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Transition of nanofluids flow in an inclined heated pipe

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ABSTRACT

A numerical investigation is carried out to investigate the transitional flow behaviour of nanofluids flow in an inclined pipe using both single and multi-phase models. Two different nanofluids are considered, and these are Al_2O_3–water and TiO_2–water nanofluids. Moreover, SST $\kappa-\omega$ transitional model is implemented to study the nanofluids flow in inclined pipe. Gravitational force is also adopted by considering Boussinesq approximation in the momentum equation. Results reveal that Buoyancy force play a significant role on the degeneration of heat transfer rate with the increase of Reynolds number for different inclination angles. It indicates that mixed convection has opposite effect on the inclined pipe than the forced convection on the horizontal pipe. Moreover, some deformation of the flow and temperature fields near the upstream region is observed with the increase of inclination angle due to Buoyancy force.

1. Introduction

A numerical study has been carried out to understand the heat transfer behaviour of Al_2O_3–H_2O and TiO_2–H_2O nanofluids flow in an inclined pipe using both the single and multi-phase models under transition flow condition in this paper. The SST $\kappa-\omega$ transitional model with different inclination angles from 0° to 75° has been used for simulating the transition flow regime. Previously, it was found that combination of the smaller size of nanoparticles (e.g. $d_p = 10\ nm$) and the higher nanoparticles concentration ($\chi = 6\%$) had produced the highest thermal performance when the Brownian motion of nanoparticles had been taken into account. Details of these findings have been discussed in Saha and Paul [1–3] respectively.

Literature review suggests that a very few experimental and numerical investigations have been carried out to date on the laminar and turbulent nanofluid flow in an inclined or a vertical pipe [4–6]. And, we are the first to have investigated the nanofluids flow inside an inclined pipe in transition regime considering a smaller size but higher concentrations (mentioned above) of nanoparticles with the Brownian motion.

2. Mathematical modelling

In this research, numerical investigations have been carried out using single and multi-phase models under transition flow condition. Here, three-dimensional model of an inclined pipe with a length L of 1.0 $m$and a circular section with diameter D_h of 0.019 m is shown in Fig. 1.

2.1. Single phase model

The dimensional steady-state governing equations of fluid flow and heat transfer for the single phase model is presented under the following assumptions:

i. Fluid flow is incompressible, Newtonian and transitional,
ii. Fluid phase and nanoparticle phase are in thermal equilibrium with no-slip between them,
iii. Nanoparticles are spherical and uniform in size and shape,
iv. Radiation effects and viscous dissipation are negligible.

$$\nabla.\left(\rho\vec{v}\right) = 0 \tag{1}$$

$$\nabla.\left(\rho\vec{v}\,\vec{v}\right) = -\nabla p + \nabla.\left[\mu\left(\nabla\vec{v} + \nabla\vec{v}^{T}\right) - \frac{2}{3}\nabla.\vec{v}\,I\right] + \rho\vec{g} \tag{2}$$

$$\nabla.\left(\rho\vec{v}C_pT_{nf}\right) = \nabla.\left(\lambda\nabla T_{nf}\right) \tag{3}$$

where $\vec{v}$, ρ, μ, λ, $\vec{g}$ are the mass-average velocity, density, viscosity, thermal conductivity and gravitational force respectively.

2.2. Multi-phase mixture model

The dimensional steady-state governing equations of continuity, momentum, energy and concentration for the multi-phase model are presented considering the assumptions (i) to (iv) given in the single phase model. Moreover, it is assumed that there is a strong coupling

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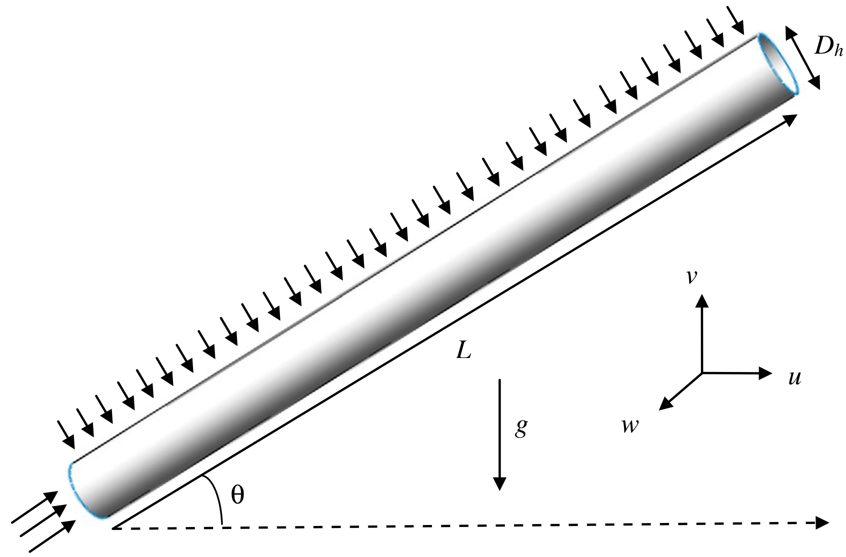

