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Mixed-convection flow and heat transfer in an inclined cavity equipped to a hot obstacle using nanofluids considering temperature-dependent properties

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ABSTRACT

Mixed-convection fluid flow and heat transfer in a square cavity filled with Al_2O_3–water nanofluid have been numerically investigated using the finite volume method (FVM) and SIMPLER algorithm. The geometry is a lid-driven square enclosure with an interior rectangular heated obstacle. The bottom, top, and left walls are adiabatic while the right wall has a constant low temperature (T_c). The upper lid of the cavity moves in a positive direction. Effects of different key parameters such as Richardson number, position and height of the block, the volume fraction of the nanoparticles, and cavity inclination angles on the fluid flow and heat transfer inside the cavity are investigated. It is observed that the average Nusselt number for all ranges of solid volume fraction increases with a decrease in the Richardson number. The results elucidate irregular changes of mean Nusselt number at different Richardson numbers versus variation of inclination angles in any case.

1. Introduction

One of the new methods used to enhance the thermal conductivity of common working fluids is the addition of nano-sized particles (1–100 nm) to heat transfer liquids such as water. The mixture of nanoparticles and a liquid is called "Nanofluid" [1]. Many studies have been done on the applications of nanofluids in renewable energy devices [2–4], microchannels [5,6], heat exchangers [7] and so on. Nanofluids can be also used in various types of cavities as the working fluid to enhance the performance. As known, the flow in enclosures may be as natural convection or mixed convection. Mixed-convection heat transfer in cavities has many technical applications, such as the cooling of electronic equipment, solar collectors, float glass manufacturing, food processing, solar ponds, crystal growth, and lubrication technologies. Here, a brief review of studies on natural convection in cavities using nanofluids is conducted.

Abu-Nada et al. [8] conducted a numerical investigation on mixed convection in an inclined square enclosure filled with Al_2O_3–water nanofluid. They found that heat transfer was enhanced significantly by the existence of the nanoparticles. Tiwari et al. [9] verified that the average Nusselt number increases substantially with an increase in the volume fraction of the nanoparticles. They used the finite volume method to investigate the flow and heat transfer in a square cavity with insulated top and bottom walls and differentially heated moving side walls.

The effect of aspect ratio of cavity was investigated by Muthtamilselvan et al. [10]. They applied the control volume method to study the mixed-convection heat transfer in a lid-driven rectangular enclosure filled with Cu–water nanofluid. The enclosure's side walls were insulated while its horizontal walls were kept at constant temperatures and the top wall could move with a constant velocity. They observed that both the aspect ratio of the cavity as well as the nanoparticle volume fraction affected the fluid flow and heat transfer inside the enclosure. Abbasian et al. [11] studied mixed-convection flow in a lid-driven square cavity filled with the Cu–water nanofluid. The cavity's horizontal walls were adiabatic while its sidewalls were under sinusoidal heating. They

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Nomenclature

c_p	specific heat, J kg^{-1} K^{-1}
Gr	Grashof number
Ri	Richardson number
Ra	Rayleigh number
g	gravitational acceleration, m s^{-2}
L	enclosure length, m
k	thermal conductivity, W m^{-1} K^{-1}
Nu	Nusselt number
p	pressure, N m^{-2}
P	dimensionless pressure
Pr	Prandtl number
q	heat flux, W m^{-2}
h	hot obstacle height, m
d	hot obstacle length, m
D	distance between left wall and obstacle, m
Re	Reynolds number
T	dimensional temperature, K
u, v	dimensional velocities components in x and y direction, m s^{-1}
U, V	dimensionless velocities components in X and Y direction
U_0	lid velocity
x, y	dimensional Cartesian coordinates, m
X, Y	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity, m^2 s
β	thermal expansion coefficient, K^{-1}
θ	dimensionless temperature
μ	dynamic viscosity, kg m^{-1} s^{-1}
v	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
φ	volume fraction of the nanoparticles
γ	cavity inclination angle

Subscripts

c	cold
eff	effective
f	fluid
h	hot
nf	nanofluid
s	solid particles
w	wall

proved that the rate of heat transfer enhanced with increase in Richardson number and constant Reynolds number.

