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Analysis of the entropy generation in a nanofluid-filled cavity in the presence of magnetic field and uniform heat generation/absorption

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ABSTRACT

This paper examines the natural convection in a square enclosure filled with a water–Al_2O_3 nanofluid in the presence of magnetic field and uniform heat generation/absorption. The left wall is hot, the right wall is cold and the horizontal walls are insulated. Lattice Boltzmann method (LBM) is applied to solve the coupled equations of flow and temperature fields. The entropy generation due to heat transfer, fluid friction and magnetic effect has been determined by the finite difference method. This study has been carried out for the pertinent parameters in the following ranges: Rayleigh number of the base fluid, $\mathrm{Ra} = 10^3$ to 10^6, Hartmann number varied from $\mathrm{Ha} = 0$ to 60, heat generation/absorption coefficient $q = -10$ to 10 and the solid volume fraction of nanoparticles between $\phi = 0$ and 6%. For $\mathrm{Ra} \leq 10^5$ and $\mathrm{Ha} \leq 30$, the results show that the heat generation/absorption coefficient influences heat transfer rate, but it does not affect the entropy generation in the range $-10 < q < 5$. Also it is observed that adding nanoparticle reduces the entropy generation. The nanoparticle effect is more intense for high Hartmann number.

1. Introduction

Natural convection in square enclosures has many engineering applications such as cooling systems of electronic components, solar collectors, thermal storage systems and nuclear reactor systems. Therefore, it is important to understand the thermal behavior of such systems when the natural convection is the dominant mode of heat transfer. The low thermal conductivity of conventional heat transfer fluids, commonly water, has restricted designers. Adding some solid nanoparticles with high thermal conductivity to the fluid is one of the ways to overcome this problem. The resulting fluid is a suspension of the solid nanoparticle in the base fluid which is called "nanofluid". The thermal conductivities of nanofluids are believed to be greater than the base fluid due to the high thermal conductivity of the nanoparticles. Khanafer et al. [1] investigated numerically natural convection heat transfer in a two-dimensional vertical enclosure utilizing nanofluids. It was revealed that the heat transfer rate increases with the increase of particle fraction at any given Grashof number. Jahanshahi et al. [2] studied natural convection of water–SiO_2 nanofluid using two different models; in the first model they have employed a set of experimental data for thermal conductivity of nanofluid and in the second model they have calculated the thermal conductivity using the theoretical formulations. Their results showed an enhancement in thermal conductivity due to the adding of nanoparticles at both models. Ghasemi et al. [3] examined natural convection in an enclosure that is filled with a water–Al_2O_3 nanofluid and is influenced by a magnetic field. The found results show that the heat transfer rate increases with an increase of the Rayleigh number but it decreases with an increase of the Hartmann number. Also an increase of the solid volume fraction may result in enhancement or deterioration of the heat transfer performance depending on the value of Hartmann and Rayleigh numbers. Abu-Nada [4,5] and Abu-Nada et al. [6] studied the effect of the variables properties of nanofluids in natural convection. They related the deterioration in heat transfer of nanofluids in natural convection to the temperature dependence of nanofluid properties. These findings were also supported by other studies [7,8]. Alam et al. [9] investigated natural convection in a rectangular enclosure due to partial heating and cooling at vertical walls. Fattahi et al. [10] applied Lattice Boltzmann Method to investigate the natural convection flows utilizing nanofluids in a square cavity. The fluid in the cavity was a water-based nanofluid containing Al_2O_3 or Cu nanoparticles. The results indicated that by increasing solid volume fraction, the average Nusselt number increased for both nanofluids. It was found that the effects of solid volume fraction for Cu were stronger than Al_2O_3. Kefayati [11] studied the magnetic field effect on natural convection flow in a nanofluid-filled cavity with sinusoidal temperature distribution. Sheikholeslami et al. [12] investigated free convection heat transfer in an enclosure filled with nanofluid; the effects of Brownian motion and thermophoresis have been included in the model of nanofluid. Mahmoudi et al. [13] studied the effect of magnetic field and its direction on water–Al_2O_3 nanofluid filled cavity with a linear boundary condition; they exhibited that the magnetic field direction has effects on the flow and heat transfer rates in the cavity. Teamah et al. [14] examined numerically MHD natural convection in a square

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Nomenclature

B	Magnetic field
c	Lattice speed
c_s	Speed of sound
$\mathbf{c_i}$	Discrete particle speeds
c_p	Specific heat at constant pressure
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
$\vec{g}_y$	Gravity vector
Ha	Hartmann number
k	Thermal conductivity
Ma	Mach number
Nu	Local Nusselt number
q	heat generation/absorption coefficient
Ra	Rayleigh number
S	Entropy generation number
T	Temperature
$\mathbf{u}(u, v)$	Velocities
$\mathbf{x}(x, y)$	Lattice coordinates

