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Numerical investigation of effective parameters in convective heat transfer of nanofluids flowing under a laminar flow regime

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ABSTRACT

This article presents a numerical investigation on heat transfer performance and pressure drop of nanofluids flows through a straight circular pipe in a laminar flow regime and constant heat flux boundary condition. Al_2O_3, CuO, carbon nanotube (CNT) and titanate nanotube (TNT) nanoparticles dispersed in water and ethylene glycol/water with particle concentrations ranging between 0 and 6 vol.% were used as working fluids for simulating the heat transfer and flow behaviours of nanofluids. The proposed model has been validated with the available experimental data and correlations. The effects of particle concentrations, particle diameter, particles Brownian motions, Reynolds number, type of the nanoparticles and base fluid on the heat transfer coefficient and pressure drop of nanofluids were determined and discussed in details. The results indicated that the particle volume concentration, Brownian motion and aspect ratio of nanoparticles similar to flow Reynolds number increase the heat transfer coefficient, while the nanoparticle diameter has an opposite effect on the heat transfer coefficient. Finally, the present study provides some considerations for the appropriate choice of the nanofluids for practical applications.

1. Introduction

Common heat transfer fluids such as oil, water and ethylene glycol have inherently poor thermal conductivity compared to most solids. This problem is the primary obstacle to the high compactness, light in weight and effectiveness of heat exchangers. In order to enhance the thermal conductivity of conventional heat transfer fluids, it has been tried to develop a new type of modern heat transfer fluid by suspending ultrafine solid particles in base fluids. In 1993, Masuda et al. [1] studied the heat transfer performance of liquids with solid nanoparticles suspension. However, the term of "nanofluid" was first named by Choi [2] in 1995, and successively gained popularity. Because of the extensively greater thermal conductivity and heat transfer performance of the nanofluids as compared to the base fluids, they are expected to be ideally suited for practical applications.

Since a decade ago, research publications related to the use of nanofluids as working fluids have been reported both numerically and experimentally. There are also some review papers that elaborate on the current stage in the thermal behaviours, thermophysical properties and flow characteristics of nanofluids [3–6]. However, this article is aimed at reviewing only the novel literature considering convective heat transfer of nanofluids with a numerical approach. These studies are briefly described as follows.

Mirmasoumi and Behzadmehr [7] reported the effect of nanoparticle diameter on convective heat transfer performance of Al_2O_3/water nanofluid flowing under a fully developed laminar flow regime numerically. In their study, a two-phase mixture model was used. The results demonstrated that the heat transfer coefficient of the nanofluid dramatically increases with decreasing the diameter of nanoparticle. Moreover, the results also indicated that nanoparticle diameter has no significant effect on the skin friction coefficient.

Kalteh et al. [8] numerically studied forced convective heat transfer of Cu/water nanofluid inside an isothermally heated microchannel under a laminar flow regime. An Eulerian two-fluid model was used to simulate the heat transfer characteristic of the nanofluid. The results indicated that the heat transfer performance increases with increasing Reynolds number as well as particle volume fraction. On the contrary, heat transfer enhancement increases with decreasing nanoparticle diameter. Finally, the results also showed that the pressure drop of nanofluids is slightly higher than that of base fluids.

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Mirmasoumi and Behzadmehr [9] investigated the laminar mixed convection heat transfer of Al_2O_3/water nanofluid flowing through a horizontal tube numerically. A two-phase mixture model was used to describe the hydrodynamic and thermal behaviour of the nanofluid. The numerical results indicated that in the fully developed region the particle concentration has insignificant effects on the hydrodynamic parameters, while it has important effects on the thermal parameters. Moreover, the results showed that nanoparticle concentration is higher at the bottom of the test tube and at the near wall region.

Akbarinia [10] and Akbarinia and Behzadmehr [11] numerically investigated the fully developed laminar mixed convection of Al_2O_3/water nanofluid flowing through a horizontal curved tube. In their studies, three-dimensional elliptic governing equations were used. The effects of the buoyancy force, centrifugal force and particle concentration on the heat transfer performance were presented. The results showed that the particle concentration has no direct effect on the secondary flow, axial velocity and skin friction coefficient. However, when the buoyancy force is more important than the centrifugal force, the effect of particle concentration on the entire fluid temperature can affect the hydrodynamic parameters. Moreover, the results also indicated that the buoyancy force decreases the Nusselt number whereas the particle concentration has a positive effect on the heat transfer enhancement and on the skin friction reduction.

Izadi et al. [12] studied the hydrodynamic and thermal behaviours of an Al_2O_3/water nanofluid flowing through an annulus under a laminar flow regime. In their study, a single-phase model was used for nanofluid simulation. The results indicated that the particle volume concentration has no significant effect on the dimensionless axial velocity, but affects the temperature field and increases the heat transfer coefficient.

