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Original Research Paper

Theoretical analysis of natural convection boundary layer heat and mass transfer of nanofluids: Effects of size, shape and type of nanoparticles, type of base fluid and working temperature

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ABSTRACT

The problem of natural convection boundary layer heat transfer of nanofluids is theoretically analyzed. Different aspects of nanoparticles, such as size, shape and constructive material, as well as the type of the base fluid and the working temperature, are examined. The drift-flux model of nanofluids, including the effects of Brownian motion, thermophoresis, and the local volume fraction of nanoparticles, is adopted to model the boundary layer heat and mass transfer of nanofluids. Following the state-of-the-art, the thermo-physical properties are extracted from five different synthesized types of nanofluids. A new non-dimensional parameter, the enhancement ratio, indicating the ratio of the convective heat transfer coefficient of the nanofluid to the base fluid, is introduced. The effect of the nanoparticles on the enhancement of natural convective heat transfer of nanofluids is discussed. The main findings of this study are as follows: (i) the type of the nanoparticles and the base fluid are the most important parameters affecting the heat transfer of nanofluids; (ii) in some cases, the presence of nanoparticles in the base fluid deteriorates the heat transfer rate; and (iii) the rise of the working temperature reduces the efficiency of the nanofluid, which is a crucial issue in applications of nanofluids as coolants.

1. Introduction

Nanofluids are a new type of engineered heat transferred fluids, containing nano-sized solid nanoparticles that are being used to enhance the heat transfer [1]. The thermal conductivity and the dynamic viscosity of nanofluids are the most important thermo-physical properties, which affect the convective heat transfer performance of nanofluids [2]. The experiments show that the thermal conductivity and the dynamic viscosity of nanofluids are functions of the size, the shape, and the constructive materials of nanoparticles, as well as the type of the base fluid and the working temperature of the nanofluid [3–7]. There are also other affective parameters such as the method of synthesis of the nanofluids, the sonication time, which affect the thermo-physical properties and the heat transfer performance of nanofluids [4,6,8]. In addition, there are mass transfer mechanisms, such as Brownian motion and thermophoresis effects, which influence the convective heat transfer performance of nanofluids [9,10].

There are many experimental reports, which have measured the thermal conductivity or the dynamic viscosity of synthesized nanofluids. In order to theoretically analysis the convective heat transfer of nanofluids, the thermal conductivity and the dynamic viscosity of a nanofluid as functions of the volume fraction of nanoparticles are required simultaneously. However, only few studies have reported the data of the thermal conductivity and the dynamic viscosity of a nanofluid, simultaneously [11–15]. Some of these studies are as follows:

Chandrasekar et al. [11] measured the thermal conductivity and the dynamic viscosity of water–Al_2O_3 nanofluids. They dispersed powders of 43 nm spherical alumina nanoparticles in the water, and then sonicated the nanofluid for 6 h. The thermal conductivity was measured using the hot wire method, and the dynamic viscosity was measured using the Brookfield cone and plate viscometer. The measurements were performed at room temperature. The results indicated the Newtonian behaviors of the samples. It was

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Nomenclature

c	specific heat in constant pressure (J/kg K)
D_B	Brownian diffusion coefficient (m^2/s)
D_T	thermophoretic diffusion coefficient (m^2/s)
f	rescaled nanoparticle volume fraction, nanoparticle concentration
g	gravitational acceleration (m/s^2)
h	thermal convective coefficient (W/m^2 K)
j_p	drift flux of nanoparticles
k	thermal conductivity coefficient (W/m K)
Le	Lewis number
Nb	Brownian motion parameter
Nc	conductivity parameter
Nr	buoyancy ratio
Nt	thermophoresis parameter
Nu	Nusselt number
Nv	viscosity parameter
P	pressure (Pa)
Pr	Prandtl number
Ra	Rayleigh number
S	dimensionless stream function
T	temperature (°C)
u	non dimensional velocity component in x-direction (m/s)
v	non dimensional velocity component in y-direction (m/s)
x	Cartesian coordinate in horizontal direction (m)
y	Cartesian coordinate in vertical direction (m)

Greek symbols

μ	thermal viscosity (kg s/m)
α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (1/K)
η	dimensionless distance
θ	non dimensional temperature
ρ	density (kg/m^3)
ϕ	volume fraction of nanoparticles
ψ	stream function

Subscript

∞	outside the boundary layer
bf	base fluid
nf	nanofluid
p	nanoparticles
w	wall

Superscript

$'$	differentiation respect to η

also found that the increase of the volume fraction of nanoparticles increased the thermal conductivity and the dynamic viscosity of the nanofluid.

Duangthongsuk and Wongwises [12] measured the thermal conductivity and the dynamic viscosity of water-based nanofluids, synthesized by 21 nm spherical nanoparticles of TiO_2. The thermal conductivity and the dynamic viscosity of the samples were measured by using the hot wire method and the rotational rheometer at three selected working temperatures of 15 °C, 25 °C and 35 °C. The results of this study also indicate the Newtonian behavior of the samples. The results revealed that the thermal conductivity of the nanofluid was a decreasing function of the working temperature while the dynamic viscosity of the nanofluid was an increasing function of the working temperature.

