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Lattice Boltzmann simulation of nanofluid heat transfer enhancement and entropy generation

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ABSTRACT

In the framework of this paper, nanofluid flow and heat transfer in a square enclosure containing a rectangular heated body is investigated computationally. The fluid in the cavity is a water-based nanofluid containing four different types of metal and metal-oxide nanoparticles: alumina (Al_2O_3), copper (Cu), silver (Ag) and titania (TiO_2). The effective viscosity and thermal conductivity of the nanofluid are calculated by the Brinkman model and Maxwell–Garnett (MG), respectively. The Lattice Boltzmann Method (LBM) has been adopted to solve this problem. The effects of various governing parameters such as nanofluid type, Rayleigh number, volume fraction of nanoparticles and height of the rectangular heated body contained in the cavity on hydrothermal characteristics are studied. The results indicate that both the Nusselt number and dimensionless entropy generation are increasing functions of the Rayleigh number and nanoparticle volume fraction of the nanofluid. Furthermore, the effect of nanoparticle volume fraction is found to be more pronounced for a low Rayleigh number as compared to a high Rayleigh number. Excellent accuracy is achieved with the LBM code.

1. Introduction

Natural convection heat transfer in a cavity arises in numerous engineering systems including chemical vapor deposition instruments (CVD) [1], electronic cooling designs [2], furnaces [3], and solar collectors [4]. It is well known in engineering thermodynamics that the generated entropy is proportional to the destroyed exergy [5]. To enhance thermodynamic performance, engineers seek to minimize the entropy generation of the system and this procedure is termed entropy generation minimization (EGM) [6]. Significant improvements in thermodynamic performance have been demonstrated in these investigations. Several authors have discussed the entropy generation in the cavity with different geometrical and boundary conditions. In particular, the natural convection by heated partitions in a cavity has been discussed by Famouri and Hooman [7]. In their study, the position of the heated partition and the dimensionless temperature difference on the local and average entropy have been investigated.

Another important development in heat transfer engineering in the past decade has been the implementation of nanofluids. The term "nanofluid" describes a colloidal mixture containing ultra-fine particles, termed nanoparticles and was introduced by Choi [8]. The nanoparticles Al_2O_3, TiO_2, CuO, SiO_2, Al and Cu (metal and metal-oxides) are commonly used in industrial applications. These nanoparticles are prepared by one of two processes: chemical and physical. The chemical processes include spray pyrolysis and chemical precipitation whereas the physical techniques include the inert condensation technique and mechanical grinding. The base fluid containing nanoparticles is normally water, ethylene glycol/water and engine oil/water. Nanofluids generally include up to a 5% nanoparticle volume fraction in order to achieve effective properties e.g. enhanced thermal conductivity and viscosity. Mathematical models of nanofluid transport include two main approaches, namely a single-phase model or a two-phase model. The convective transport in nanofluids was investigated by Buongiorno [9], who considered the two-phase non-homogenous model with a number of slip mechanisms and identified Brownian motion and thermophoresis as the principal mechanisms for thermal enhancement. Subsequently an extensive range of studies have been communicated for convection flows of nanofluids. Rana and Bhargava [10] used a finite element method to analyze steady, laminar boundary layer flow of nanofluids from a nonlinear stretching sheet incorporating the effect of thermophoresis and Brownian motion. Rana et al. [11] investigated mixed convection nanofluid boundary layer flows along an inclined surface in a porous medium. Bég and Tripathi [12] studied peristaltic pumping of nanofluids in a deformable channel, showing that pressure difference is slightly enhanced with Brownian motion effect, whereas it is very strongly enhanced with increasing thermophoresis effect. Khanafer et al. [13] numerically studied the natural convection in a two-dimensional enclosure utilizing nanofluids. They showed that the Nusselt number is an increasing function of Cu nanoparticle volume

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Nomenclature

Be	Bejan number
c_s	speed of sound in lattice scale
e_α	discrete lattice velocity in direction
FFI	fluid friction irreversibility
f_k^{eq}	equilibrium distribution
g	internal energy distribution functions
g^{eq}	equilibrium internal energy distribution functions
g_y	acceleration due to gravity
Gr	Grashof number $(=g\beta\Delta TL^3/\upsilon^2)$
Ge	Gebhart number $(=\frac{g\beta H}{C_p})$
HTI	heat transfer irreversibility
k	thermal conductivity $(\mathrm{W/m\cdot K})$
H	height/width of the enclosure
$\overline{Nu}$	average Nusselt number
Ns	dimensionless entropy generation number
Pr	Prandtl number $(=\upsilon/\alpha)$
Ra	Rayleigh number $(=g\beta\Delta T(L)^3/\alpha\upsilon)$
$\dot{S}_{gen}$	volumetric entropy generation rate
t	height of rectangular heated body
T	fluid temperature
u, v	velocity components in the x-direction and y-direction
(x,y)	Cartesian coordinates