The effects of Reynolds number, type of nanofluids, size and location of the heater, and the volume fraction of the nanoparticles on mixed convection in a lid-driven, nanofluid-filled square cavity with cold side and top wall and constant heat flux heater on the bottom wall and moving lid are expressed by Mansour et al. [12]. Their results showed that the rate of heat transfer increased with increase in the length of the heater, Reynolds number, and the nanoparticle volume fraction.

Mixed-convection heat transfer in a ventilated cavity with hot obstacle was studied by Abouei et al. [13]. They employed the lattice Boltzmann method to investigate the effect of nanoparticles on mixed convection in a square cavity with inlet and outlet ports and hot obstacle in the center of the cavity. Their result indicated that by adding nanoparticles to the base fluid and increasing the volume fraction of nanoparticles, the heat transfer rate was enhanced at different Richardson numbers and outlet port positions. In other work, Mahmoodi et al. [14] investigated natural convection in a square cavity containing a nanofluid and an adiabatic square block at the center point. They showed that for all Rayleigh numbers with the exception of $Ra = 10^4$, the average Nusselt number increased with an increase in the volume fraction of the nanoparticles. Also, at $Ra = 10^4$ the average Nusselt number decreases with particle loading. Moreover, at low Rayleigh numbers (10^3 and 10^4), the rate of heat transfer decreased when the size of adiabatic square body increased, while at high Rayleigh numbers (10^5 and 10^6), it increased.

The effects of inclination angle in a two lid-driven cavity filled with water and SiO_2 nanofluid on mixed convection was studied by Alinia et al. [15]. The left and right walls were maintained at different constant temperatures while the upper and lower insulated walls were moving lids. The two-phase mixture model had been used to investigate the thermal behaviors of nanofluid at various inclination angles of enclosure ranging from $\theta = -60°$ to $\theta = 60°$, volume fraction from 0% to 8%, Richardson numbers varying from 0.01 to 100, and constant Grashof number 10^4. Their results revealed that addition of nanoparticles enhanced heat transfer in the cavity remarkably and caused significant changes in the flow pattern. Besides, effect of inclination angle was more pronounced at higher Richardson numbers. Abu-Nada et al. [16] investigated the effects of variable properties of Al_2O_3–water and CuO–water nanofluids on the natural convection heat transfer in rectangular enclosures. They observed that at high Rayleigh numbers the viscosity model had a higher impact on the average Nusselt number than the thermal conductivity model. The problem of mixed convection fluid flow and heat transfer of Al_2O_3–water nanofluid with temperature and nanoparticle concentration-dependent thermal conductivity and effective viscosity inside a square cavity was studied numerically by Mazrouei et al. [17]. They compared the Maxwell–Garnett model and the Brinkman model. Also, their results indicated that significant differences existed between the calculated overall heat transfers for the two different combinations of formulas. Moreover, the difference increased with increase in nanoparticle volume fraction.

In this study, new variable property formulations have been employed to analyze the nano-filled lid-driven cavity at various cavity inclination angles. The thermal conductivity and dynamic viscosity of nanofluid inside the cavity are simulated numerically. Also, the effect of changes in the cavity inclination angles, solid volume fraction of Al_2O_3–water nanofluid, and Richardson number are investigated in each case. Furthermore, the rate of heat transfer is studied for different locations and the height of the hot obstacle.

2. Physical model and governing equations

A schematic view of the inclined nano-filled lid-driven cavity considered in this paper is presented in Fig. 1. The height and the width of the square cavity are denoted L. The bottom and horizontal walls are kept insulated, and the right wall is maintained at a low temperature (T_c), whereas the upper moving lid is adiabatic. A rectangular obstacle with a relatively higher temperature (T_h) is located on the bottom wall of the enclosure. The length and the location of the hot obstacle are d and h, respectively. The cavity is filled with a suspension of Al_2O_3 nanoparticles in water such that the nanoparticles and the base fluid are in thermal equilibrium and there is no slip between them.