He et al. [13] 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 methods were used to investigate the effects of volume concentration, Reynolds number and aggregate size on the convective heat transfer and flow behaviour of the nanofluid. Their results indicated that the nanofluid significantly enhances the Nusselt number, especially in the entrance region. Moreover, the numerical results were consistent with experimental data.

Bianco et al. [14] investigated the heat transfer performance of an Al_2O_3/water nanofluid flowing through a circular tube under a laminar flow regime numerically. A single-phase model and two-phase model were used to determine the heat transfer coefficient of the nanofluid. The results demonstrated that the heat transfer performance increases with increasing Reynolds number as well as particle volume concentration. Moreover, differences in the average heat transfer coefficient between the single-phase and two-phase models were observed as approximately 11%.

Kumar et al. [15] used a single-phase thermal dispersion model to numerically investigate the thermal properties and flow field of a Cu/water nanofluid in a thermally driven cavity. The results indicated that the Grashof number, particle volume fraction and particle shape factor augment the average Nusselt number of nanofluids.

Talebi et al. [16] presented the numerical formulation to evaluate the laminar mixed convection heat transfer of Cu/water nanofluid flowing through a square lid-driven cavity. They found that, at a given Reynolds number, the particle concentration affects the thermal behaviour and flow characteristic at larger Rayleigh numbers. Moreover, the effect of particle concentration decreased with increasing Reynolds number.

Shahi et al. [17] reported a numerical investigation to simulate the heat transfer performance of Cu/water nanofluid flowing through a square cavity under a laminar flow regime. Their results indicated that the average Nusselt number of the nanofluid increases with increasing particle concentration. In contrast, the results also showed that the bulk temperature of the nanofluid decreases with increasing particle concentration.

Akbarinia and Laur [18] presented the laminar mixed convection heat transfer of Al_2O_3/water nanofluid flows in a circular curved tube numerically. A two-phase mixture model and the control-volume technique were used to investigate the effect of particle diameter on the hydrodynamic and thermal parameters. Their results indicated that the Nusselt number and secondary flow decrease with increasing the particle diameter and uniform distribution of nanoparticles is observed.

Zeinali Heris et al. [19] numerically investigated the convective heat transfer of nanofluid in a circular tube with constant wall temperature, employing a dispersion model. Their results showed that decreasing nanoparticle size and increasing nanoparticle concentration augment the heat transfer coefficient.

Raisi et al. [20] carried out a numerical study on laminar convective heat transfer of Cu/water nanofluid inside a microchannel with slip and no slip boundary conditions. They investigated the effect of different parameters such as Reynolds number, particle concentration, and slip velocity coefficient on the nanofluid heat transfer characteristics. The results indicated that the particle concentration and slip velocity coefficient have significant effects on the heat transfer rate at high Reynolds numbers.

Ghasemi and Aminossadati [21] investigated the natural convective heat transfer of CuO/water nanofluid inside an inclined enclosure with top and bottom wall at different temperatures. The effects of Rayleigh number, inclination angle, and particle concentration on heat transfer performance were studied. The results showed that the flow pattern, temperature field and heat transfer rate are affected by inclination angle at high Rayleigh numbers. Furthermore, it was found that the heat transfer rate is maximised at specific particle concentration and inclination angle.

Zhou et al. [22] presented the lattice Boltzman method (LB method) to study the microscale characteristics of the multicomponent flow of nanofluids. In this method, the computation domain was separated into fine mesh and coarse mesh regions, respectively. The multicomponent LB method was used in the fine mesh region and the single-component LB method was applied in the coarse mesh region. The results indicated that the present model can be used to predict the microscopic characteristics of the nanofluid and the computational efficiency can be significantly improved.

Although numerous papers are currently available on the numerical study of laminar convective heat transfer of nanofluids, there is no comprehensive study on different effective parameters in this field. The effect of several parameters such as nanoparticle shape, based fluid type and nanoparticle material are not considered in literature. On the other hand, naturally the increase in heat transfer performance due to the nanofluids is accompanied by several undesirable effects such as an increase in pressure drop. Therefore, it needs to find the suitable nanofluid for optimum operation. No significant attention is paid to find some criteria for the choice of appropriate nanofluids in different heat transfer applications. In the present study a modified single-phase model for predicting the heat transfer performance of nanofluids is proposed and a home-made FORTRAN computer program is developed. The model has been validated against the measured data of Kim et al. [23] and the predicted values from Shah and London [24] for the base fluid. The effects of particle concentration, mean particle diameter, Reynolds number, Brownian motion, nanoparticle material and shape, and type of base fluid on the heat transfer performance of nanofluids are then investigated in detail. Finally, some guidelines related to choice of the appropriate nanofluid for particular applications are provided.