Jeong et al. [13] studied the effect of the shapes of nanoparticles on the thermal conductivity and the dynamic viscosity of nanofluids. The authors synthesized two types of water-based nanofluids using nanopowers of rectangular (150 nm) and spherical (40 nm) zinc-oxide nanoparticles. The nanoparticles were well dispersed in the base fluid by the aid of the ultrasonic method. The dynamic viscosity and the thermal conductivity of the samples were measured at room temperature using the hot wire method and Ubbelohde viscometer, respectively. The results indicated that the thermal conductivity and the dynamic viscosity of the nanofluid containing rectangular nanoparticles were higher than those containing the spherical nanoparticles. However, the size of the spherical nanoparticles was much smaller than that of the rectangular ones.

Esfe et al. [14] examined the thermal conductivity and the dynamic viscosity of manganese-oxide water-based nanofluids at the room temperature. The nanofluid was synthesized using a powder of 40 nm spherical nanoparticles. The nanoparticles were dispirited in the water using the ultrasonic waves. The thermal conductivity and the dynamic viscosity of the samples were measured by using the hot wire method and Brookfield viscometer, respectively. The results showed that the increase of the volume fraction of the nanoparticles increased the thermal conductivity and the dynamic viscosity of the nanofluid.

Agarwal et al. [15] studied the influence of the size of nanoparticles on the thermal conductivity and the dynamic viscosity of nanofluids. They synthesized two types of kerosene–Al_2O_3 nanofluids using powders of spherical alumina nanoparticles with two sizes of 21 nm and 44 nm. The nanoparticles were well dispersed in the kerosene utilizing the ultrasonic waves. The thermal conductivity and the dynamic viscosity of the nanofluids were measured at room temperature using the hot wire and the Brookfield viscometer, respectively. The results indicated that the thermal conductivity and the dynamic viscosity of the samples of nanofluids containing smaller size of nanoparticles (21 nm particles) were higher than those containing larger size of nanoparticles (44 nm particles).

As a benchmark study, Buongiorno et al. [16] and Venerus et al. [17] have analyzed the effect of volume fraction of nanoparticles on the thermal conductivity and dynamic viscosity of nanofluids for different samples of nanofluids in 30 different laboratories around the world using different measurement methods. The results indicated that the thermal conductivity and dynamic viscosity of nanofluids are linear functions of the volume fraction of nanoparticles for low volume fractions of nanoparticles. Therefore, the linear function of concentration of particles for conductivity and viscosity is valid only in low concentrations of nanoparticles, and for high concentration of nanoparticles non-linear relations are required.

In the present study, the results of the measured thermal conductivity and dynamic viscosities of nanofluids reported by the previous researchers [11–15] are utilized to analysis the different aspects of nanoparticles and base fluids on the convective heat transfer of nanofluids.

Rana and Bhargava [18], using a homogenous model, examined natural convection heat transfer of nanofluids over a vertical flat plate. They investigated the effect of the presence of different types of nanoparticles (silver, copper, copper oxide, alumina, and titanium oxide) on the boundary layer heat transfer of water-based nanofluids. The Maxwell model and the Brinkman model were utilized to model the thermal conductivity and the dynamic viscosity of the nanofluids, respectively. The results indicated that the presence of nanoparticles increased the heat transfer rate. The highest enhancement was achieved for the silver nanoparticles. However, the effects of the sizes of the nanoparticles, the shape of nanoparticles and the working temperature cannot be seen in the Maxwell and Brinkman models. Therefore, these effects have not been examined in the study of Rana and Bhargava [18]. It is worth noticing that the mass transfer mechanism, including the Brownian motion and the thermophoresis effects, are neglected in the homogeneous model of Rana and Bhargava [18].

Kuznetsov and Nield [9] studied natural convection heat transfer of nanofluids over an isothermal flat plate. They assumed a constant volume fraction of nanoparticles at the surface, which is possible by an active control of volume fractions of nanoparticles at the surface of the plate. The presence of a concentration boundary layer of nanoparticles was taken into account, due to the Brownian motion and the thermophoresis effects. Aziz and Khan [19] as well as Uddin et al. [19] extended the study of Kuznetsov and Nield [9] to the case of natural convection boundary layer heat transfer of nanofluids over a flat plate, which was subject to a convective heat transfer boundary condition. Later on, Kuznetsov and Nield [21] proposed a new enhanced boundary condition for the volume fraction of nanoparticles at the surface of the plate. Using the enhanced boundary condition, the mass flux of nanoparticles at the surface of the plate is zero, and the volume fraction of nanoparticles can be adjusted passively at the surface of the plate by the boundary layer. This new boundary condition is in better agreement with the practical applications of nanofluids. In the study of Kuznetsov and Nield [21] as well as the studies of Aziz and Khan [19] and Uddin et al. [20], the effect of the local variation of the thermo-physical properties due to the migration of nanoparticles were neglected. In these studies, the results were reported in a general non-dimensional form, and hence, the different aspects of nanoparticles, or the base fluid were not discussed.

