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Mixed convection of Al_2O_3-water nanofluid in a double lid-driven square cavity with a solid inner insert using Buongiorno's two-phase model

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ABSTRACT

The present paper investigates steady conjugate mixed convection in a double lid-driven square cavity including a solid inner body. The annulus is filled with water-Al_2O_3 nanofluid based on Buongiorno's two-phase model. The top horizontal wall is maintained at a constant low temperature and moves to the right while the bottom horizontal wall is maintained at a constant high temperature and moves to the left. The governing equations are solved numerically using the finite element method. The governing parameters are the inner solid location (case 1-case 4), the nanoparticles volume fraction ($0 \leqslant \phi \leqslant 0.04$), Reynolds number ($1 \leqslant Re \leqslant 500$), Richardson number ($0.01 \leqslant Ri \leqslant 100$), the size of the inner solid ($0.1 \leqslant D \leqslant 0.7$) and thermal conductivity of the inner solid ($k_w = 0.01$, 0.045, 0.1, 0.76 and 1.95 W/m °C). The other parameters; Prandtl number, Lewis number, Schmidt number, ratio of Brownian to thermophoretic diffusivity and the normalized temperature parameter are fixed at $Pr = 4.623, Le = 3.5 \times 10^5, Sc = 3.55 \times 10^4, NBT = 1.1$ and $\delta = 155$, respectively. The results show that the nanofluid strategy in such a cavity has a noticeable augmentation of heat transfer. However, at low Reynolds number, the addition of nanoparticles has an adverse effect on the Nusselt number when the Richardson number is very high. It is also found that a big size solid body can augment heat transfer in the case of high values of both the Reynolds and the Richardson numbers.

1. Introduction

Mixed convection or combined convection fluid flow and heat transfer in cavities is a significant phenomenon in science and engineering systems due to its wide applications in the operation of solar collectors, heat exchangers, drying technologies, home ventilation, high-performance building insulation and lubrication technologies. Mixed convection is more complicated compared to other modes of convection due to the coupling between the buoyancy force by the temperature difference and the shear force by the movement of the wall(s). The study of Papanicolaou and Jaluria [1] performed a numerical investigation of laminar mixed convection in a rectangular cavity with an isolated thermal source. Huang and Lin [2] studied numerically the effects of Grashof and Reynolds numbers on the vortex flow and thermal characteristics in laminar mixed convection in a horizontal rectangular duct. Prasad and Koseff [3] investigated experimentally the recirculating mixed convection flow in a lid-driven rectangular cavity filled with pure fluid (water). Their results indicated that the convection heat transfer is a very weak function of the Grashof number for the examined range of the Reynolds number. Khanafer and Chamkha [4] considered the mixed convection flow in a lid-driven cavity filled with a Darcian fluid-saturated porous medium. The low thermal conductivity of conventional heat transfer fluids such as water and oils is a primary limitation in enhancing the performance and the compactness of many engineering electronic devices. An innovative and new technique to enhance heat transfer is using solid particles in the base fluid (i.e. nanofluids) in the range of sizes 10–50 nm. A nanofluid is defined as a smart fluid with suspended nanoparticles of average sizes below 100 nm in conventional heat transfer fluids such as water, oil, and ethylene glycol [5]. Due to small sizes and very large specific surface areas of the nanoparticles, nanofluids have superior properties like high thermal conductivity, minimal clogging in flow passages, longterm stability and homogeneity. Also, nanoparticles are used because they stay in suspension longer

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Nomenclature

C_p	specific heat capacity
d	side length of inner solid square
d_f	diameter of the base fluid molecule
d_p	diameter of the nanoparticle
D	dimensionless side length of the inner body, $D = d/L$
D_B	Brownian diffusion coefficient
D_{B0}	reference Brownian diffusion coefficient
D_T	thermophoretic diffusivity coefficient
D_{T0}	reference thermophoretic diffusion coefficient
g	gravitational acceleration
Gr	Grashof number
k	thermal conductivity
K_r	square wall to nanofluid thermal conductivity ratio, $K_r = k_w/k_{nf}$
L	side length of enclosure
Le	Lewis number
N_{BT}	ratio of Brownian to thermophoretic diffusivity
$\overline{Nu}$	average Nusselt number
Pr	Prandtl number
Re	Reynolds number
Re_B	Brownian motion Reynolds number
Ri	Richardson number, $Ri = Gr/Re^2$
Sc	Schmidt number
T	temperature
T_0	reference temperature (310 K)
T_{fr}	freezing point of the base fluid (273.15 K)
u, v	velocity components in the x and y-direction, respectively
U, V	dimensionless velocity components in the X and Y-direction, respectively
u_B	Brownian velocity of the nanoparticle
x, y & X, Y	space coordinates & dimensionless space coordinates

