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Thermal management for free convection of nanofluid using two phase model

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ABSTRACT

In this study, free convection heat transfer in an enclosure filled with nanofluid is investigated. The important effects of Brownian motion and thermophoresis have been included in the model of nanofluid. Control volume based finite element method is used to solve the governing equations. Effects of angle of turn, buoyancy ratio number and Lewis number on streamline, isotherm and isoconcentration are considered. Also a correlation for Nusselt number corresponding to active parameters is presented. Results indicated that Nusselt number is an increasing function of buoyancy ratio number while it is a decreasing function of Lewis number and angle of turn. Also it can be found that Lewis number has no significant effect on Nusselt number at low values of buoyancy ratio number.

1. Introduction

Control volume finite element method (CVFEM) is a scheme that uses the advantages of both finite volume and finite element methods for simulation of multi-physics problems in complex geometries [1–2]. Soleimani et al. [3] studied natural convection heat transfer in a semi-annulus enclosure filled with nanofluid using CVFEM. They found that the angle of turn has an important effect on the streamlines, isotherms and maximum or minimum values of local Nusselt number. Sheikholeslami et al. [4] studied the problem of natural convection between a circular enclosure and a sinusoidal cylinder. They concluded that streamlines, isotherms, and the number, size and formation of the cells inside the enclosure strongly depend on the Rayleigh number, values of amplitude and the number of undulations of the enclosure. Also this method was applied successively for simulating different practical problems [5–10].

The nanofluid can be applied to engineering problems, such as heat exchangers, cooling of electronic equipments and chemical processes. Almost all of the 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 aren't any slip velocities between the nanoparticles and fluid molecules, thus they have a uniform mixture of nanoparticles. Khanafer et al. [11] conducted a numerical investigation on the heat transfer enhancement due to adding nano-particles in a differentially heated enclosure. They found that the suspended nanoparticles substantially increase the heat transfer rate at any given Grashof number. Rashidi et al. [12] considered the analysis of the second law of thermodynamics applied to an electrically conducting incompressible nanofluid fluid flowing over a porous rotating disk. They concluded that using magnetic rotating disk drives have important applications in heat transfer enhancement in renewable energy systems and industrial thermal management. Sheikholeslami et al. [13] studied the natural convection in a concentric annulus between a cold outer square and heated inner circular cylinders in presence of static radial magnetic field. They reported that average Nusselt number is an increasing function of nanoparticle volume fraction as well as Rayleigh number, while it is a decreasing function of Hartmann number. Sheikholeslami et al. [14] analyzed the magnetohydrodynamic nanofluid flow and heat transfer between two horizontal plates in a rotating system. Their results indicated that, for both suction and injection Nusselt number has a direct relationship with nanoparticle volume fraction. Recently several authors investigated about nanofluid flow and heat transfer [15–35].

All the above studies assumed that the nanoparticle concentration is uniform. It is believed that in natural convection of nanofluids, the nanoparticles could not accompany fluid molecules

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Nomenclature

C_p	specific heat at constant pressure
D_B	Brownian diffusion coefficient
D_T	Thermophoretic diffusion coefficient
$\vec{g}$	Gravitational acceleration vector
k	Thermal conductivity
L	Gap between inner and outer boundary of the enclosure $(=r_{out}-r_{in})$
Le	Lewis number $(=\alpha/D_B)$
N	Number of undulations
Nb	Brownian motion parameter $(=(\rho c)_p D_B(\phi_h-\phi_c)/(\rho c)_f\alpha)$
Nt	Thermophoretic parameter $(=(\rho c)_p D_T(T_h-T_c)/[(\rho c)_f\alpha T_c])$
Nu	Nusselt number
Pr	Prandtl number $(=\mu/\rho_f\alpha)$
r	Non-dimensional radial distance
Ra	Thermal Rayleigh number $\left(=(1-\phi_c)\rho_{f_0}g\beta L^3(T_h-T_c)/(\mu\alpha)\right)$
Nr	Buoyancy ratio number $\left(=\left(\rho_p-\rho_0\right)(\phi_h-\phi_c)/\left[(1-\phi_c)\rho_{f_0}\beta L(T_h-T_c)\right]\right)$
T	Fluid temperature
u, v	Velocity components in the x-direction and y-direction
U, V	Dimensionless velocity components in the X-direction and Y-direction
x, y	Space coordinates