To the best of the authors' knowledge, the effects of size, shape, and type of nanoparticles, the type of the base fluid and the working temperature have not yet been investigated for the heat transfer boundary layer of nanofluid while these parameters are very important in the synthesis of nanofluids [3,5–8,22–24]. In addition, there is no theoretical study to report the effect of mass transfer of nanoparticles on the heat transfer of nanofluids in the boundary layer for practical case studies.

In this study, the effects of size, shape, and type of nanoparticles as well as the types of the base fluid and the working temperature on the heat transfer performance of nanofluids in natural convection boundary layer heat transfer applications are examined. The new enhanced boundary condition, the zero mass flux of nanoparticles at the surface, is utilized. In addition, the effect of the mass transfer mechanism of nanoparticles because of the Brownian motion and thermophoresis on the local volume fraction of nanoparticles and buoyancy forces is theoretically analyzed and the results are reported for practical case studies. The effect of thermal conductivity and dynamic viscosity are being linearized and analyzed in the form of two new non-dimensional parameters of dynamic viscosity and thermal conductivity parameters.

2. Mathematical model

Consider a two-dimensional steady-state boundary layer flow and heat transfer of a nanofluid over an isothermal vertical flat plate. The hot plate with uniform temperature of T_w is placed in a quiescent nanofluid at the temperature of T_∞ and a uniform

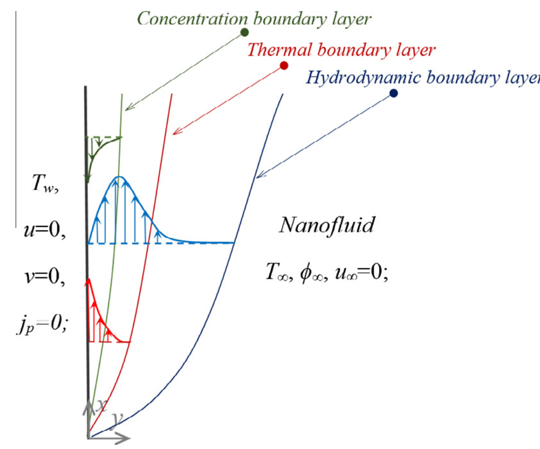

Fig. 1. The schematic view of the flat plate in a nanofluid.

volume fraction of nanoparticles ϕ_∞. The geometry of the flat plate is chosen in the present study as a benchmark geometry, which indicates the general behaviors of external flows. In addition, there are numerous industrial and physical applications for natural convection heat transfer over a flat plate such as cooling of hot spot sheets immersed in nanofluid coolants. The nanofluid in the vicinity of the hot plate has a tendency to move upward because of the buoyancy force induced in the fluid. The schematic view of the physical model is depicted in Fig. 1. In addition, the presence of thermophoresis tends to move nanoparticles from the hot regions to the cold regions [9]. Therefore, the migration of heavy nanoparticles from the plate into the boundary layer induces a secondary buoyancy force in the vicinity of the plate. The migration of nanoparticles would also change the local thermo-physical properties of the nanofluid in the boundary layer.

The experiments show that the thermal conductivity and the dynamic viscosity of nanofluids are very sensitive to the variation of the volume fraction of nanoparticles [2,4–6]. Hence, the influence of the variation of the local volume fraction of nanoparticles on the thermal conductivity and the dynamic viscosity of the nanofluid are important and cannot be neglected; however, these effects have been neglected in previous studies. Here, in order to increase the physical significance of the present study, the thermal conductivity and the dynamic viscosity of nanofluids are considered as functions of the local volume fraction of nanoparticles. It is assumed that the size of nanoparticles is uniform, and the effect of the agglomeration of nanoparticles on the thermo-physical properties and the Brownian motion is neglected because of the lack of accurate physical models and experimental results.

In the present study, the following assumptions are also considered: (1) there is no chemical reaction between the nanoparticles and the base fluid. (2) The external force can be assumed by the Oberbeck-Boussinesq approximation. (3) The mixture of the base-fluid and nanoparticles is a dilute mixture. (4) The radiation heat transfer are neglected. (5) The nanoparticles and the base fluid are in local thermal equilibrium. (6) The viscous dissipation is neglected. The first assumption is applicable because the materials of nanoparticles are chosen to be in chemical inertness with the base fluid. The assumption of (2) and (6) are applicable as the nanofluids can be utilized with a limited range of the temperature differences (to avoid boiling and solidification problems), and hence, the temperature difference between the wall and the surrounding is limited. The assumption (3) is justified, as the nanofluid are synthesized with very low volume fraction of nanoparticles. The assumption (5) is realistic as the nanoparticles are very fine and conductive, and hence, they are in the same