Fig. 1. Schematic diagram of the geometry under consideration.

between the fluid and nanoparticles phases and these phases move at the same local velocity. Interaction between the fluid and nanoparticles is also taken into account. It is also assumed that fluid and nanoparticles phases are in local thermal equilibrium in multi-phase mixture model. It means, mean temperature of the fluid phase and the nanoparticles phase are same. Moreover, the multi-phase mixture model allows the phases to move at different or same velocities using the concept of drift velocity. When the phases can also be assumed to move at same velocities then the mixture model is called the homogeneous multi-phase model. Moreover, the momentum equation for the mixture can be obtained by summing the individual momentum equations for all the phases.

Under the above assumptions, the governing equations for the multi-phase mixture model can be expressed as (Fluent [7]):

$$\nabla.\left(\rho\vec{v}\right)=0 \tag{4}$$

$$\nabla.\left(\rho\vec{v}\vec{v}\right)=-\nabla p+\nabla.\left[\mu\left(\nabla\vec{v}+\nabla\vec{v}^{T}\right)\right]+\rho\vec{g}+\nabla.\left(\sum_{s=1}^{n}\chi_s\rho_s\vec{v}_{dr,s}\vec{v}_{dr,s}\right) \tag{5}$$

$$\nabla.\left[\sum_{s=1}^{n}\chi_s\vec{v}_s(\rho_s H_s+p)\right]=\nabla.\left(\sum_{s=1}^{n}\chi_s(\lambda+\lambda_t)\nabla T_{nf}\right) \tag{6}$$

$$\nabla.\left(\chi_p\rho_p\vec{v}\right)=-\nabla.\left(\chi_p\rho_p\vec{v}_{dr,p}\right) \tag{7}$$

Also, $\vec{v}, \rho, \mu, \lambda, n, \lambda_t, \chi_s$ are the mass-average velocity, mixture density, viscosity of the mixture, mixture thermal conductivity coefficient, number of phases, turbulent thermal conductivity and nanoparticles concentration respectively. These are also defined as

$$\vec{v}=\sum_{s=1}^{n}\frac{\chi_s\rho_s\vec{v}_s}{\rho} \qquad \rho=\sum_{s=1}^{n}\chi_s\rho_s$$

$$\mu=\sum_{s=1}^{n}\chi_s\mu_s \qquad \lambda=\sum_{s=1}^{n}\chi_s\lambda_s$$

Here, H_s is the sensible enthalpy for phase s. The drift velocity ($\vec{v}_{dr,s}$) for the secondary phase s is defined as

$$\vec{v}_{dr,s}=\vec{v}_s-\vec{v} \tag{8}$$

The relative or slip velocity is defined as the velocity of the secondary phase (s) relative to the velocity of the primary phase (f):

$$\vec{v}_{sf}=\vec{v}_s-\vec{v}_f \tag{9}$$

Then the drift velocity related to the relative velocity becomes

$$\vec{v}_{dr,s}=\vec{v}_{sf}-\sum_{k=1}^{n}\vec{v}_{fk}\frac{\chi_k\rho_k}{\rho} \tag{10}$$

Manninen et al. [8] and Naumann and Schiller [9] proposed the following respective equations for the calculation of the relative velocity, $\vec{v}_{pf}$, and the drag function, f_{drag}.

$$\vec{v}_{pf}=\frac{\rho_p d_p^2}{18\mu_f f_{drag}}\frac{\rho_p-\rho}{\rho_p}\vec{a} \tag{11}$$

$$f_{drag}=\begin{cases}1+0.15Re_p^{0.687} & Re_p\leq 1000\\ 0.0183Re_p & Re_p>1000\end{cases} \tag{12}$$

Here, the acceleration $\vec{a}$ is determined by

$$\vec{a}=-\left(\vec{v}\cdot\nabla\right)\vec{v} \tag{13}$$

And, d_p is the diameter of the nanoparticles of secondary phase s and $\vec{a}$ is the secondary phase particle's acceleration, T_{nf} is the temperature, p is the pressure.

Also, the buoyancy term in the momentum Eqs. (2) and (5) is approximated (Fluent [7]) by

$$(\rho-\rho_0)g\approx-\rho_0\beta(T-T_0)g \tag{14}$$

which is considered when Boussinesq approximation is taken into account for mixed convection case. Here β is the thermal expansion coefficient of the fluid, ρ_0 and T_0 are the reference density and temperature respectively.