



Comparison of the pseudo-single-phase continuum model and the homogeneous single-phase model of nanofluids

H.M. Park

Department of Chemical and Biomolecular Engineering, Sogang University, Seoul, South Korea



ARTICLE INFO

Article history:

Received 21 February 2017

Received in revised form 6 December 2017

Accepted 6 December 2017

Keywords:

Nanofluids

Laminar forced convection

Homogeneous single-phase model

Pseudo-single-phase continuum model

ABSTRACT

We investigate forced convection of a nanofluid in the entrance region of a cylinder and in the fully-developed region of a coaxial cylinder employing the pseudo-single-phase continuum model and the homogeneous single-phase model. While the homogeneous single-phase model assumes a uniform nanoparticle distribution, the pseudo-single-phase continuum model takes care of nonuniform nanoparticle distribution. There has been controversy regarding the cause of heat transfer enhancement in nanofluids. Whether it is caused solely by the variation of thermophysical properties or the nanoparticle distribution also affect it. This controversy may be resolved employing these two models. It is found that nanoparticles drift from hot wall to cold central region in the entrance region, while they drift from cold inner surface to hot outer surface in the fully-developed coaxial cylinder due to the thermophoresis. The resulting nonuniform distributions of nanoparticles are found to add the heat transfer enhancement slightly. On the other hand, the frictional dissipation increases when the heat transfer rate increases. In a sense, the enhanced heat transfer rate is partly achieved at the expense of a higher energy consumption.

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1. Introduction

In the nanofluids, the suspended nanoparticles enhance the thermal conductivity and, as a result, heat transfer coefficient in the thermal convection. Several investigators [1,2] show that the thermal conductivity of suspensions can increase significantly with a small addition of metallic nanoparticles. There are numerous results available on the effects of nanoparticles in the heat transfer characteristics of nanofluids. Vajjha et al. [3] studied numerically the fluid dynamics and heat transfer performance of Al_2O_3 and CuO nanofluids in a flat tube. Xuan and Li [4] presented a procedure for preparing nanofluid and investigated heat transfer performance employing a model. Xuan and Roetzel [5] suggested a heat transfer correlation of nanofluids, which consider the effects of transport properties of nanofluids and thermal dispersion. Ding et al. [6] considered the heat transfer of aqueous suspensions of carbon nanotubes and specified the desirable properties of nanofluids. Li and Kleinstreuer [7] investigated a microchannel heat sink with nanofluids and showed that the nanofluids enhance thermal performance with an extra pressure drop. Most of the above investigators regard the nanofluids as homogeneous single-phase fluids with modified thermophysical properties

affected by the presence of nanoparticles. On the other hand, Kalteh et al. [8] adopted an Eulerian two-phase model to simulate the nanofluid flow inside a microchannel, and compared their results with those from the homogeneous single-phase model. Santra et al. [9] regard nanofluids as non-Newtonian power law fluid and conducted numerical simulation through two parallel plates. Wen and Ding [10] investigated the effect of particle migration on heat transfer in nanofluid flows through microchannels. In addition to flow through channels, nanofluid convection in enclosures were studied by Oztop and Abu-Nada [11] and Celli [12]. Various published articles on enhancement of the forced convection heat transfer with nanofluids are summarized in the review articles [13–15]. These studies concluded that the presence of nanoparticles enhances heat transfer rate in the nanofluids as compared to their respective base fluids. However, the cause of heat transfer enhancement is still controversial. Some authors [3,4,6,7,11] suggest that the changes in the thermophysical properties of nanofluids enhance heat transfer rate, while others [5,8,10,12] conjecture that the enhancement is caused by the dynamic effects of nanoparticles in addition to variations in the thermophysical properties. A rational approach to resolve this controversy is to construct a rigorous model for nanofluids incorporating various dynamic phenomena as well as variations of the thermophysical properties, and compare the results of numerical simulation using the rigorous

