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Nanofluid convective heat transfer using semi analytical and numerical approaches: A review

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ABSTRACT

The use of additives in the base fluid like water or ethylene glycol is one of the techniques applied to augment the heat transfer. Newly an innovative nanometer sized particles have been dispersed in the base fluid in heat transfer fluids. The fluids containing the solid nanometer size particle dispersion are called 'nanofluids'. Two main categories were discussed in detail as the single-phase modeling which the combination of nanoparticle and base fluid is considered as a single-phase mixture with steady properties and the two-phase modeling in which the nanoparticle properties and behaviors are considered separately from the base fluid properties and behaviors. Both single phase and two phase models have been presented in this paper. This paper intends to provide a brief review of researches on nanofluid flow and heat transfer via semi analytical and numerical methods. It was also found that Nusselt number is an increasing function of nanoparticle volume fraction, Rayleigh number and Reynolds number, while it is a decreasing function of Hartmann number.

1. Introduction

Nanofluids are produced by dispersing the nanometer-scale solid particles into base liquids with low thermal conductivity such as water, ethylene glycol (EG), oils, etc. Control of heat transfer in many energy systems is crucial due to the increase in energy prices. In recent years, nanofluids technology is proposed and studied by some researchers experimentally or numerically to control heat transfer in a process. The nanofluid can be applied to engineering problems, such as heat exchangers, cooling of electronic equipment and chemical processes. There are two ways for simulation of nanofluid: single phase and two phase. In first method, researchers assumed that nanofluids treated as the common pure fluid and conventional equations of mass, momentum and energy are used and the only effect of nanofluid is its thermal conductivity and viscosity which are obtained from the theoretical models or experimental data. These researchers assumed that nanoparticles are in thermal equilibrium and there are not any slip velocities between the nanoparticles and fluid molecules, thus they have a uniform mixture of nanoparticles. In second method, researchers assumed that there are slip velocities between nanoparticles and fluid molecules. So the volume fraction of nanofluids may not be uniform anymore and there would be a variable concentration of nanoparticles in a mixture. There are several numerical and semi analytical methods which have been used by several authors in order to simulate nanofluid flow and heat transfer.

1.1. Definition of nanofluid

Low thermal conductivity of conventional heat transfer fluids such as water, oil, and ethylene glycol mixture is a serious limitation in improving the performance and compactness of many engineering equipment such as heat exchangers and electronic devices. To overcome this disadvantage, there is strong motivation to develop advanced heat transfer fluids with substantially higher conductivity. An innovative way of improving the thermal conductivities of fluids is to suspend small solid particles in the fluid. Various types of powders such as metallic, non-metallic and polymeric particles can be added into fluids to form slurries. The thermal conductivities of fluids with suspended particles are expected to be higher than that of common fluids. Nanofluids are a new kind of heat transfer fluid containing a small quantity of nanosized particles (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 changes their thermal conductivity remarkably. Compared to the existing techniques for enhancing heat transfer, the nanofluids show a superior potential for increasing heat transfer rates in a variety of cases [1].

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1.2. Model description

In the literature, convective heat transfer with nanofluids can be modeled using mainly the two-phase or single approach. In the two-phase approach, the velocity between the fluid and particles might not be zero [2] due to several factors such as gravity, friction between the fluid and solid particles, Brownian forces, Brownian diffusion, sedimentation and dispersion. In the second approach, the nanoparticles can be easily fluidized and therefore, one may assume that the motion slip between the phases, if any would be considered negligible [3]. The latter approach is simpler and more computationally efficient.

1.3. Conservation equations

1.3.1. Single phase model

Although nanofluids are solid–liquid mixtures, the approach conventionally used in most studies of natural convection handles the nanofluid as a single-phase (homogenous) fluid. In fact, due to the extreme size and low concentration of the suspended nanoparticles, the particles are assumed to move with same velocity as the fluid. Also, by considering the local thermal equilibrium, the solid particle–liquid mixture may then be approximately considered to behave as a conventional single-phase fluid with properties that are to be evaluated as functions of those of the constituents. The governing equations for a homogenous analysis of natural convection are continuity, momentum, and energy equations with their density, specific heat, thermal conductivity, and viscosity modified for nanofluid application. The specific governing equations for various studied enclosures are not shown here and they can be found in different references [4]. It should be mentioned that sometime this assumption is not correct. For example, Ding and Wen [5] this assumption may not always remain true for a nanofluid. They investigated the particle migration in a nanofluid for a pipe flow and stated that at Peclet numbers exceeding 10 the particle distribution is significantly non-uniform. Nevertheless, many studies have performed the numerical simulation using single-phase assumption and reported acceptable results for the heat transfer and hydrodynamic properties of the flow.