Greek symbols

ζ	Angle measured from the isolated right plane
α	Thermal diffusivity
ϕ	Volume fraction
μ	Dynamic viscosity
υ	Kinematic viscosity
ψ & Ψ	Stream function & dimensionless stream function
Θ	dimensionless temperature
ρ	Fluid density
β	Thermal expansion coefficient
ω, Ω	Vorticity & dimensionless vorticity

Subscripts

c	Cold
h	Hot
loc	Local
ave	Average
in	Inner
out	Outer

due to some slip mechanisms such as Brownian motion and thermophoresis, so the volume fraction of nanofluids may not be uniform anymore and there would be a variable concentration of nanoparticles in a mixture. Nield and Kuznetsov [36] studied the natural convection in a horizontal layer of a porous medium saturated by a nanofluid. Their analysis revealed that for a typical nanofluid (with large Lewis number) the prime effect of the nanofluids is via a buoyancy effect coupled with the conservation of nanoparticles, the contribution of nanoparticles to the thermal energy equation being a second-order effect. Sheikholeslami et al. [37] used heatline analysis to simulate two phase simulation of nanofluid flow and heat transfer. Their results indicated that the average Nusselt number decreases as buoyancy ratio number increases until it reaches a minimum value and then starts increasing. Khan and Pop [38] published a paper on boundary-layer flow of a nanofluid past a stretching sheet. They indicated that the reduced Nusselt number is a decreasing function of each dimensionless number. Hassani et al. [39] investigated the problem of boundary layer flow of a nanofluid past a stretching sheet. They found that the reduced Nusselt number decreases with the increase in Prandtl number for many Brownian motion numbers.

The main aim of present study is to investigate nanofluid flow and heat transfer in a semi-annulus enclosure via CVFEM. The combined effects of thermophoresis and Brownian motion are considered to get the gradient of nanoparticles' volume fraction. Effects of buoyancy ratio number, Lewis number and angle of turn for the enclosure on flow and heat transfer are considered.

2. Geometry definition and boundary conditions

The schematic diagram and the mesh of the semi-annulus enclosure used in the present CVFEM program are shown in Fig. 1. The inner and outer walls are maintained at constant temperatures T_h and T_c respectively while the two other walls are thermally insulated. Also the boundary conditions of concentration are similar to temperature.

3. Mathematical modeling and numerical procedure

3.1. Problem formulation

The nanofluid's density, ρ, is

$$\begin{aligned}\rho &= \phi\rho_p + (1-\phi)\rho_f \\ &\cong \phi\rho_p + (1-\phi)\left\{\rho_{f0}(1-\beta(T-T_c)\right\}\end{aligned} \tag{1}$$

where ρ_f is the base fluid's density, T_c is the reference temperature, ρ_{f0} is the base fluid's density at the reference temperature, and β is the volumetric coefficient of expansion. Taking the density of base fluid as that of the nanofluid, the density ρ in Eq. (2), thus becomes

$$\rho \cong \phi\rho_p + (1-\phi)\{\rho_0(1-\beta(T-T_c)\} \tag{2}$$

where ρ_0 is the nanofluid's density at the reference temperature.

The continuity and momentum under Boussinesq approximation and energy equations for the laminar and steady state natural convection in a two-dimensional enclosure can be written in dimensional form as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{3}$$

$$\rho_f\left\{u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right\} = -\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{4}$$

$$\rho_f\left\{u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right\} = -\frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - (\phi-\phi_c)\left(\rho_p-\rho_{f_0}\right)g + (1-\phi_c)\rho_{f_0}(T-T_c)g \tag{5}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \frac{(\rho c)_p}{(\rho c)_f}\left[\begin{array}{l} D_B\left\{\dfrac{\partial \phi}{\partial x}\cdot\dfrac{\partial T}{\partial x} + \dfrac{\partial \phi}{\partial y}\cdot\dfrac{\partial T}{\partial y}\right\} \\ +(D_T/T_c)\left\{\left(\dfrac{\partial T}{\partial x}\right)^2 + \left(\dfrac{\partial T}{\partial y}\right)^2\right\}\end{array}\right] \tag{6}$$

$$u\frac{\partial \phi}{\partial x} + v\frac{\partial \phi}{\partial y} = D_B\left\{\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2}\right\} + \left(\frac{D_T}{T_c}\right)\left\{\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right\}. \tag{7}$$