Greek symbols

η	magnetic resistivity
α	thermal diffusivity
ϕ	volume fraction
φ	dimensionless viscous dissipation function
θ	dimensionless temperature $(=(T-T_c)/(T_h-T_c))$
μ	dynamic viscosity
υ	kinematic viscosity
τ	lattice relaxation time
ρ	fluid density
ψ	stream function
β	thermal expansion coefficient

Subscripts

c	cold
h	hot
ave	average
nf	nanofluid
f	base fluid
s	solid particles

fraction. Muthtamilselvan et al. [14] presented numerical solutions for mixed convection in a lid-driven enclosure filled with Cu–water nanofluid, observing that both the aspect ratio and solid volume fraction of the nanofluid have a significant influence on the streamlines, isotherms and maximum or minimum values of the local Nusselt number in the enclosure. The convective heat transfer analysis for Ag–water and Cu–water on a stretching sheet has also been investigated by Vajravelu et al. [15]. Sheikholeslami and Abelman [16] used a two phase model for the simulation of nanofluid flow and heat transfer in an annulus in the presence of an axial magnetic field. Force convective heat transfer of a magnetic nanofluid in a lid driven semi annulus enclosure has been investigated by Sheikholeslami et al. [17]. Their results showed that the Nusselt number has a direct relationship with the Reynolds number and nanoparticle volume fraction while it has a reverse relationship with the Hartmann number. Also, nanofluid flow and heat transfer were investigated by several authors [18–37].

In recent years, Lattice Boltzmann Method (LBM) [38] has emerged as a powerful numerical technique for simulating complex flows including multi-phase systems, suspension flows, biophysical transport and magnetohydrodynamic. LBM simulates fluids in the molecular state rather than at the classical macroscopic level and involves solving the Boltzmann transport equation for particle distribution functions on a simplified phase space, designated the lattice [39]. Ashorynejad et al. [40] studied the influence of a static radial magnetic field on natural convection nanofluid flow and heat transfer in a horizontal cylindrical annulus enclosure. Sheikholeslami and Ellahi [41] studied three dimensional mesoscopic simulation of the magnetic field effect on natural convection of nanofluids. They found that thermal boundary layer thickness increases with an increase of Lorentz forces. Sheikholeslami et al. [42] applied LBM to simulate three dimensional nanofluid flow and heat transfer in the presence of a magnetic field. They indicated that adding a magnetic field leads to a decrease in the rate of heat transfer. Kefayati [43] studied the magnetic field effect on mixed convection in a two sided lid-driven cavity filled with non-Newtonian nanofluid. He found that an increase in the Hartmann number affects the power-law index and nanoparticle influences. Recently LBM and other new methods were applied for different types of problems [44–58].

In the present article, the Lattice Boltzmann Method is employed to simulate nanofluid flow and convective heat transfer in square enclosures containing a rectangular heated body. A range of nanoparticles including copper (Cu), silver (Ag), alumina (Al_2O_3) and titania (TiO_2) with water as their base fluid has been considered. We describe the physical geometry and mathematical analysis of the problem with LBM formulation for a nanofluid. Furthermore, the effects of solid volume fraction of nanoparticles, types of nanofluid, Rayleigh number, height of the rectangular heated body on the flow, Nusselt number and dimensionless entropy generation number on streamlines and isotherms are elaborated. The present study has important applications in solar energy collector performance enhancement with nanofluids [59].

2. Problem definition and mathematical model

2.1. Problem statement

The physical geometry of the problem and coordinate system with related parameters are shown in Fig. 1(a). A rectangular body with height t and width $H/2$ is placed in the center of the square enclosure (of dimensions H by H), and is assumed to be isothermal at a comparatively higher temperature as compared with the two vertical isothermal walls. The top and bottom walls are insulated.

2.2. The Lattice Boltzmann Method

The thermal LB model [60] utilizes two distribution functions, f and g, for the flow and temperature fields, respectively. Thermal LBM employs modeling of the movement of fluid particles to capture macroscopic fluid quantities such as velocity, pressure and temperature. In this approach, the fluid domain is discretized to uniform Cartesian cells. The probability of finding particles within a certain range of velocities at a certain range of locations replaces tagging each particle as in the computationally-intensive molecular dynamics simulation approach. In LBM, each cell holds a fixed number of distribution functions, which represent the number of fluid particles moving in these discrete directions. The D2Q9 model has been implemented [61] 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. f and g, are calculated by solving the Lattice Boltzmann equation (LBE), which is a special discretization of the kinetic Boltzmann equation. After introducing the BGK approximation, the general form of the Lattice Boltzmann equation with external force is: