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Effects of nanoparticle shapes on laminar forced convective heat transfer in curved ducts using two-phase model

Fang Liu [a,c,*], Yang Cai [a], Liqiu Wang [b], Jun Zhao [c]

[a] College of Energy and Mechanical Engineering, Shanghai University of Electric Power, 2103 Pingliang Road, Yangpu District, Shanghai 200090, PR China
[b] Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong
[c] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, Tianjin University, 300350 Tianjin, PR China

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ABSTRACT

In this study, effects of particle shape on Al_2O_3-water nanofluids laminar forced convection in developing and fully developed regions of a curved square duct were investigated numerically using Eulerian-Lagrangian two-phase approach. In order to improve the accuracy of the two-phase model for laminar convective heat transfer of nanofluids containing non-spherical nanoparticles, two new nanoparticle shape descriptors, flatness and elongation, were introduced. Compared with base fluid (water), nanofluids containing platelet shaped nanoparticles has the highest heat transfer enhancement, which is followed by nanofluids containing nanoparticles with cylinder, blade, sphere and brick shapes, respectively. Non-spherical nanoparticles with a suitable shape, small size and relatively high volume fraction are beneficial for enhancement of heat transfer in laminar forced convection. In developing region, a pair of Dean vortices formed and grew along the duct axis, which affected nanoparticle concentration distribution and heat and mass transfer. In fully developed region, convective heat transfer efficiencies of nanofluids are larger than 1 and vary with nanoparticle shape, size, volume fraction and Reynolds number. Enhancement of the convective heat transfer in nanofluids was attributed to the enhancement of effective thermal conductivity and effective viscosity, change of flow structure and reduction of thermal boundary layer thickness due to the presence of nanoparticles and their shapes. New correlations of Nusselt number and fraction factor with nanoparticle shape (sphericity, flatness and elongation), size and volume fraction were developed in order to predict convective heat transfer of nanofluids containing spherical and non-spherical nanoparticles.

1. Introduction

Nanofluids have been shown to have advantages and potentials in improving heat transfer rates when they are applied as working fluids in thermal systems [1,2]. Compared to the pure base fluid, heat transfer enhancement with nanofluid depends on many factors, i.e., material of nanoparticles, size and shape, volume fraction, properties of the base fluid, and the presence of other substances, surfactants, electrolyte strength, and pH [3,4]. Many experimental, theoretical or numerical studies on the nanofluid convective heat transfer in the tubes have been reported in literature as mentioned below.

Some experimental investigations have been conducted on effects of nanoparticle shape, size and volume fraction on convective heat transfer characteristics of nanofluids [3–9]. Hwang et al. [5] found that the convective heat transfer coefficient of water-based Al_2O_3 nanofluids is increased from 7.41% for brick shape (40 nm × 40 nm × 20 nm) to 1.17% for platelet shape (15 nm × 15 nm × 5 nm) compared with that of pure water flowing through a uniformly heated circular tube under a fully developed laminar flow region. Yu et al. [6] conducted experimental studies and found that aspect ratio, dispersion state and aggregation of nanoparticles as well as shear field, have significant impact on the effective properties of the nanofluids, especially of the nanofluids containing non-spherical particles. Ferrouillat et al. [7] found that Nusselt number of water-based ZnO nanofluids is increased by 8% for polygonal nanoparticles and by 3% for rod-like nanoparticles compared with pure water, while Nusselt numbers of water-based SiO_2 nanofluids are both increased by 4% for spherical and banana-like nanoparticles. Timofeeva et al. [8] evaluated experimentally the particle size effect on convective heat transfer in the developing laminar region, and found that the

* Corresponding author at: College of Energy and Mechanical Engineering, Shanghai University of Electric Power, 2103 Pingliang Road, Yangpu District, Shanghai 200090, PR China.

E-mail addresses: fangliu@shiep.edu.cn, fangliu_shiep@163.com (F. Liu).

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Nomenclature

A_p	surface area (nm^2)	Re_p	Reynolds number of particle (–)
C_D	drag coefficient (–)	S	shortest length of the particle (m)
c_p	specific heat at constant pressure (J/kg/K)	T	temperature (K)
D	hydraulic diameter of curved duct (mm)	V	velocity (m/s)
d_p	equivalent spherical diameter (nm)	θ	axis angle (–)
d_f	Equivalent molecular diameter of base fluid (nm)	ρ′	particle-to-fluid density ratio, (–)
δV	cell volume (m^3)	μ	dynamic viscosity (Pa·s)
E	elongation (I/L) (–)	φ	nanoparticle volume fraction (%)
F	forces per unit particle mass (N/kg)	$\varnothing$	particle sphericity (–)
f	friction factor, flatness (S/I) (–)	η	convective heat transfer efficiency (–)
H	heat transfer coefficient W/(m^2·K)	α_2	empirical expression defined (–)
I	intermediate length of the particle (m)		
k_N	Newton's drag correction (–)	*Subscripts*	
k_S	Stokes' drag correction (–)	f	base fluid
k	thermal conductivity (W/m/K)	c	continuous phase
L	longest length of the particle (m)	*i*	inlet
m_p	particle mass (kg)	m	mean
Nu	Nusselt number (–)	nf	nanofluids
ΔP	pressure drop (Pa)	np	number of discrete phase particles in a cell volume
Pr	Prandtl number (–)	p	particle
Q	heat flux density (W/m^2)		
Re	Reynolds number (–)		

nanofluid with 45 nm alumina particles showed higher heat transfer coefficients than that with 150 nm alumina particles. Meriläinen et al. [9] carried out extensive experimental studies of turbulent convective heat transfer of several water-based Al_2O_3, SiO_2, and MgO nanofluids with a nanoparticle volume fraction up to 4%, and found that increasing the nanoparticle volume fraction beyond 2% enhances the heat transfer coefficient but at the same time lowers heat transfer efficiency due to pressure losses, which result from the increased fluid density and viscosity [9]. The experimental investigations on the convective heat transfer performance of various nanofluids indicate that the key mechanisms may include dispersion of the suspended nanoparticles, particle migration resulting in a non-uniform distribution of thermal conductivity and viscosity in the flow field, reduction of thermal boundary layer thickness, particle shape effect and aggregation, flattened velocity profile due to particle migration induced by Brownian diffusion, thermophoresis and so on [10]. It is necessary to further investigate the mechanisms for enhancement of heat transfer by addition of nanoparticles with different shapes.

There are some theoretical analysis or single-phase modeling studies for the heat transfer and friction factor of the nanofluids containing particles with various shapes [11,12]. Elias et al. [11] studied theoretically the effect of different particle shapes (e.g. cylindrical, bricks, blades, and platelets) on the performance of a shell and tube heat exchanger. They found that cylindrical shape nanoparticles showed best performance in respect to overall heat transfer coefficient and heat transfer rate. Conventional single-phase modeling has been the most common approach in majority of theoretical studies of convective heat transfer using nanofluids. Vanaki et al. [12] investigated effect of nanoparticle shapes on the heat transfer enhancement using a *single-phase* model without considering nanoparticle size; they found that nanofluids containing nanoparticles with platelet shape has the highest heat transfer enhancement, which is followed by nanofluids containing nanoparticle with cylindrical, brick, blade, and spherical shapes, respectively. The numerical predictions resulted from the single-phase approach may lead to some deviations as compared with the experimental data due to the neglect of slip mechanisms between nanoparticle and base fluid [13]. The two-phase model can provide the better views in the nanofluid flow field, since the solid and liquid phases are considered separately [1,13]. Bahremand et al. [14] investigated the turbulent convection flow of water–silver nanofluid with *spherical* nanoparticles in helically coiled tubes numerically using Lagrangian–Eulerian two-phase approach, and found that two-phase approach predicted much more accurate results than the homogeneous model [14]. However, there is few study using two-phase approach for the effects of particle shape on nanofluid convective heat transfer reported in the literature.

The correlations for Nusselt number and friction factor of nanofluid in a tube have been developed based on experimental and theoretical studies, however, most of the correlations are developed for spherical nanoparticle dispersions [1,6,15]. Lin et al. [16] investigated friction factor and heat transfer of nanofluids containing cylindrical nanoparticles for a laminar flow in a horizontal straight pipe through numerical simulations; they derived the expression of friction factor as a function of particle volume concentration, particle aspect ratio, and Reynolds number, and expression of Nusselt number as a function of particle volume concentration, particle aspect ratio, Reynolds number, Prandtl number, and axial length, based on the numerical data [16]. They found that it is more effective to use nanofluids containing cylindrical or rod-like nanoparticles with larger aspect ratio, at higher Reynolds number and with a suitable particle volume concentration [16,17]. More investigation is needed to develop the correlations of heat transfer and friction factor for nanofluids containing other non-spherical nanoparticles, e.g. platelet, blade and brick.

Sphericity, the ratio of the surface area of the sphere and the surface area of the real particle with equal volumes, is the most used shape descriptor in the literature [18]. In many applications, the drag force is the most important force acting on a particle, which is exerted in the opposite direction of particle motion. A large number of empirical correlations for predicting the drag coefficient of spherical and non-spherical particles are introduced, and most formulations are based on sphericity [18,19]. Bagheri et al. [18] presented a new general model for the prediction of the drag