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Latest development on computational approaches for nanofluid flow modeling: Navier–Stokes based multiphase models☆

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ABSTRACT

Nanofluids have gained significant attention in recent years due their great potential for heat transfer enhancement. The heat transfer of nanofluids can be numerically studied using a single-phase or two-phase approaches. The first assumes that the fluid phase and nanoparticles are in thermal equilibrium and move with the same velocity, while the second requires more computational effort but provides the possibility of understanding the behavior of both fluid phase and solid particles in the heat transfer mechanism. This paper reviews various computational approaches to predict fluid flow and heat transfer characteristics of nanofluids. The characteristics of single-phase and two-phase (volume of fluid, mixture, Eulerian–Lagrangian and Eulerian–Eulerian) approaches have been analyzed and discussed systematically. Latest development and recent researches related to the computational nanofluids are also given.

1. Introduction

During the past decades, technology to make particles in nanometer dimensions was improved and a new kind of solid–liquid mixture that is called nanofluid was appeared [1]. The nanofluid is an advanced kind of fluid containing small quantity of nanoparticles (usually less than 100 nm) that are uniformly and stably suspended in a liquid. The dispersion of a small amount of solid nanoparticles in conventional fluids such as water or ethylene glycol changes their thermal conductivity remarkably.

Thermal conductivity of nanofluids has been measured by several authors with different nanoparticle volume fractions, materials and dimensions in several base fluids and most of the findings show that thermal conductivity of nanofluid is higher than the base fluids. Among them, Lee et al. [2] demonstrated that oxide ceramic nanofluids consisting of CuO or Al_2O_3 nanoparticles in water or ethylene-glycol exhibit enhanced thermal conductivity. For example, using Al_2O_3 nanoparticles having mean diameter of 13 nm at 4.3% volume fraction increased the thermal conductivity of water under stationary conditions by 30% [3]. On the other hand, larger particles with an average diameter of 40 nm led an increase of less than 10% [3]. Ho et al. [4], Godson et al. [5], Duangthongsuk and Wongwises, [6], Lee et al. [7], Mahbubul et al. [8], Lelea and Laza [9], and Zakaria et al. [10] also found similar results indicating the enhancement of thermal conductivity of various nanofluids. However, surprisingly, a few researchers have found insignificant improvement of thermal conductivity as shown by Putnam et al. [11], Zhang et al. [12], Eapen et al. [13] and Timofeeva [14].

Different concepts have been proposed to explain the enhancement of heat transfer in nanofluid. Xuan and Li [15] and Xuan and Roetzel [16] have identified two causes of improved heat transfer by nanofluids: the increased thermal dispersion due to the chaotic movement of nanoparticles that accelerates energy exchanges in the fluid and the enhanced thermal conductivity of nanofluid. On the other hand, Keblinski et al. [17] have studied four possible mechanisms that contribute to the increase in nanofluid heat transfer: Brownian motion of the particles, molecular-level layering of the liquid/particles interface, ballistic heat transfer in the nanoparticles and nanoparticles clustering.

The heat transfer of nanofluids can also be numerically studied using a single-phase or two-phase approaches. The first assumes that the fluid phase and nanoparticles are in thermal equilibrium and move with the same velocity. While the second requires more computational effort but provides the possibility of understanding the behavior of both fluid phase and solid particles in the heat transfer mechanism.

Most of the previous studies on heat transfer of nanofluids have been considering single-phase model as their numerical tool. In 2004, Maiga et al. [18] have predicted the heat transfer enhancement of γ-Al_2O_3/water and γ-Al_2O_3/ethylene glycol nanofluids inside a uniformly heated tube using standard k–ε turbulence model. They discovered that the