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
δ	normalized temperature parameter
θ	dimensionless temperature
λ	constant moving parameter (+1 or −1)
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
φ	solid volume fraction
φ^*	normalized solid volume fraction
ϕ	average solid volume fraction

subscript

b	bottom wall
c	cold
f	base fluid
h	hot
nf	nanofluid
p	solid nanoparticles
t	top wall
w	solid inner square

than larger particles. Thus, nanofluid seems a good candidate for heat removal mechanisms in practical, thermal, fluid-based applications. The thermal conductivity of nanoparticles is higher than that of traditional fluids. Thus, nanofluids can be used in a large industrial applications such as oil industry, nuclear reactor coolants, solar cells, construction, electronics, renewable energy and many others. The solid particles are usually metal or metal oxides such as copper (Cu), copper oxide, aluminum oxide (Al_2O_3), titanium (TiO_2) and silver (Ag).

A comprehensive work on natural convection in cavities that are partially occupied by nanofluids was reported by Khanafer and Vafai [6]. Tiwari and Das [7] numerically investigated the mixed convection heat transfer in a two-sided lid-driven square cavity filled with nanofluid by using the finite volume method. They found that the presence of nanoparticles in water tended to increase the heat transfer capacity and both the Richardson number and the direction of the moving walls affect the fluid flow and heat transfer within the cavity. The numerical simulation of the fluid and temperature distributions and the convective heat transfer of the nanofluid could be classified by two main approaches, namely a single-phase model (homogenous) or a two-phase model [8]. The single-phase approach considers the fluid phase and the nanoparticles as being in thermal equilibrium where the slip velocity between the base fluid and the nanoparticles is negligible. On the other hand, the two-phase approach assumes that the relative velocity between the fluid phase and the nanoparticles may not be zero where the continuity, momentum and energy equations of the nanoparticles and the base fluid are handled using different methods. There are number of numerical studies used the single-phase model for simulation of the nanofluids. Abu-Nada and Chamkha [9] considered the mixed convection flow in a lid-driven inclined square enclosure filled with a nanofluid. Salari et al. [10] modeled a numerical study on the mixed convection flow inside a square lid-driven cavity filled with nanofluid when both bottom and side walls are heated simultaneously by finite heat sources. Ismael et al. [11] investigated numerically the mixed convection inside a lid-driven square cavity filled with pure fluid. Ghalambaz et al. [12] numerically studied the effects of the diameter and concentration of nanoparti-

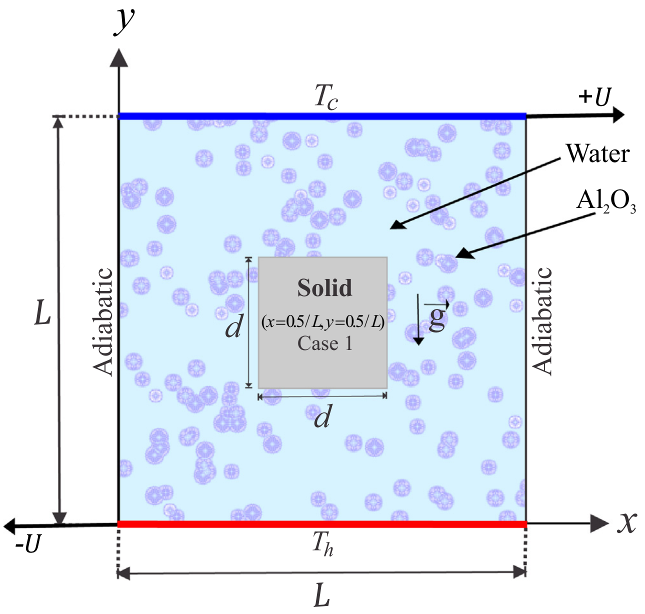

Fig. 1. Physical model of convection in a square cavity together with the coordinate system for case 1 ($x = 0.5/L$, $y = 0.5/L$).