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A dispersion model for predicting the heat transfer performance of TiO_2–water nanofluids under a laminar flow regime

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ABSTRACT

Nanofluids are a suspension of particles with ultrafine size in a conventional base fluid that increases the heat transfer performance of the original base fluid. They show higher thermal performance than base fluids especially in terms of the thermal conductivity and heat transfer coefficient. During the last decade, many studies have been carried out on the heat transfer and flow characteristics of nanofluids, both experimentally and theoretically. The purpose of this article is to propose a dispersion model for predicting the heat transfer coefficient of nanofluids under laminar flow conditions. TiO_2 nanoparticles dispersed in water with various volume fractions and flowing in a horizontal straight tube under constant wall heat flux were used. In addition, the predicted values were compared with the experimental data from He et al. [14]. In the present study, the results show that the proposed model can be used to predict the heat transfer behaviour of nanofluids with reasonable accuracy. Moreover, the results also indicate that the predicted values of the heat transfer coefficient obtained from the present model differ from those obtained by using the Li and Xuan equation by about 3.5% at a particle volume fraction of 2.0%.

1. Introduction

Conventional heat transfer fluids such as oil, water and ethylene glycol have inherently poor thermal properties. Thus, over the past ten years, many researchers have attempted to rectify the poor heat transfer properties of these fluids, in particular their thermal conductivity. In general, solids have several hundred-fold greater thermal conductivity than common fluids. In order to overcome this problem, ultrafine solid particles can be suspended in base fluids to increase their thermal performance. The earliest studies of the thermal performance of liquids with a nanoparticle suspension were reported by Masuda et al. [1] in 1993. However, the term nanofluids was introduced by Choi [2] in 1995, and subsequently gained popularity. Nanofluids were expected to be ideally suited for practical application because they have a substantially higher thermal conductivity and convective heat transfer coefficient relative to the base fluids.

Over the past decade, many researchers have reported the heat transfer and flow behaviour of various types of nanofluids, especially their thermal conductivity and heat transfer coefficient. A number of researchers have attempted to investigate the thermal behaviour of nanofluids both theoretically and experimentally. The available literature with respect to the heat transfer performance and flow characteristics of nanofluids is summarized elsewhere [3–5]. However, such reviews are not up to date. Recent papers dealing with the heat transfer and flow features of nanofluids both experimentally and theoretically are summarized below.

He et al. [6] experimentally studied the heat transfer and flow behaviours of TiO_2–distilled water nanofluids flowing through a vertical pipe in an upward direction under a constant heat flux in both a laminar and a turbulent flow regime. The experimental results showed that the local heat transfer coefficient increased with increasing particle concentration in both laminar and turbulent flow regimes in a given condition. They also showed that the pressure drop of the nanofluids was similar to that of the base fluid.

Nguyen et al. [7] experimentally investigated the heat transfer coefficient of an Al_2O_3–water nanofluid flowing through a small liquid cooling system of microprocessors under a turbulent flow regime. The results showed a much higher heat transfer coefficient for nanofluids than for the base liquid, with a nanofluid with a 36 nm particle diameter giving a higher heat transfer coefficient than that with a 47 nm particle diameter.

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Nomenclature

C_p	specific heat, J/kgK
d	nanoparticle diameter, m
D	tube diameter, m
h	heat transfer coefficient, W/m^2K
k	thermal conductivity, W/mK
L	length of the test tube, m
Nu	Nusselt number
Pe	Peclet number
Pr	Prandtl number
q	heat flux, W/m^2
R	tube radius, m
Re	Reynolds number
T	temperature, K
u	mean velocity, m/s

Greek symbols

β	dispersion coefficient, W/mK
ϕ	volume fraction
κ_B	Boltzmann constant (1.3807×10^{-23} m^2 kg/ s^2K)
ρ	density, kg/m^3
α	thermal diffusivity, m^2/s
μ	viscosity, kg/ms

Subscript

ave	average
o	inlet
p	particles
nf	nanofluid
w	water or wall

Ko et al. [8] reported on an experiment in which the viscosity and pressure drop of CNT nanoparticles was dispersed in distilled water flowing through a horizontal tube. The effect of the CNT concentrations and preparation methods on the viscosity of nanofluids was also reported. Under laminar flow conditions, the results indicated that the nanofluids had larger friction factors than the base fluid. In contrast, under turbulent flow conditions, the friction factor of the nanofluids was very close to that of the base fluids.

