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Effects of inclination angle on mixed convective nanofluid flow in a double lid-driven cavity with discrete heat sources

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ABSTRACT

In the present study, numerical simulations are performed to examine the effect of inclination angle on the heat transfer of Al_2O_3–water nanofluid for mixed convection flows in a partially heated double lid driven inclined cavity. At the lower wall of the cavity, two heat sources are fixed with the condition that the remaining part of the bottom wall is kept insulated. Top wall and vertically moving walls are maintained at constant cold temperature. Buoyant force is responsible for the flow along with two moving vertical walls. The governing equations are discretized with the help of finite element method in space and the Crank–Nicolson in time. For the spatial discretization, nonconforming Stokes element $\widetilde{Q}_1/Q_0$ of 2nd order accuracy for velocity, temperature and 1st order accuracy for pressure is utilized. The discretized nonlinear systems of equations are treated by using the Newton method and the associated linear subproblems are solved using Gaussian elimination method in each time level. Numerical results are presented and analyzed by means of streamlines, isotherms, tables and some useful plots. Impact of emerging parameters on the flow, in specific ranges such as Reynolds number ($1 \leqslant Re \leqslant 100$), Richardson number ($0.01 \leqslant Ri \leqslant 10$), nanoparticle volume fraction ($0 \leqslant \phi \leqslant 0.04$) as well as inclination angle of cavity ($0^\circ \leqslant \gamma \leqslant 45^\circ$) are investigated and findings are exactly of the same order as that of the previously performed analysis in the literature. Calculations of average Nusselt number, average temperature, average entropy generation due to heat transfer and fluid friction and kinetic energy are the main focus of our study.

1. Introduction

Human being has intense curiosity about fluid flow for centuries. From the ebb and flow of the sea and raging rivers to small ponds and controlled cooling mechanisms, the study, understanding and prediction of fluid flow patterns has a certain attraction to it. In the fifteenth century Leonardo Da Vinci responded to this attraction by observing and recording the phenomenon that we recognize today as a fundamental law of physics; "the conservation of mass", in various flowing rivers. In this regard, he was the first who took the task of making sketches of various flow fields. From the time of Da Vinci there has been a remarkable change in the studies of fluid dynamics.

Heat transfer and mixed convection in lid-driven cavities is one of the most extensively studied problem by researchers and industrialists due to its growing practical applications. Furthermore, to accelerate the heat conductivity of base fluids like water, ethylene glycol, oil, etc., modern techniques have been adopted. First of all, Choi [1] has contributed in this field by introducing nanofluids. Later on, many researchers have utilized nanoparticles to study heat transfer mechanism [2–12]. In the last two decades, numerous scientists have participated a lot to solve the heat transfer problems in cavities filled with nanofluids experimentally, analytically as well as numerically. Sheikholeslami et al. [13] have conducted numerical study on MHD free convection of Al_2O_3–water nanofluid considering thermal radiation. It was observed that Nusselt number enhanced with Rayleigh number, nanoparticles volume fraction and radiation parameter while it decreased with an increase in Hartmann number and viscous dissipation parameter. In another study, Sheikholeslami [14] utilized Ko–Kleinstreuer–Li (KKL) correlation for simulation of nanofluid flow and heat transfer in a permeable channel. KKL correlation was applied to calculate the effective thermal conductivity and viscosity of nanofluid. Sheikholeslami and Rashidi [15] considered influence of space dependent magnetic field on free convection of Fe_3O_4–water nanofluid. Sheikholeslami et al. [16] have investigated forced

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Nomenclature

e	heat source length (m)
C_p	specific heat (J kg^{-1} K^{-1})
x, y	dimensional space coordinates (m)
X, Y	dimensionless space coordinates
g	gravitational acceleration (m s^{-2})
Gr	Grashof number, $\beta g \Delta T L^3/\nu_f^2$
k	thermal conductivity (W m^{-1} K^{-1})
L	length of cavity (m)
$Nu_{avg,s1}$	average Nusselt number of left heater
$Nu_{avg,s2}$	average Nusselt number of right heater
Nu	Nusselt number (local)
p	pressure (N m^{-2})
P	dimensionless pressure
Pr	Prandtl number, ν_f/α_f
q	heat flux (W m^{-2})
Re	Reynolds number, $V_w L/\nu_f$
Ri	Richardson number, Gr/Re^2
S_T	dimensionless total entropy
s	dimensional entropy (J/K)
t	time (s)
T	temperature (K)
ΔT	temperature gradient
u, v	dimensional velocity components (m s^{-1})
U, V	dimensionless velocity components
V_w	lid velocity

Greek symbols

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

Subscripts

c	cold
f	fluid
h	hot
nf	nanofluid
s	nanoparticles
$S1$	left heater
$S2$	right heater

convection heat transfer in a semi annulus under the influence of a variable magnetic field.

