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Numerical solution of nanofluid mixed convection heat transfer in a lid-driven square cavity with a triangular heat source

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ABSTRACT

This study deals with the numerical solution of steady laminar mixed convection flow in a lid-driven square cavity with a triangular heat source filled with water-based nanofluid. The left and down walls of the enclosure are kept insulated, the top wall moving at constant speed is maintained at constant temperature and the right wall is kept at constant temperature. The governing equations are presented in terms of the stream function-vorticity formulation and are solved numerically with suitable boundary conditions by a second-order accurate finite-difference method. A comparison with other works is done and a good agreement is obtained. A parametric study is done and graphical results are shown and discussed to show the effects of the volume fraction, nanoparticle diameter and different nanoparticle types on the flow and Nusselt number. It is found that suspending the nanoparticles in pure fluid leads to a significant heat transfer increase.

1. Introduction

Heat transfer is an important event in the various industries. Mixed convection in lid-driven cavities is consisting of free convection due to temperature gradient and forced convection due to lid movement. Mixed convection heat transfer in square lid-driven cavity has many applications in the different industries such as cooling of electronic devices and MEMS applications, furnaces, lubrication technologies, high-performance building insulation, multi-shield structures used for nuclear reactors, food processing, glass production, solar power collectors, drying technologies, chemical processing equipment and others [1].

There are many studies concerning the pure fluid flow and heat transfer in the lid-driven cavities. Rahman et al. [2] investigated mixed convection flow in a rectangular ventilated cavity with a heat conducting solid circular cylinder and observed that the average Nusselt number at the heated surface is highest at the lowest values of the aspect ratios. Guo and Sharif [3] investigated mixed convection in rectangular cavities at various aspect ratios with moving isothermal side walls, constant flux heat source on the bottom wall and found that the aspect ratio is an important factor on heat transfer. Varol et al. [4] studied natural convection in triangular enclosures with heater and found that the average Nusselt number increases by increasing the Rayleigh number. Also it was observed that to have a higher heat transfer, higher channel aspect ratios must be chosen and the heater should be located on the center of the bottom wall. Indeed, the peak values of local Nusselt number are observed on the top of the heater. Basak et al. [5] studied mixed convection flows within a square cavity with linearly heated side walls and observed that the average Nusselt number on the bottom wall increases by increasing the Prandtl and Grashof numbers. Sharif [6] investigated laminar mixed convection in shallow inclined rectangular cavities with hot moving lid on top and cooled from the bottom and found that the average Nusselt number increases mildly with cavity inclination angle for forced convection-dominated regime ($Ri = 0.1$), while it increases much more rapidly for natural convection dominated regime ($Ri = 10$).

Due to the importance of nanofluids in heat transfer, some studies of mixed convection heat transfer using nanofluids have been submitted in recent years. Fereidoon et al. [7] studied mixed convection in inclined square lid-driven cavity filled with nanofluid and found that the average Nusselt number increases with an increase in the volume fraction and Richardson number. Shahi et al. [8] studied mixed convection cooling in a square cavity with inlet and outlet ports using a nanofluid and found that the average bulk temperature decreases with an increase in the volume concentration. Sheikhzadeh et al. [9] investigated heat transfer increase in two-sided lid-driven enclosure with Cu–water nanofluid and showed that the Nusselt number increases by increasing the volume fraction. Billah et al. [10] reported a numerical study on the heat transfer performance of nanofluid in lid-driven triangular enclosure and found that the tilt angle is a very important parameter affecting the fluid flow and heat transfer and the highest values of the average Nusselt number occurred at a tilt angle of 0°. Kefayati et al. [11] studied the natural convection in tall enclosures using water/SiO_2 nanofluid and showed that the average Nusselt number increases with increasing the volume fraction for all of the Rayleigh numbers and aspect ratios. Aminossadati and Ghasemi [12] studied natural convection in triangular enclosure using nanofluid with heat source on the bottom wall and

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Nomenclature

a	height of heat source [m]
b	distance of heat source from x coordinate [m]
C_P	specific heat [J kg^{-1} K^{-1}]
D	dimensionless distance of heat source from y coordinate
d	distance of heat source from y coordinate [m]
d_p	diameter of nanoparticle [nm]
H	height of main enclosure [m]
h	Convective heat transfer coefficient [W m^{-2} K^{-1}]
Gr	Grashof number [$g\beta_f L^3 \Delta T/\nu^2{}_f$]
g	Gravitational acceleration [ms^{-2}]
k	thermal conductivity [W m^{-1} K^{-1}]
K_B	Boltzmann constant (1.38×10^{-23})[JK^{-1}]
L	length of the cavity [m]
Nu_m	average Nusselt number along the heat source walls
Pr	Prandtl number
q_w	heat transfer rate [W]
Re	Reynolds number
Ri	Richardson number
S	dimensionless length of left or right wall of heat source $\left[\sqrt{(w/2)^2 + a^2}/L\right]$
T	Temperature [K]
U	dimensionless velocity component
U_0	velocity of enclosure upper wall [ms^{-1}]
u	velocity component in x direction [ms^{-1}]
u_p	Brownian velocity [ms^{-1}]
V	dimensionless velocity component
v	velocity component in y direction [ms^{-1}]
w	length of heat source upper wall [m]
W	dimensionless length of heat source upper wall
x, y	Cartesian coordinates [m]
X, Y	dimensionless coordinates [x/L, y/L]