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Nomenclature

a	empirical constant (= 1631)
b	empirical constant (= 25,000)
B	Kapitz resistance
c	empirical constant (= 3.0)
C_1, C_2, C_3	empirical constant (= 1.17, 2.18, 1.14 respectively)
C_c	Cunningham correction
C_p	heat capacity (J kg^{-1} K^{-1})
d	diameter (m)
d_{ij}	deformation tensor
D_T	thermophoretic coefficient
E	empirical constant (= −1/4)
$\mathbf{F}$	total force (N)
$\mathbf{F}_B$	Brownian force (N)
$\mathbf{F}_{col}$	collision force (N)
$\mathbf{F}_D$	drag force (N)
$\mathbf{F}_G$	gravitational force (N)
$\mathbf{F}_L$	Saffman's lift force (N)
$\mathbf{F}_P$	pressure gradient force (N)
$\mathbf{F}_T$	thermophoresis force (N)
$\mathbf{F}_{VM}$	virtual mass force (N)
f_D	drag function
$\mathbf{g}$	gravitational acceleration (m s^{-2})
G	particle–particle interaction modulus (N m^{-2})
H	self-crowding factor ($= 1.35 < h < 1.91$)
h_V	volumetric interphase heat transfer coefficient (W m^{-3} K^{-1})
I	momentum exchange coefficient
K	constant (= 2.594)
k	thermal conductivity (W m^{-1} K^{-1})
k_B	Boltzmann constant (J K^{-1})
Kn	Knudsen number
m	mass (kg)
n	empirical constant (= 2.8)
Nu	Nusselt number
P	pressure (N m^{-2})
Pe	Peclet number
Pr	Prandtl number
$\dot{Q}$	rate of total transferred energy (W)
Re	Reynolds number
S_d	source term of momentum transfer between the fluid and nanoparticle phases
S_e	source term of heat transfer between the fluid and nanoparticle phases
T	temperature (K)
t	time (s)
$\mathbf{u}$	velocity (m s^{-1})
w	empirical constant (= 1.5 for low Pe$_s$; = 0.091 for high Pe$_s$)

Greek letters

α	thermal diffusivity (m^2 s^{-1})
Γ	function of particle interaction due to temperature and concentration
ζ	zero-mean, unit-variance-independent Gaussian random numbers
η	empirical constant (= 280)
λ	mean free path (m^{-1})
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (kg m^{-1} s^{-1})
ξ	fitting parameter (= 2.5)
π	constant (= 3.142)
ρ	density (kg m^{-3})
σ	ratio of interfacial layer thickness to the radius of nanoparticle
τ	relaxation time (s)
ϕ	volume concentration
ϕ_{max}	maximum particle packing fraction
ψ	function of hydrodynamic interaction between nanoparticles
Ω	empirical constant (= 3 for spherical; = 6 for cylindrical)

Subscripts

dr	drift velocity
f	base fluid
nf	nanofluid
s	nanoparticle
t	tube

γ-Al_2O_3/ethylene glycol showed better heat transfer enhancement than γ-Al_2O_3/water. Two years later, Maiga et al. [19] revisited the case but with Al_2O_3/saturated water at various concentrations. Based on their study, they proposed a correlation to calculate the heat transfer coefficient of the tested nanofluid.

Namburu et al. [20] have considered a mixture of water and ethylene glycol as the based fluid with three different nanoparticles (CuO, Al_2O_3, and SiO_2) flowing through a circular tube under constant heat flux. They claimed that at constant Reynolds number, all types of nanofluids contribute to the enhancement of Nusselt number compared to base fluid. However, a later study by Javad and Amir [21] did not support the above findings. They found that in the turbulent region, the use of nanofluid would lead to large pressure drop and pumping power, and thus makes it not suitable for real engineering application.

Recently, some of the researchers consider two-phase numerical approach in their investigation on nanofluid. The motivation comes from several factors such as gravity, friction between fluid and solid particles, Brownian and thermophoretic forces, the phenomenon of Brownian diffusion, sedimentation, and dispersion which significantly affect the heat transfer of nanofluid.

Behzadmehr et al. [82] were possibly the first who considered the two-phase approach to study the turbulent forced convection of nanofluid in a tube with uniform heat flux. In their study, k–ε turbulence model was used to predict heat transfer enhancement of 1 wt% of Cu in water-based nanofluid. The obtained results showed 15% enhancements while no significant effect on the skin friction. They also confirmed that the two-phase model give more accurate results than single-phase model. One possible reason why the findings by Akbari et al. [22] did not support the findings by Behzadmehr et al. [82] was due to the limitation of computing resources.

Turbulent forced convection flow on TiO_2/water nanofluid in a heated circular tube using two-phase model has been investigated by Hejazian and Moraveji [23], Peng et al. [24], and Beheshti et al. [25]. All of them shared similar findings in which two-phase models have given closer results to the experimental data when compared to a single-phase model.

Based on the above brief review, many articles admitted the accuracy of two-phase approaches since the models regard the movement between the solid and fluid molecular and yield the predictions with more precise. However, the efficiency of the model is greatly dependent on the various conditions of nanofluid such as nanoparticles volume concentration, laminar or turbulent flow, nanoparticles diameter, type of base fluids, etc. Therefore, the goal of this work is to further review the different approaches used to predict various nanofluids using two-phase models with much more details. To the best of authors' knowledge, there is no comprehensive literature on the subject.