1.3.2. Two-phase model

Several authors have tried to establish convective transport models for nanofluids [6]. Nanofluid is a two-phase mixture in which the solid phase consists of nano-sized particles. In view of the nanoscale size of the particles, it may be questionable whether the theory of conventional two-phase flow can be applied in describing the flow characteristics of nanofluid. On the other hand, several factors such as gravity, friction between the fluid and solid particles and Brownian forces, the phenomena of Brownian diffusion, sedimentation, and dispersion may affect a nanofluid flow. Consequently, the slip velocity between the fluid and particles cannot be neglected for simulating nanofluid flows. Since the two phase approach considers the movement between the solid and fluid molecule, it may have better prediction in nanofluid study. To fully describe and predict the flow and behavior of complex flows, different multiphase theories have been proposed and used. The large number of published articles concerning multiphase flows typically employed the Mixture Theory to predict the behavior of nanofluids [7]. A comprehensive survey of convective transport in nanofluids was made by Buongiorno [8], using a model in which Brownian motion and thermophoresis are accounted for. Buongiorno developed a two-component four-equation non-homogeneous equilibrium model for mass, momentum, and heat transfer in nanofluids. The nanofluid is treated as a two-component mixture (base fluid–nanoparticles) with the following assumptions: No chemical reactions; Negligible external forces; Dilute mixture ($\phi = 1$); Negligible viscous dissipation; Negligible radiative heat transfer; Nanoparticle and base fluid locally in thermal equilibrium. Invoking the above assumptions, the following equations represent the mathematical formulation of the non- homogenous single phase model for the governing equations as formulated by Buongiorno [8]:

1.3.2.1. Continuity equation.

$$\nabla.v = 0 \tag{1}$$

where v is the velocity

1.3.2.2. Nanoparticle continuity equation.

$$\frac{\partial \phi}{\partial t} + v.\nabla\phi = \nabla.\left(D_B\nabla\phi + D_T\frac{\nabla T}{T}\right) \tag{2}$$

Here ϕ is nanoparticle volume fraction, D_B is the Brownian diffusion coefficient given by the Einstein–Stokes's equation:

$$D_B = \frac{k_B T}{3\pi\mu d_p} \tag{3}$$

where μ is the viscosity of the fluid, d_p is the nanoparticle diameter, $k_B = 1.385\times10^{-23}$ is Boltzmann constant and D_T is the thermophoretic diffusion coefficient, which is defined as

$$D_T = \left(\frac{\mu}{\rho}\right)\left(0.26\frac{k}{k+k_p}\right) \tag{4}$$

In Eq. (4), k and k_p are the thermal conductivity of the fluid and particle materials, respectively.

1.3.2.3. Momentum equation.

$$v.\nabla v = -\frac{1}{\rho_{nf}}\nabla p + \nabla.\tau + g \tag{5}$$

where

$$\tau = -\mu_{nf}\left(\nabla v + (\nabla v)^t\right) \tag{6}$$

where the superscript 't' indicates the transpose of ∇v. Also p is pressure.

1.3.2.4. Energy equation.

$$v.\nabla T = \nabla\left(\alpha_{nf}\nabla T\right) + \frac{\rho_p c_p}{\rho_{nf}c_{nf}}\left(D_B\nabla\phi.\nabla T + D_T\frac{\nabla T.\nabla T}{T}\right) \tag{7}$$

where ϕ and T are nanoparticle concentration and temperature of nanofluid, respectively.

This nanofluid model can be characterized as a 'two-fluid' (nanoparticles + base fluid), four-equation (mass, momentum, energy), non-homogeneous (nanoparticle/fluid slip velocity allowed) equilibrium (nanoparticle/fluid temperature differences not allowed) model. Note that the conservation equations are strongly coupled. That is, v depends on ϕ via viscosity; ϕ depends on T mostly because of thermophoresis; T depends on ϕ via thermal conductivity and also via the Brownian and thermophoretic terms in the energy equation: ϕ and T obviously depends on v because of the convection terms in the nanoparticle continuity and energy equations, respectively.

In a numerical study by Behzadmehr et al. [9] for the first time a two-phase mixture model were implemented to investigate the behavior of Cu–water nanofluid in a tube and the results were also compared with previous works using a single-phase approach. The authors claimed that the simulation done by assuming that basefluid and particles behave separately possessed results that are more precise compared to the previous computational modeling. They implemented the mixture theory for their work. It was suggested that the continuity, momentum and energy equations be