Mixed convection in cavities has been studied by many researchers due to its numerous applications including cooling of electronic devices, heat exchangers, chemical reactors, solar collectors, heating and cooling of buildings. Sourtiji et al. [17] examined mixed convective heat transfer of Al_2O_3–water nanofluid in a ventilated cavity. It is observed that the average Nusselt number increases with an increase in the values of Reynolds number, Richardson number and nanoparticle volume fraction. Teamah et al. [18] have investigated laminar mixed convection in shallow inclined cavities using numerical simulation. They showed the effects of inclination of the cavity on the flow, thermal and mass fields for inclination angles ranging from 0° to 30°. Ahmed et al. [19] have examined mixed convection from a discrete heat source in enclosures with two adjacent moving walls and filled with micropolar nanofluid. It is noticed that average Nusselt number along the heat source decreases as the heat source length increases while it increases when the solid volume fraction increases. Sheremet and Pop [20] have analysed mixed convection in a lid-driven square cavity filled by a nanofluid using Buongiorno's mathematical model. They found that Richardson number and the moving parameter play a dominant role in the transfer of heat and mass and other flow characteristics within a cavity. More studies on mixed convection in cavity can be found in [21–26].

Das and Tiwari [27] numerically examined the problem of mixed convection of differentially heated cavity saturated with Cu–water nanofluid. It was observed that the average Nusselt number increases significantly with the augmentation of nanoparticles volume fraction keeping Richardson number at unity. Using finite volume method, Subdani et al. [28] investigated the flow and heat transfer in a square cavity filled with Al_2O_3–water nanofluid, with a heat source on the bottom wall. Both the left and right walls of the cavity moving downward with a constant velocity are kept at low temperature. For constant Rayleigh number and heat source placed in the middle of the bottom wall, it was noticed that heat transfer enhanced with increasing Reynolds number. Nguyen et al. [29] and Minsta et al. [30] performed several experiments under wide range of temperatures to study the effect of nanoparticle concentration and size on the nanofluid viscosity. A drastic decrease in viscosity was observed with increase in temperature, specifically for high concentration of nanoparticles. Lid-driven enclosure filled with copper–water nanofluid was investigated numerically for the mixed convection by Muthtamilselvan et al. [31] and found that fluid flow and heat transfer were affected both by aspect ratio of the cavity and nanoparticle volume fraction. The same nanofluid was studied numerically for natural convection by Ho et al. [32] in a two-dimensional cavity. Their study revealed that transfer of heat in a cavity was enhanced due to augment in concentration of copper–water nanoparticles at some fixed Grashof number. Free convection in a cavity saturated with Al_2O_3–water nanofluid using numerical simulation was performed by Khanafer et al. [33]. It was seen that heat transfer may increase or decrease due to the model that was used for viscosity and thermal conductivity of the nanofluid. Talebi et al. [34] conducted numerical study of square lid driven cavity filled with copper–water nanofluid in order to elaborate mixed convection. During this procedure only vertical walls of the cavity were differentially heated keeping top and bottom walls insulated. For given Reynolds and Rayleigh numbers, an increase in average Nusselt number was observed with an increase in nanoparticles concentration. Arani et al. [35] investigated mixed convection flow problem of Cu–water nanofluid inside a lid driven square cavity using adiabatic top and bottom walls and sinusoidal heating on side walls. A decrease in Richardson number with increase in volume fraction of nanoparticles was observed however there was an increase in heat transfer rate with increase in Richardson number, keeping Reynolds number constant. Mahmoudi et al. [36] numerically studied mixed convection problem in a vented square cavity filled with Cu–water nanofluid. The special criteria they adopted were consideration of four different placement configurations of the inlet and outlet ports to observe the effect of inlet and outlet location. It was noticed that Re, Ri and ϕ have significant effect on the numerical characteristic of the flow field. