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Comparative assessment of numerical models for nanofluids' laminar forced convection in micro and mini channels

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ABSTRACT

In the present study, laminar forced convection of Al_2O_3 + water and TiO_2 + water nanofluids in the respective micro and mini channels has been investigated under constant heat flux boundary condition. The effectiveness of homogeneous, discrete phase model and Eulerian-Eulerian (Mixture, Volume of Fluid, Eulerian) models has been evaluated for experimental conditions reported by Karimzadehkhouei et al. (2015) and He et al. (2009). Hydrothermal characteristics of Al_2O_3 + water ($d_p = 20$ nm) nanofluid have been studied for 0.25%, 0.5% and 2% particle volume fractions in Reynolds number range of 200–2000 whereas 0.24%, 0.6% and 1.18% particle volume fractions of TiO_2 + water ($d_p = 21$ nm) has been studied at 900 and 1500 Reynolds numbers. Results illustrate that for all nanoparticle volume fractions under consideration, discrete phase model (DPM) estimates most satisfactory hydrothermal results. For higher thermal conductive nanofluids, single phase model underestimates while Eulerian-Eulerian models over predict thermal fields. Though all the numerical models determine fairly analogous friction factor with respect to experimental as well as theoretical results.

1. Introduction

Innovation in microelectromechanical systems demands efficient thermal management techniques and nanofluids can be a possible avenue in this pursuit. Nanofluids, the conventional thermo-fluids comprising nano-sized metallic and nonmetallic suspended particles with enhanced thermal conductivity, were first introduced by Choi et al. [3]. Since then multiple experimental and numerical studies has been performed in order to explore hydrothermal characteristics of various nanofluids. In numerical analysis, two general approaches have been adopted by researchers; single phase (homogeneous) approach and the two-phase (suspended particles) approach. In single phase approach, nanofluids are treated as homogeneous fluid (molecular-sized nanoparticles) with improved thermophysical properties estimated either by experimental results or by theoretical models, whereas in two-phase model both base fluid and nanoparticles are modeled individually and their interactive forces are computed. However, reported results of the two approaches have not been always consistent hence, selection of an appropriate model to simulate nanofluids for CFD studies remained under debate [4].

Single phase approach has been widely adopted by researchers [5–17] because of its simplicity and reduced computation time. Although, multiple authors [18–20] illustrated that in addition to effective thermal conductivity, nano-particle migration induced by viscosity gradient, non-uniform shear rate, particle Brownian diffusion and interfacial heat transfer also plays influential part in heat transfer coefficient enhancement and Single-phase model fails to account these forces. Hwang et al. [21] reported similar results in their experimental investigation and additionally stated that flattening of velocity profile can also be credited for nanofluid higher heat transfer coefficient. Akhtari et al. [10] reported maximum 15.6% deviancy of their single phase model results with the experimental predictions for 0.5 vol% of Al_2O_3 + water nanofluid.

Presently in Ansys Fluent 17.1 [22] module, Eulerian-Eulerian (Mixture Model, Eulerian Model, Volume of Fluid model) and Lagrangian-Eulerian models can be used for numerical calculation of two phase flows. In Eulerian-Eulerian approach, the different phases are mathematically treated as interpenetrated continua. The concept of phasic volume fraction is introduced and volume fractions are assumed to be continuous functions of space and time with their sum equal to unity. Phases are also allowed to move at different velocities and dynamic viscosity of each phase needed is to be specified.

Some researchers [20,23–29] employed Eulerian-Eulerian models for their studies and proclaimed that Eulerian-Eulerian models

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Nomenclature

Ag	silver (–)
Al_2O_3	aluminum oxide (Alumina)
C	property combinations (–)
C_p	specific heat (J/kg K)
C_c	cunningham correlation (–)
Cu	copper (–)
D_h	channel hydraulic diameter (mm)
d_p	nanoparticle diameter (nm)
d_f	equivalent diameter of base fluid (nm)
d_{ij}	deformation tensor (–)
d_r	drift velocity (ms^{-1})
DPM	discrete phase model (–)
E-E	Eulerian model (–)
F	force (N/kgm^3)
f	darcy friction factor (–)
F_{drag}	drag force (N/kgm^3)
$F_{gravity}$	gravity force (N/kgm^3)
F_{lift}	Saffman lift (N/kgm^3)
$F_{pressure}$	pressure gradient force (N/kgm^3)
$F_{thermophoresis}$	thermophoresis force (N/kgm^3)
$F_{virtual}$	force due to virtual mass(N/kgm^3)
g	gravitation acceleration (m/s^2)
h	convective heat transfer coefficient (W/m^2k)
m	mass (kg)
k	thermal conductivity (W/mk)
K_B	Boltzmann constant ($m^2kg/s\ K$)
K_n	Knudson number (–)
Nu	Nusselt Number (–)
Mix	Mixture model (–)
Pr	Prandtl number (–)
Re	Reynolds number (–)
r	radius of nanoparticles (nm)
S_u	source term (energy equation)
S_E	source term (momentum equation)
SPM	single phase model (–)
T	temperature (Kelvin)
t	time (s)
TiO_2	titanium dioxide (–)
V	fluid total velocity (m/s^2)
VOF	volume of fluid model (–)
X	channel length (m)
x_+	dimensionless axial distance (–)
Y+	dimensionless wall distance of first node (–)

Greek symbols

λ	molecular mean free path (m)
μ	viscosity (–)
ρ	density of fluid ($kg\ m^{-3}$)
φ	particle volume fraction (–)

Subscripts

avg	average
c	cluster
eff	effective
f	fluid
h	hydraulic
m	mixture
p	particle
X	characteristic length

predict improved results when compared with homogenous model, yet their statements are in contradiction with those reported by Akbari et al. [30,31], Bianco et al. [32], Salemi et al. [33] and a recently published article by Ganesan et al. [34] for moderate to high nanoparticle concentrations. Lot et al. [35] demonstrated that mixture approach estimates quite acceptable results as compared to Eulerian approach for 1 vol% of Al_2O_3 + water nanofluid. Also the values predicted by Eulerian model are analogous to single phase model. Naphon and Nakharintr [36] reported analogous results of the mixture and single phase models (maximum difference of 3.74%) in their work for 0.4 vol% of TiO_2 + water nanofluid. Similar predictions have been made by Moghadassi et al. [37] for aqueous nanofluids containing 0.1 vol% of Al_2O_3 and Al_2O_3/Cu nanoparticles.

In discrete phase model (Lagrangian-Eulerian), the base fluid is treated as a continuum (Eulerian) while the nanofluids are tracked by implementing the Lagrangian approach. He et al. [2] applied this model to simulate 0.24–1.18 vol% of TiO_2 + water nanofluids and claimed the consistency of calculated results with experimental findings. Bianco et al. [38] implemented single phase model and DPM Model to compute 1, 4 vol% Al_2O_3 + water nanofluid and illustrated that two models present concordant results with the maximum deviation of 11% for average heat transfer coefficient. For single phase model they used temperature dependent thermo-physical properties. Using DPM Model, Aminfar and Motallebzadeh [39] studied the nanoparticle diameter influence on particle distribution as well as velocity field in the laminar range of Reynolds number. Bahremand et al. [40] numerically studied 0.03 vol% of Ag + water nanofluid by single phase and DPM models and narrated that results computed by DPM model are in compliance with the experimental values whereas single phase model under predict the results. In a similar analysis, Sonawane et al. [41] reported analogous results for less than 0.5% nanoparticle volume concentration.

In the context of these controversial conclusions, Pramuanjaroenkij [42] and Vanaki et al. [4] summarized in their recent review articles that the credibility of different numerical approaches to model nanofluids is still ambiguous. Moreover, the majority of authors focused mainly on thermal characteristics to assess different numerical models and only a few discussed hydrodynamic characteristics which are an essential aspect of an optimum heat exchanger design. Therefore, the present research is aimed at comparative analysis of single phase (SPM), Eulerian-Eulerian (Mixture, Eulerian, VOF) and discrete phase (Lagrangian-Eulerian) model in commercial CFD software Ansys fluent 17.1 [22]. Hydrothermal characteristics of two type of nanofluids Al_2O_3 + water and TiO_2 + water has been computed for experimental conditions specified by Karimzadehkhouei et al. [1] and He et al. [2].

2. Problem description and modeling

The laminar forced convection of Al_2O_3 + water and TiO_2 + water nanofluids in a horizontal channel with constant heat flux boundary condition at solid liquid interface for experimental conditions specified by Karimzadehkhouei et al. [1] and He et al. [2], has been considered in the study. The flow is assumed as hydrodynamically developed and thermally developing in case 1 [1] and thermally and hydrodynamically developing in case 2 [2]. In first case, channel hydraulic diameter and length are D_h = 0.5 mm and X = 0.12 m for nanoparticle (d_p = 20 nm) volume fraction 0.25%, 0.51%, 2% whereas in second case channel diameter and length are D_h = 4 mm and X = 2 m respectively for nanoparticle (d_p = 21 nm) nanoparticle volume concentrations 0.24%, 0.6% and