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Numerical study of dynamic thermal conductivity of nanofluid in the forced convective heat transfer

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ABSTRACT

In this work, forced convective heat transfer of nanofluid in the developing laminar flow (entrance region) in a circular tube is considered. The nanofluid thermal conductivity, as an important parameter, is considered as two parts: static and dynamic part. Simulated results show that the dynamic part of nanofluid thermal conductivity due to the Brownian motion has a minor effect on the heat transfer coefficients, on the other hand, static part of thermal conductivity including nanolayer around nanoparticle has an important role in heat transfer.

1. Introduction

Conventional heat transfer fluids, e.g. water, are poor heat transfer fluids and have low efficiency in cooling or heating processes. Numerous methods have been taken to improve the thermal behavior of these fluids by suspending micro or larger-sized particle materials in liquids [1].

Since solid materials have thermal conductivities much higher than fluids, such an attempt results in a thermal conductivity enhancement; when the particle sizes are on the order of millimeters or micrometers, there exist severe problems in the usage of these mixtures in practice (e.g. sedimentation and pressure lost) [2].

The term nanofluid is envisioned to describe a solid–liquid mixture which consists of nanoparticles and a base liquid in which the ultrafine particles may be either metallic or nonmetallic and result in a much better heat transfer performance [3].

Most of researches published so far in the filed of nanofluids can be divided into the two broad categories: (1) study of the thermophysical properties of nanofluids in which the main focus is on the thermal conductivity and the viscosity (2) study of the convective heat transfer of nanofluids or application of nanofluids in the thermal processes. Using theoretical or experimental models developed in the first category, the heat transfer coefficients were calculated in the second category.

In this work, we consider the thermal conductivity of nanofluid as two parts (static + dynamic), as postulated by some researchers, and examine role of dynamic part due to the Brownian motion of nanoparticles and show effectiveness of it in the forced convective heat transfer of nanofluid.

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2. Material and methods

2.1. Choosing suitable model for nanofluid

Assuming the nanofluid as solid–liquid suspension, an important dimensionless parameter governing the dynamics of a particle in a flow is the Stokes number (St) defined as the ratio of the characteristic time of the particle response to the flow to that of the flow itself [4]:

$$\mathrm{St} = \frac{t_p}{t_f}, \tag{1}$$

where t_p is the particle response time (the time that a particle takes to respond to a change in suspending liquid flow velocity) and t_f is the characteristic time-scale of the continuous liquid phase.

The Reynolds number for particles in a fluid, called the particle Reynolds number ($\mathrm{Re_p}$), is defined in the following manner [5]:

$$\mathrm{Re_p} = \frac{\rho u_p d_p}{\mu} = \mathrm{Re_{tube}} \frac{d_p}{D} \times C_1, \quad C_1 = \frac{u_p}{u_l}. \tag{2}$$

Here, u_p is the particle velocity (relative to the fluid), d_p is the particle diameter, μ is the viscosity, u_l is the superficial velocity of the fluid (based on the free cross-sectional area for fluid flow), ρ is the fluid density, D is the tube diameter (characteristic length of the system) and $\mathrm{Re_{tube}}$ is the Reynolds number for the tube (based on the tube diameter and the average fluid velocity).

To obtain regime of particle, order of magnitude of $\mathrm{Re_p}$ is estimated:

$$o(d_p) \approx 10^{-8}\ \mathrm{m},$$

$$o(D) \approx 10^{-2}\ \mathrm{m}\ (\text{tube diameter in this work}),$$

$$o(C_1) \ll 1,$$

$$\rightarrow o(\mathrm{Re_p}) \ll 10^{-6}\mathrm{Re_{tube}} \ll 10^{-4}(\mathrm{Re_{tube}} < 1000), \tag{3.a}$$

$$o(\mathrm{Re_p}) \ll 10^{-3}(\mathrm{Re_{tube}} > 1000, \text{laminar}), \tag{3.b}$$

where o( ) denotes order of magnitude and relative nanoparticle velocity due to the slip mechanisms (u_p) is much smaller than the fluid velocity ($o(C_1) \ll 1$) [6,7].

Even if clustering of nanoparticles is considered in estimation of $\mathrm{Re_p}$, we can estimate $o(d_p) \approx 10^{-6}$ m [8]:

$$o(\mathrm{Re_p}) \ll 10^{-2}(\mathrm{Re_{tube}} < 1000). \tag{4}$$

Thus, $\mathrm{Re_p}$ is less than unity, so the particles move in the Stokes regime and t_p is given by [9]:

$$t_p = \frac{\rho_p (d_p)^2}{18\mu}, \tag{5}$$

where ρ_p is the particle density. Also, t_f for the tube is obtained:

$$t_p = \frac{D}{u_f}. \tag{6}$$

Now, we can evaluate stokes number (St):

$$\mathrm{St} = \frac{\rho_p u_f (d_p)^2}{18\mu D} = \mathrm{Re_{tube}} \left(\frac{\rho_p}{18\rho}\right)\left(\frac{d_p}{D}\right)^2, \tag{7}$$

$$o(\rho_p) \approx 10^3\ \mathrm{kg/m^3}\ (\text{e.g. alumina density} \sim 3920\ \mathrm{kg/m^3}),$$

$$o(\rho) \approx 10^3\ \mathrm{kg/m^3}\ (\text{water density} \sim 1000\ \mathrm{kg/m^3}),$$

$$\mathrm{Re_{tube}} < 1000,$$

$$o(\mathrm{St}) \approx 10^{-11}\left(o(\mathrm{St}) \approx 10^{-7}\ \text{considering clustering of nanoparticles}\right). \tag{8}$$

Considering order of magnitude of Stokes number, we can use single phase model, in other words, nanoparticle is not considered as a separated phase [9]. As mentioned before, relative velocity of nanoparticle in the fluid (slip mechanisms) can be