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Nanofluid in tilted cavity with partially heated walls

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A B S T R A C T

Lattice Boltzmann Method is applied to investigate the natural convection flow utilizing nanofluids in square enclosure with partially heated walls. The fluid in the cavity is a water-based nanofluid containing different types of nanoparticles: copper (Cu), silver (Ag), alumina (Al_2O_3) and titania (TiO_2). The effective thermal conductivity and viscosity of nanofluid are calculated by the Maxwell–Garnetts (MG) and Brinkman models, respectively. This investigation was compared with other numerical methods and found to be in excellent agreement. Numerical results for the flow and heat transfer characteristics are obtained for various values of the nanoparticle volume fraction, Rayleigh numbers and inclination angles together with different kinds of nanofluids. The type of nanofluid is a key factor for heat transfer enhancement. Choosing copper as the nanoparticle proved to have the highest cooling performance for this problem. It is also shown that the Nusselt number is an increasing function of each of the nanoparticle volume fraction and Rayleigh numbers.

1. Introduction

The problem of natural convection in a cavity has been a major topic of research studies due to its occurrence in industrial and technological applications such as chemical vapor deposition instruments (CVD) [1], electronic cooling [2], furnace engineering [3], and solar collectors [4]. Recently, due to the rising demands of modern technology, including chemical production, power station, and microelectronics, there is a need to develop new types of fluids that will be more effective in terms of heat exchange performance. Nanofluids are produced by dispersing the nanometer-scale solid particles into base liquids with low thermal conductivity such as water, ethylene glycol (EG), and oils. [5]. The term "nanofluid" was first coined by Choi [6] to describe this new class of fluids. The materials with nanometer sizes possess unique physical and chemical properties [7]. The presence of the nanoparticles in the fluids noticeably increases the effective thermal conductivity of the fluid and consequently enhances the heat transfer characteristics. Therefore, numerous methods have been taken to improve the thermal conductivity of these fluids by suspending nano/micro-sized particle materials in liquids.

Several investigators have experimentally studied flow and thermal characteristics of nanofluids. Especially, in order to understand buoyancy-driven heat transfer of nanofluids in a cavity several investigations have been theoretically and experimentally conducted. Putra et al. [8] conducted the experiment for observation on the natural convective characteristics of water based on Al_2O_3. They reported that natural convective heat transfer in a cavity is decreased with the increment of the volume fraction of nanoparticles. Kim et al. [9] analytically researched the convective instability driven by buoyancy and heat transfer characteristics of nanofluids with theoretical models which are used to estimate properties of nanofluids and indicated that as the thermal conductivity and shape factor of nanoparticles decrease, the convective motion in a nanofluid sets in easily and their results were similar with Putra et al.'s [8] experimental investigation. Khanafer et al. [10] numerically investigated buoyancy-driven heat transfer enhancement in a two-dimensional enclosure utilizing nanofluids. Their paper shows that the Nusselt number for the natural convection of nanofluids is increased with the volume fraction. They reported an enhancement of heat transfer in horizontal annuli. A theoretical study on a heated cavity was reported by Hwang et al. [11]. They observed that the heat transfer coefficient of Al_2O_3–water nanofluids is reduced when there is an increase in the size of nanoparticles and a decrease in average temperatures. Rashidi et al. [12] studied the effects of magnetic interaction number, slip factor and relative temperature difference on velocity and temperature profiles as well as entropy generation in magnetohydrodynamic (MHD) flow of a fluid with variable properties over a rotating disk. Rashidi et al. [13] considered the analysis of the second law of thermodynamics applied to an electrically conducting incompressible nanofluid flowing over a porous rotating disk. Recently several papers were published about nanofluid flow and heat transfer [14–49].

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Nomenclature

c	lattice speed
c_i	discrete particle speeds
C_p	specific heat at constant pressure [kJ kg^{-1} K^{-1}]
F	external forces
f	density distribution functions
f^{eq}	equilibrium density distribution functions
g	internal energy distribution functions
g^{eq}	equilibrium internal energy distribution functions
g_y	gravitational acceleration [m s^{-2}]
Gr	Grashof number ($=g\beta\Delta TH^3/\upsilon^2$)
H	height/width of the enclosure
k	thermal conductivity
$\overline{Nu}$	average Nusselt number
p	pressure [Pa]
Pr	Prandtl number ($=\upsilon/\alpha$)
Ra	Rayleigh number ($=g\beta\Delta TH^3/\alpha\upsilon$)
T	fluid temperature
(u, v)	velocity components in the (x,y) directions, respectively
w_i	weighting factor
(x, y)	Cartesian coordinates
(X, Y)	dimensionless coordinates