Chein and Chuang [9] reported the performance of the microchannel heat sink (MCHS) using CuO–water nanofluids as coolants. At a low flow rate, the experimental results showed that nanofluids absorbed more energy than the base fluid. However, there was no contribution from heat absorption when the flow rate was high.

Duangthongsuk and Wongwises [10,11] studied the effect of thermophysical properties on the prediction of the heat transfer coefficient and also reported the heat transfer performance and friction characteristics of a TiO_2–water nanofluid. The results indicated that a number of thermophysical models have an insignificant effect on the calculated Nusselt number of the nanofluid. Moreover, the results also showed that the presence of nanoparticles leads to a higher heat transfer coefficient than that of water and that the pressure drop of the nanofluid is similar to that of the base fluid.

Nguyen et al. [12] studied the heat transfer performance of Al_2O_3–water nanofluids in a confined and submerged jet impinging on a horizontal and circular heated surface. The experimental results indicated that nanofluids with high particle fractions (6.0 vol.% and even 2.8 vol.%) do not seem to be appropriate for heat transfer enhancement purposes under such a configuration. Moreover, their results also showed that the use of nanofluids does not increase heat transfer, and in the worst cases, there was a clear decrease in the heat transfer coefficient. Thus, the use of nanofluids does not always guarantee enhancement of heat transfer.

Izadi et al. [13] numerically investigated the hydrodynamics and thermal behaviours of an Al_2O_3–water nanofluid flowing through an annulus under a laminar flow regime, using a single-phase model. The numerical results showed that the convective heat transfer coefficient increased with increasing particle concentration. Moreover, the results also indicated that the particle volume concentration has no significant effect on the dimensionless axial velocity, but does affect the temperature profile.

He et al. [14] numerically studied the convective heat transfer of a nanofluid with TiO_2 nanoparticles dispersed in water under laminar flow conditions. A single-phase model and combined Euler and Lagrange method (Discrete method) were used to determine the effects of volume concentrations, Reynolds number and aggregate sizes on the convective heat transfer and flow behaviour of the nanofluid. Their results indicated that the nanofluid significantly enhanced the Nusselt number, especially in the entrance region. Moreover, the numerical results were consistent with experimental data.

Bianco et al. [15] numerically investigated the heat transfer performance of an Al_2O_3–water nanofluid flowing through a circular tube under a laminar flow regime. A single-phase model and two-phase model were employed to describe the heat transfer coefficient of the nanofluid. The results showed that the heat transfer coefficient increased with increasing particle volume fraction as well as Reynolds number and was higher than that of the base fluid. Moreover, there was an approximately 11% difference in the average heat transfer coefficient between the single-phase and two-phase model.

Kumar et al. [16] used a single-phase thermal dispersion model to analyse the thermal properties and flow field of a nanofluid numerically. The results showed that suspended nanoparticles increased the heat capacity and surface area of the conventional base liquid, which led to an increase in the Nusselt number, especially at high volume fractions.

The review of literature shown above includes all studies of nanofluids flowing in channels, both experimental and theoretical. However, most of the models used involved commercial software and few compared the simulation results with the experimental data. In the present study, main concern is to develop a mathematical model to describe the convective heat transfer characteristics of nanofluids under a laminar flow conditions, and then compare the results with experimental data. This dispersion model is different from that proposed by He et al. [14] which is based on single phase method and combined Euler and Lagrange method.

2. Mathematical model and data reduction

2.1. Mathematical model

There are two different approaches to analysing the heat transfer enhancement of nanofluids. One is the two-phase model and the other is the single-phase model. Although the former describes the functions of both the liquid phase and solid phase in the heat transfer process, it requires a long time for computation and a high performance computer. The second model, assuming that both the liquid and particle phases are in thermal equilibrium and flow at the same velocity, is simpler and requires less computation time. However, although the behaviour of a nanofluid is more similar to a liquid than solid–liquid mixtures, several factors such as gravity, Brownian forces, friction between the liquid and solid particles, sedimentation and dispersion may coexist in the main flow of