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Discrete modelling of nanoparticles in mixed convection flows

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ABSTRACT

The effects of nanoparticles in distilled water are investigated in mixed convective flows in a tube with different inclination angles. Heat transfer and hydrodynamic features of the flow itself can be roughly estimated by any single-phase or homogenous models in the literature. However, the precise values, and especially the particle tracking, would be impossible with such models. Therefore, discrete modelling of the particles is employed in this study to understand the nature of migration and concentration of nanoparticles in complex mixed convection flow. An attempt is made to clarify the significant phenomena in particle-fluid and particle-wall interactions. A proper model of heat transfer between nanoparticles and fluid is considered and implemented in ANSYS-Fluent 17.0 through user-defined functions (UDFs). The results are validated by comparing them to similar experimental measurements for nanofluids in the literature, and good agreement is found. The results of the tracking and concentration of nanoparticles are naturally found in complete contractions compared to other models such as two-phase multiphase models. The deposition of particles on the walls due to low flow velocity is predicted in this paper.

1. Introduction

The advantages and disadvantages of using fine particles in different types of flows have interested researchers in recent years. Enhancement and deterioration in heat transfer were observed in nanofluids, depending on the type of nanoparticles, flows and their application in different industries [1–9]. Mixed convection involves many phenomena due to strong secondary flow that highly influences the nanoparticles' deposition, settlement and migration. Some experimental works can be found for mixed convective nanofluid in the literature [6,10–16]. Since this study aims to investigate and develop the numerical modelling of nanoparticles in a flow, a short literature review on these aspects is presented in this section. A large proportion of nanofluid modelling is concerned with the mixture model, with the assumption of small or even negligible interactions between solid and liquid phases (by default). This approach is simple, and the only important parameters are contributed by the mixture's thermophysical and transport properties, which are mainly obtained empirically. Bianco, Manca and Nardini [17], Garoosi, Rohani and Rashidi [18] and some others [19–21] are examples of this approach in the literature. Since this method is entirely based on properties, the results of heat transfer and pressure drop can be in agreement with measurements. However, the results of particle distribution and aggregation can remain in doubt. This method provides almost uniform particle concentration everywhere inside the flow, which somehow contradicts the visual observation in a few case studies, especially natural convection [22]. In recent years, the effects of mass diffusion due to concentration and temperature gradient were included in mixture equations. This method considers the slip mechanisms between solid and liquid phase as separate terms. Choi, Hwang and Jang [20] Kuznetsov and Nield [21] and others [22–24] reported the improvement in numerical results about heat transfer, pressure drops and particle migration. Nevertheless, the real physics of nanofluids are still far from the simulation method. For instance, the process of aggregation and deposition on the walls play essential roles in heat transfer and pressure drop, which cannot be seen in this approach. The deposition on the walls can be the major matter in nanoparticles. The reason is that both the nanoparticles and the walls are normally metallic in a polar medium such as water, which means that the Van der Waals force can be one of the strongest attraction forces between the particles and the walls that are in contact with each other.

The discrete modelling of nanoparticles in a continuum medium can be one of the approaches that considers some parts of real physics. Some of the important phenomena that occur in the nanoparticle liquid medium include interactions between the particles and the flow, interactions between the nanoparticles, the possibility of collision or deposition with or on the walls, cluster formation, energy and momentum transfer between the solid and the flow, and breaking clusters. It is noted that each of the mentioned interactions includes a large number of nanoscale phenomena. The discrete model has only been used in recent years for nanofluids by researchers such as Behroyan, Vanaki and Ganesan [23] in laminar tube flow with <1.6% vol., Sundar, Singh, Bidkin and Sousa [24] in a microchannel with maximum 1% vol., Mamourian, Shirvan, Mirzakhanlari and Rahimi [25] in a channel with a vortex

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Nomenclature

H	Hamaker constant (J)
A_p	Particle projected area (m^2)
Axial	Flow direction in heated section (m)
C_c	Cunningham correction factor
C_D	Drag coefficient
C_{ML}	Rotational coefficient
C_ω	Rotational drag coefficient
c_p	Specific heat (J/kg.K)
d_p	Particle diameter (m)
d_0	equilibrium distance (m)
D_T	Thermophoresis coefficient
F_B	Brownian force (N)
F_{thermo}	thermophoresis force (N)
F_{Magnus}	Magnus force (N)
F_{lift}	lift force (N)
F_{drag}	drag force (N)
$F_{adhesion}$	adhesion force (N)
F_{VDW}	Van der Waals force (N)
h, HTC	Heat transfer coefficient ($W/m^2.K$)
Gr	Grashof number
G_w	Gaussian weight function
I_p	Moment of inertia (kg/m^2)
ID	Tube inner diameter (m)
k	Thermal conductivity (W/m.K)
Kn	Knudsen number
K_B	Boltzmann constant ($m^2.kg/°K.s^2$)
m_p	Particle mass (kg)
$N_{particle}$	Number of particles
Q_s	Heat exchange (W)
r	Radial coordinate (m)
Re_p	Particle Reynolds number
Re_{ω_p}	Rotational Reynolds number
Ri	Richardson number
T	Temperature (K)
Δt_p	Particle time step (s)
u_p	Particle velocity (m/s)
V,u	Velocity (m/s)