Greek symbols

α	thermal diffusivity [m^2s^{-1}]
β	thermal expansion coefficient [K^{-1}]v
ΔT	reference temperature difference [$T_H - T_C$]
φ	nanoparticles volume fraction
θ	dimensionless temperature [$(T - T_C)/(T_H - T_C)$]
μ	dynamic viscosity [kg m^{-1} s^{-1}]
ν	kinematic viscosity [m^2 s^{-1}]
ρ	density [kg m^{-3}]
ψ	dimensionless stream function
ω	vorticity [s^{-1}]
Ω	dimensionless vorticity

Subscripts

C	cold wall
f	pure fluid
H	hot wall
m	average
nf	nanofluid
p	nanoparticle

concluded that the average Nusselt number increases with increasing the Rayleigh number and volume fraction. Shekholeslami et al. [13] investigated the nanofluid natural convection heat transfer in a square cavity with curve boundaries using the lattice Boltzmann method. They considered the effects of nanoparticle volume fraction, Rayleigh numbers and inclination angle on nanofluid flow and heat transfer. Kefayati [14] considered the nanofluid MHD natural convection in a square cavity with sinusoidal temperature distribution. Their numerical solution was done using the lattice Boltzmann method and they found that heat transfer decreases by increasing the Hartmann number for various Rayleigh numbers. Khanafer et al. [15] studied buoyancy-driven heat transfer enhancement in a two-dimensional enclosure utilizing nanofluid and found that the heat transfer performance improves with the presence of nanoparticles. Kefayati et al. [16] investigated the natural convection in an open enclosure subjugated to water/copper nanofluid using the lattice Boltzmann method and concluded that the average Nusselt number increases with an increasing Rayleigh number and volume fraction. Mahmoodi [17] investigated mixed convection flows in a square lid-driven cavity with heat source filled by nanofluid and showed that for different ranges of the Richardson numbers, the Nusselt number increases with an increasing volume fraction. Sajjadi et al. [18] reported a lattice Boltzmann simulation of turbulent natural convection in tall enclosures using Cu/water nanofluid and showed that the average Nusselt number increases with increasing the volume fraction for various aspect ratios and Rayleigh numbers. Mansour and Ahmed [19] studied mixed convection flows in a square lid-driven cavity with heat source filled with nanofluid and observed that the average Nusselt number increases by increasing the nanoparticle volume fraction. Santra et al. [20] submitted a study on heat transfer in a differentially heated square cavity using copper–water nanofluid according to the Maxwell-Garnett and Bruggeman model. Their results showed that in the Bruggeman model, heat transfer enhancement is more than the Maxwell-Garnett model. Muthtamilselvan [21] studied the forced convection in a two-sided lid-driven cavity and observed that the average Nusselt number increases by increasing the Darcy number. Kefayati [22] studied the effect of a magnetic field on natural convection in an open cavity subjugated to water/alumina nanofluid using the lattice Boltzmann method and concluded that heat transfer decreases with an increasing Hartmann number for various Rayleigh numbers and volume fraction. Teamah et al. [23] studied mixed convection heat transfer and fluid flow in a cubical lid-driven cavity. It was found that the Nusselt number increases as the Richardson number decreases due to the speed of the top lid. Abbasian et al. [24] investigated mixed convection flows in a square double lid-driven cavity using nanofluid and found that the heat transfer increases by increasing the volume fraction and Richardson number. Abu-Nada and Chamkha [25] studied mixed convection flow in a lid-driven inclined square enclosure filled with a nanofluid. It was found that heat transfer increases with the presence of the nanoparticles. Kefayati [26] studied the natural convection in nanofluid-filled 2D long enclosures in the presence of a magnetic source for inclination angles 0, 30, 60 and 90° and showed that the heat transfer decreases with an increasing Hartmann number for various Rayleigh numbers and aspect ratios. Chamkha and Abu-Nada [27] investigated mixed convection flow in single-lid and double-lid driven square cavities filled with nanofluid and found that the average Nusselt number increases by raising the volume fraction. Oztop and Abu-Nada [28] studied heat transfer and fluid flow due to buoyancy forces in a heated enclosure using nanofluids with various kinds of nanoparticles. They concluded that using the nanofluid results in heat transfer enhancement. Ogut [29] investigated the natural convection of water-based nanofluids in an inclined enclosure with a heat source. Abu-Nada et al. [30] investigated the effect of nanofluid variable properties on natural convection in enclosures. Ghasemi and Aminossadati [31] considered periodic natural convection in a nanofluid-filled enclosure with oscillating heat flux. Abu-Nada and Oztop [32] studied the effects of inclination angle on natural convection in enclosures filled with Cu–water nanofluids. Rahmannezhad et al. [33] studied the nanofluid mixed convection heat transfer in a lid-driven square cavity under a magnetic field effect. They used stencil adaptive method for their numerical study and observed that the heat transfer rate increases with an increase in Reynolds number and decreases with an increasing