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Entropy generation analysis and heatline visualization of free convection in nanofluid (KKL model-based)-filled cavity including internal active fins using lattice Boltzmann method

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ABSTRACT

Two-dimensional natural convection and entropy generation in a square cavity filled with CuO–water nanofluid is performed. The lattice Boltzmann method is employed to solve the problem numerically. The influences of different Rayleigh numbers $(10^3 < Ra < 10^6)$ and solid volume fractions $(0 < \varphi < 0.05)$ on the fluid flow, heat transfer and total/local entropy generation are presented comprehensively. Also, the heatline visualization is employed to identify the heat energy flow. To predict the thermo-physical properties, dynamic viscosity and thermal conductivity, of CuO–water nanofluid, the KKL model is applied to consider the effect of Brownian motion on nanofluid properties. It is concluded that the configurations of active fins have pronounced effect on the fluid flow, heat transfer and entropy generation. Furthermore, the Nusselt number has direct relationship with Rayleigh number and solid volume fraction, and the entropy generation has direct and reverse relationships with Rayleigh number and solid volume fraction, respectively.

1. Introduction

The natural convection heat transfer and fluid flow have been analyzed by many investigators due to wide applications in the industries and engineering researches. Some of these applications may be found in nuclear reactors, lead–acid batteries, double-pane windows, furnaces, building ventilation, passive cooling, etc. [1–9]. As such, it can be concluded that it is logical to spend time to extract the details of heat transfer and fluid flow due to different effective parameters in natural convection phenomenon in the enclosures.

In the recent decades, some modern fluids with improved heat transfer performance have been introduced to be used instead of convectional fluids with weak heat transfer performance such as water, oil and air. To produce these modern

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Be	Bejan number
C_S	Speed of sound
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 of gravity
Gr	Grashof number $\left(Gr = g\beta \Delta TL^3/\nu^2\right)$
Ge	Gebhart number $(Ge = g\beta H/C_P)$
HTI	Heat transfer irreversibility
k	Thermal conductivity (W/m k)
H	Height/width of the cavity
Nu_{Avg}	Average Nusselt number
N_S	Dimensionless entropy generation
Pr	Prandtl number
$\dot{S}_{gen}$	Total entropy generation
T	Fluid temperature
u, v	Velocity components
x, y	Cartesian coordinates

Greek symbols

α	Thermal diffusivity
ϕ	Solid volume fraction
φ	Dimensionless viscous dissipation
θ	Dimensionless temperature $(\theta = (T - T_C)/(T_H - T_C))$
ν	Kinematic viscosity
ρ	Fluid density
ψ	Stream function
β	Thermal expansion coefficient

Subscripts

C	Cold
H	Hot
Avg	Average
nf	Nanofluid
f	Base fluid
s	Solid particles

fluids which are named nanofluids, the metallic and non-metallic nanoparticles such as Cu [10], CuO [11], TiO_2 [12,13], Al_2O_3 [14,15], Ag [16], MgO [17], Fe_2O_3 [18], Fe_3O_4 [19], CNTs [20,21], SWCNTs [22], DWCNTs [23–25], MWCNTs [26–29] are being added to different base fluids such as water [30], oil [31] and ethylene glycol [32]. The numerical investigation of heat transfer of laminar mixed convection inside a two-dimensional enclosure was conducted by Muthtamilselvan and Doh [33]. Inside the enclosure, nanofluid including water base fluid and Ag, Cu, CuO, Al_2O_3, TiO_2 nanoparticles with volume fraction ($\varphi = 0 - 0.06$) were used and the enclosure was affected by magnetic field. Steady magnetic field was vertically imposed on enclosure upper moving wall. The governing differential equations were discretized by control volume method and coupling between velocity and pressure was solved by SIMPLE algorithm. Mass and heat transfer mechanisms and flow properties inside the enclosure greatly depended on magnetic field power and flow and heat transfer inside the enclosure was strongly sensitive to Reynolds and Hartman numbers. Ghafouri and Salari [34] investigated the heat transfer enhancement in a two-dimensional enclosure. In their study, eight different models of viscosity were used for evaluating heat transfer enhancement. Also, average Nusselt number on hot wall and the explanation of results of streamlines, isotherm lines and velocity components in the range of Richardson number parameters, nanoparticles volume fractions ($\varphi = 0.01, 0.02, 0.03, 0.04, 0.05$) and in a constant Reynolds number for natural, force and mixed convections was performed.

Many researchers analyzed the influences of different governing parameters on the fluid flow and heat transfer in the enclosures [8,21,28,29]. Alam et al. [35] performed a numerical analysis on the natural convection by using finite element

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