E-mail address: hmpark@sogang.ac.kr

Nomenclature

C_p^l	liquid phase heat capacity	α_T	thermal diffusion coefficient
C_p^p	particle phase heat capacity	β	thermal conductivity ratio defined in Eq. (5)
D^p	particle Brownian diffusivity	μ	mixture viscosity
\mathbf{g}	gravity vector	μ^l	liquid phase viscosity
\mathbf{j}^p	diffusion flux of particle defined in Eq. (18)	ν	mixture kinematic viscosity
k	mixture thermal conductivity	$\boldsymbol{\pi}$	mixture stress tensor
k^l	liquid phase thermal conductivity	$\boldsymbol{\pi}^{diff}$	diffusive stress tensor defined in Eq. (19)
k^p	particle thermal conductivity	ρ	mixture density
L	length of the domain	ρ^l	bulk density of liquid phase
P	mixture pressure	ρ^p	bulk density of particle phase
ΔP	pressure drop	$\hat{\rho}_l$	intrinsic density of liquid
Q	volumetric flow rate	$\hat{\rho}_p$	intrinsic density of particle
T	mixture temperature	ϕ	volume fraction of particle phase
T^l	liquid phase temperature	ω^p	mass fraction of particle phase
T^p	particle phase temperature		
\mathbf{v}	mixture velocity vector		
v^r, v^z	components of mixture velocity vector	Superscript	
\mathbf{v}^l	liquid phase velocity vector	l	liquid phase
\mathbf{v}^p	particle phase velocity vector	p	particle phase
Greek symbols		Subscript	
α	thermal diffusivity	in	inlet condition
		out	outlet condition

model together with those from the homogeneous model which considers only the variation of homogeneous thermophysical properties.

In the homogeneous single-phase model, nanoparticles are assumed to be distributed uniformly, thus, this model adopts the momentum and energy balance equations of the base fluid as those for nanofluid, only with the modification of thermophysical properties caused by nanoparticles [15]. However, the effects of particle mass loading on the dynamics of nanofluids are significant, especially in the nonisothermal systems where the thermophoretic drift of particles is not negligible [16]. A straightforward method to incorporate the particle phase dynamics into the nanofluid dynamics is to regard the nanofluids as two-phase flows and solve the set of mass, momentum and energy conservation equations for each phase simultaneously [8]. Although the two-phase model is rigorous, it is very difficult to solve the coupled sets of equations numerically since they are strongly stiff equations especially for tiny particles such as nanoparticles. Namely, the time constants or the Stokes numbers [17] for momentum and energy exchange between phases are so small that one must employ a very small time-step size to integrate the sets. The Stokes numbers are proportional to particle diameter. This dilemma is resolved in Park [18,19], where the extremely smallness of the Stokes numbers is exploited to derive the pseudo-single-phase continuum model of nanofluids from a two-phase model. The pseudo-single-phase continuum model [18,19] takes care of the nanoparticle dynamics as faithfully as the two-phase model and considers the variations of thermophysical properties accurately as the nanoparticle mass fraction changes. Moreover, the pseudo-single-phase continuum model does not have numerical difficulties since the stiffness of the two-phase model is removed by keeping only the outer solution of the singular perturbation problem [18].

In the present investigation both the homogeneous single-phase model and the pseudo-single-phase continuum model are implemented for a steady-state forced convection in the entrance region of a cylinder and for a fully-developed forced convection in a coaxial cylinder as depicted in Fig. 1a and b. By comparing the results from those two models, it shall be investigated how

the movement and distribution of nanoparticles affect the heat transfer characteristics in the forced convection of nanofluids.

2. The homogeneous single-phase model

In the homogeneous single-phase model, we neglect the nanoparticle dynamics and assume that the nanoparticles are distributed uniformly within the nanofluid. The uniformly distributed nanoparticles change the density, thermal conductivity, heat capacity and viscosity of nanofluid. If the base fluid is an incompressible fluid such as water, the nanofluid may be considered as an incompressible fluid since the particle mass fraction ω^p is spatially constant. The governing equations for the homogeneous single-phase model may be summarized as follows.

$$\nabla \cdot \mathbf{v} = 0 \quad (1)$$

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla P + \mu \nabla^2 \mathbf{v} + \rho \mathbf{g} \quad (2)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) = k \nabla^2 T \quad (3)$$

In the above equations, the thermal conductivity k and the viscosity μ of nanofluid are found using the following mixing rule, where the superscripts l and p denote the properties of base liquid and those of nanoparticles, respectively [15].

$$k = k^l \frac{1 + 2\beta\phi}{1 - \beta\phi};$$

$$\mu = (123\phi^2 + 7.3\phi + 1)\mu^l \quad (4)$$

In Eq. (4), ϕ is the volume fraction of nanoparticles and β is defined as

$$\beta \equiv \frac{k^p - k^l}{k^p + 2k^l} \quad (5)$$

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