	heat transfer coefficient (W/K/m^2)
Re	Reynolds number (–)
Nu	Nusselt number (–)
$\overline{\text{Nu}}$	average Nusselt number (–)
k	the turbulence kinetic energy (–)
T	temperature (K)
f	friction factor (–)
ΔP	pressure loss (Pa)
u	velocity of tube (m/s)
Pr	Prandtl number (–)
V	volume (–)

Greek alphabet

ρ	density (kg/m^3)
φ	volume fraction (vol.%)
w	mass concentration (wt.%)
η	viscosity of fluid (Pa s)
λ	heat conduction coefficient (W/m K)
ε	dissipation rate of the turbulence kinetic energy
τ	the stress–strain tensor

Subscripts

np	nanoparticles
bf	base fluid
nf	nanofluid
q	the qth phase
m	mass
i	inner surface of tube
l	liquid
s	solid
q	the qth phase (represent liquid and solid phase)
sl	the interaction between sold phase and liquid phase
sl	the interaction between particle and particle
w	wall

increase is the main reason for enhancing heat transfer coefficient. Moreover, compared with water, the flow resistance of nanofluid is slightly bigger in the region of laminar flow, and slightly smaller in the turbulent flow. Besides, the fluid temperature has little influence on the flow characteristics. Wen [5] and Anoop [6] experimentally studied the laminar forced convection heat transfer of nanofluid. The nanofluid used is a kind of water-based γ-Al_2O_3 suspension. Their results all show that nanofluid could enhance the convection heat transfer characteristics. Specifically, the strengthening effect of heat transfer is increased with increasing the nanoparticles concentration, especially in the entrance region.

Recent years, there appeared a lot of numerical studies for investigating forced convection heat transfer of nanofluid in tubes. However, most papers regarded the nanofluid as single phase fluid, and use various traditional concepts to calculate the physical parameters of nanofluids such as thermal conductivity and viscosity [7–9]. However, this kind of method cannot discover the mechanism of heat transfer and flow characteristics of nanofluids as a special solid–liquid two phase fluid. Maiga [10] carried out some numerical calculations for the turbulent forced convection heat transfer coefficient and wall shear stress of γ-$A1_2O_3$ water-based nanofluid and γ-$A1_2O_3$ glycol-based nanofluid in small tubes. The nanofluids were regarded as single phase fluids. Therefore, the sliding velocity between particles and base fluid was neglected. Reynolds-averaged Navier–stokes equation and k–ε model were used to calculate the stress and HTC of nanofluid. The results indicate that the friction force of wall and HTC are increased with the increase of nanoparticles concentration. In addition, the HTC of γ-$A1_2O_3$ glycol-based nanofluid is higher than that of γ-$A1_2O_3$ water-based nanofluid under the same condition. Roy [11] also employed the same model from Maiga [10], and studied the effect of γ-$A1_2O_3$ nanoparticles on forced convection heat transfer and shear stress in tube under radial flow using water, glycol and oil, respectively. The research shows that the heat transfer and shear stress are enhanced by the increase of particle concentration and Reynolds number. Nguyen [12] also investigated numerically the flow and heat transfer process of γ-$A1_2O_3$ water-based nanofluid and γ-$A1_2O_3$ glycol-based nanofluid as cooling fluids for microprocessor using single flow model. The results almost coincide with those of Maiga [10].

So far, a few numerical studies on the flow and heat transfer characteristic of nanofluid in a tube using multiphase model were carried out [13–22]. However, some simulation just employed the mixture model. Beside the range of Reynolds number is in either laminar flow or turbulent flow and not wide enough. Moreover, the simulated results did not have a detailed comparison with the experimental data. Lastly, the conclusions of past research are mainly about the applicable of two phase model, and the adding of nanoparticles can enhance the heat transfer. However, according to the experimental investigations [4–6], the enhancement appeared when the concentration increases big enough, and nanofluid with low concentration may not have an obvious enhancement of heat transfer.

Behzadmehr [13] employed multiphase mixture model to calculate the convective heat transfer of Cu nanofluid with volume concentration of 1.0 vol.% under the constant wall heat flux and turbulent flow. Compared to the single model, the results using two phase mixture model have better agreement with experimental data, which indicates that the multiphase model is superior to the single phase model to numerically study the heat transfer of nanofluid. He [14] studied the laminar convective heat transfer of TiO_2 water-based nanofluid using single phase and Euler–Lagrange two phase models respectively. Drag force in phases, thermophoretic force, lift force, mass force, virtual mass force, pressure gradient force and Brownian force are considered in the disperse phase. The study indicates that not all forces in the model are proper for nanoparticles; on the other hand, some forces like lift force and thermophoretic force could be neglected.

In terms of the study on the flow and heat transfer property of nanofluid in a tube, a number of numerical researches about the microcosmic mechanism of thermal conductivity enhancement have been published, except for the macroscopic simulating literature. A method of molecular dynamics was carried out to discover the thermal conductivity enhancement mechanism of nanofluid in Suranjanp [23]. Cu nanoparticle and argon base fluid are used for reducing calculated quantity. Besides, the model is based on the method of Green–Kubo. The effect of nanoparticle concentration on thermal conductivity is discussed. The calculation results demonstrate that the thermal conductivity is increased with