Greek symbols

Δx	Lattice spacing
Δt	Time increment
τ_α	Relaxation time for temperature
τ_ν	Relaxation time for flow
ν	Kinematic viscosity
α	Thermal diffusivity
ρ	Fluid density
σ	electrical conductivity
ψ	Non-dimensional stream function
ϕ	Solid volume fraction
μ	Dynamic viscosity

Subscript

b	bottom
bf	base fluid
c	cold
f	fluid
h	hot
l	left
m	mean
nf	nanofluid
n	particle

cavity filled with different nanofluids in the presence of heat generation or absorption. The found results show that for weak magnetic field, the addition of nanoparticles is necessary to enhance the heat transfer but for strong magnetic field there is no need for nanoparticles because the heat transfer will decrease. Also, to augment the heat transfer; nanoparticles volume fraction must be increased but with a small value of heat absorption coefficient at constant Hartmann and Rayleigh numbers. Kefayati [15] studied heat dissipation effect of a ferrofluid on natural convection flow in a cavity with linearly temperature distribution at the presence of an external magnetic source with Lattice Boltzmann method. The cavity is filled with kerosene as the carrier fluid and nanoscale ferromagnetic particle of cobalt. Kefayati [16] analyzed natural convection of non-Newtonian molten polymer in a cavity with a sinusoidal heated wall by Finite Difference Lattice Boltzmann method (FDLBM). The molten polymer is modeled on power-law non-Newtonian fluid. Results indicated that the innovative FDLBM is an appropriate method for the problem as the augmentation of the power-law index causes heat transfer to drop generally. Kefayati [17] applied FDLBM to simulate effect of magnetic field on non-Newtonian blood flow in a lid-driven cavity with two moving lids. The power-law model for the non-Newtonian fluid was utilized in the paper as different Stuart numbers were studied on the flow. Mahmoudi et al. [18] investigated the entropy generation and the heat transfer rate for MHD natural convection in a trapezoidal enclosure filled with water–Cu nanofluid. They observed that the entropy generation is decreased when the nanoparticles are present, while the magnetic field generally increases the magnitude of the entropy generation. Jalilpour et al. [19] present an investigation for MHD stagnation-point flow of a nanofluid past a heated porous stretching sheet with suction or blowing conditions and prescribed surface heat flux. They found that the magnitude of the reduced Nusselt number decreases with an increase in magnetic number, thermophoresis parameter and Lewis number. Mahian et al. [20] presented an analytical study of the second law of thermodynamics for the flow and heat transfer of water–TiO_2 nanofluid in a vertical annulus with isoflux walls and under the influence of MHD field. They found that using water–TiO_2 nanofluid reduces the entropy generation while an increase in the Hartmann number increases the entropy generation number. Parvin et al. [21] studied natural convective flow, heat transfer and entropy generation in an odd-shaped geometry. The geometry considered is a combination of the horizontal and vertical enclosure shapes. The cavity is filled with water–Cu nanofluid. They observed that the proper choice of Rayleigh number could be able to maximize heat transfer rate simultaneously minimizing entropy generation. Kashani et al. [22] investigated numerically the entropy generation due to laminar natural convection of water–Cu nanofluid near the density maximum of water in a two-dimensional enclosure with various patterns of vertical wavy walls. They found that both the density inversion and the presence of nanoparticles play a significant role in the flow field structure, heat transfer characteristics and entropy generation. In addition, the average Nusselt number and entropy generation were found to decrease as the volume fraction of nanoparticle increased. Cho et al. [23] studied numerically the natural convection heat transfer characteristics and the entropy generation of water-based nanofluids in an enclosure bounded by wavy vertical walls and flat upper and lower surfaces. The analysis considers three different nanofluids: water–Cu, water–Al_2O_3 and water–TiO_2. It is shown that the water–Cu nanofluid yields the best heat transfer performance and the lowest total entropy generation of the three nanofluids. Rashidi et al. [24] studied the second law of thermodynamics applied to an electrically conducting incompressible nanofluid flowing over a porous rotating disk in the presence of an externally magnetic field, for three different types of nanoparticles: Cu, CuO and Al_2O_3. The disk surface acts as a strong source of irreversibility. Khorasanizadeh et al. [25] studied mixed convection and entropy generation of Cu–water nanofluid and pure water in a lid-driven square cavity. The results have shown that for pure fluid as well as nanofluid, increasing Reynolds number increases the average Nusselt number, linearly. The maximum entropy generation occurs in nanofluid at low Rayleigh number but high Reynolds number. The minimum entropy generation occurs in pure fluid at low Rayleigh and low Reynolds numbers. Alipanah et al. [26] investigated the entropy generation due to heat transfer and fluid friction irreversibility in a square cavity subjected to different side wall temperatures for compressible and incompressible natural convection flows. It is found that the entropy generated for compressible flow always is more than for the case of incompressible flow. Shahi et al. [27] examined the entropy generation due to natural convection of water–Cu nanofluid in a cavity with a protruded heat source. They found that the maximum value of Nusselt number and minimum entropy generation are obtained when heat source mountains in the bottom horizontal wall.