Greek letters

α	Inclination angle (°)
μ_c	Fluid viscosity (Pa.s)
λ	Mean free path (m)
$\dot{\gamma}$	Shear rate (s^{-1})
$\boldsymbol{\omega}_p$	Particle angular velocity (1/s)
$\boldsymbol{\Omega}$	Relative particle-liquid angular velocity (1/s)
ρ_c	Fluid density (kg/m^3)
τ	Particle relaxation time (s)
$\theta_{particle}$	particle variable
$\vec{\zeta}$	Random function

Subscripts

c	Fluid
p	Particle

generator and alumina nanofluids with a volume fraction <0.04% vol., Bianco, Chiacchio, Manca and Nardini [26] in a pipe with 1% and 4% vol., and Shirvan, Mamourian, Mirzakhanlari and Ellahi [27] in a two-dimensional channel and volume fraction <0.05. In all the simulations, the researchers only considered the interactions between the particles and the fluid as the source terms in fluid equations. The interactions consisted of drag, gravity, virtual mass, pressure gradient force, lift, Brownian motion and thermophoresis. Also, most of the works only covered forced convective and laminar flows and lower ranges of particle concentrations. Kumar and Puranik [28] state that the discrete model can predict heat transfer features accurately for volume fractions <0.5% for nanoparticles of 13 nm in size. They concluded that only gravity and drag could be contributing factors in this model when compared to other interactions.

The literature review shows that the discrete modelling approach is still at an early stage of nanofluid simulation and that further development for this particular field of study is necessary. As a result of the complicated nature of flow in mixed convection, the tracking and modelling of nanoparticles will bring up issues other than forced flows. This may be the result of the increase and decrease in heat transfer that were observed in experimental measurements [10,12,13,29]. The other important aspect of nanofluid mixed convection is related to the wall collisions and deposition, which can affect the whole flow and particles' migration [30–32]. Therefore, nanoparticle migration and its effects on a mixed convective tube flow are investigated at different inclination angles. The significant forces are discussed and analysed at the contact point with the walls, and the possibility of deposition on the walls is studied.

2. Geometry description and mathematical equations

The schematic of the tube under study is shown in Fig. 1. The idea of this geometry is borrowed from the experimental work of Mansour, Galanis and Nguyen [6]. To authors, it is essential that the results of discrete modelling are validated with a real case of nanofluid mixed convection and not just mixed convective flow with pure water. In other words, further predictions can only be reliable regarding real experiment comparison. The tube has an inside diameter of 6.35 mm, an adiabatic section of 318 mm and a heat flux section of 1270 mm. The specific heat, density, thermal conductivity and size of the alumina nanoparticles that were used in this study are 773 J/kg·K, 3880 kg/m^3, 36 W/m·K and 36 nm, respectively. Distilled water is the base fluid which is mixed with alumina nanoparticles up to 4% vol. concentration. It can safely be assumed that the flow is fully developed after passing the adiabatic section. It means that the parabolic velocity section could be used for the first section of the heated part, and that the insulated part of the simulation is neglected, as follows:

$$V = 2V_{ave}\left(1-{}^{4r^2}\!/_{ID^2}\right), \tag{1}$$

where V_{ave}, r and ID are the average fluid velocity, radial coordinate of the tube and tube inside diameter, respectively. Since there is no information about nanoparticle distribution after passing the insulated part, it was added to the simulation. Flow and particles are uniformly injected at the inlet.

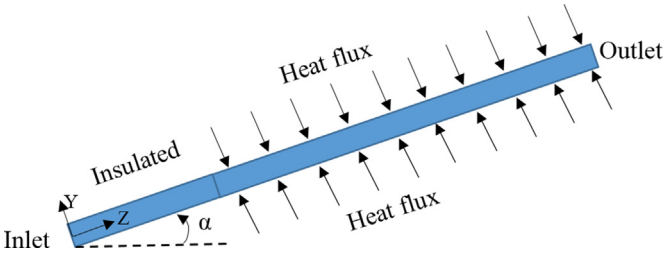

Fig. 1. Schematic of the inclined tube under investigation in this study.