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
ϕ	volume fraction
θ	dimensionless temperature
μ	dynamic viscosity [Pa s^{-1}]
υ	kinematic viscosity [m^2 s]
ρ	fluid density [kg m^{-3}]
τ_c	relaxation time for temperature
τ_v	relaxation time for flow
β	thermal expansion coefficient [K^{-1}]
ψ	stream function
γ	inclination angle

Subscripts

c	cold
h	hot
∞	condition at infinity
nf	nanofluid
f	base fluid
n	solid particles

One of the useful numerical methods that have been used in the recent years is the Lattice Boltzmann Method. Sheikholeslami et al. [50] studied the magnetic field effect on CuO–water nanofluid flow and heat transfer in an enclosure which is heated from below. They found that the effect of Hartmann number and heat source length is more pronounced at high Rayleigh number. Sheikholeslami et al. [51] studied the problem of MHD free convection in an eccentric semi-annulus filled with nanofluid. They showed that Nusselt number decreases with increase of position of inner cylinder at high Rayleigh number. Nanofluid flow and heat transfer have been considered by several authors [52–57].

The main aim of the present study is to identify the ability of Lattice Boltzmann Method (LBM) for solving natural convection flow utilizing nanofluids in a square enclosure with partially heated walls. Different types of nanoparticles such as copper (Cu), silver (Ag), alumina (Al_2O_3) and titania (TiO_2) with water as their base fluid have been considered. The results of LBM are compared with predictions of the finite volume method. The streamline and temperature field and average Nusselt number for different values of volume fraction, Rayleigh number and inclination angles are also illustrated.

2. Problem definition and mathematical model

2.1. Problem statement

The geometry and the coordinate system are schematically shown in Fig. 1. The partially thermally active side walls of the cavity are maintained at two different but uniform temperatures, namely, T_h and T_c respectively with $T_h > T_c$, and the bottom wall, top wall and remaining parts of the side walls are insulated. In Fig. 1, γ denotes the tilted angle with respect to horizon.

2.2. The Lattice Boltzmann Method

The LB model used here is the same as that employed in [58,59]. The thermal LB model utilizes two distribution functions, f and g, for the flow and temperature fields, respectively. It uses modeling of movement of fluid particles to capture macroscopic fluid quantities such as velocity, pressure, and temperature. In this approach, the fluid domain discretized to uniform Cartesian cells. Each cell holds a fixed number of distribution functions, which represent the number of fluid particles moving in these discrete directions. The D2Q9 model was used and values of $w_0 = 4/9$ for $|c_0| = 0$ (for the static particle), $w_{1-4} = 1/9$ for $|c_{1-4}| = 1$ and $w_{5-9} = 1/36$ for $|c_{5-9}| = \sqrt{2}$ are assigned in this model.

The density and distribution functions i.e. the f and g, are calculated by solving the Lattice Boltzmann equation (LBE), which is a special discretization of the kinetic Boltzmann equation. After introducing BGK approximation, the general form of the lattice Boltzmann equation with external force is:

For the flow field:

$$f_i(x + c_i\Delta t, t + \Delta t) = f_i(x, t) + \frac{\Delta t}{\tau_v}\left[f_i^{eq}(x, t) - f_i(x, t)\right] + \Delta t c_i F_k \quad (1)$$

For the temperature field:

$$g_i(x + c_i\Delta t, t + \Delta t) = g_i(x, t) + \frac{\Delta t}{\tau_C}\left[g_i^{eq}(x, t) - g_i(x, t)\right] \quad (2)$$

where Δt denotes the lattice time step, c_i is the discrete lattice velocity in direction i, F_k is the external force in direction of lattice velocity, and τ_v and τ_C denote the lattice relaxation time for the flow and temperature fields. The kinetic viscosity υ and the thermal diffusivity α, are defined

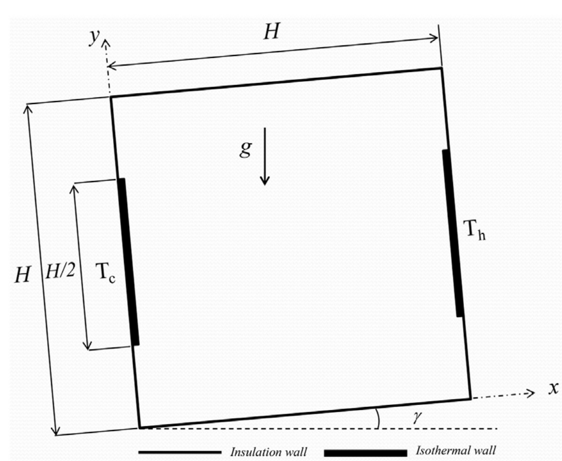

Fig. 1. Geometry of the problem.

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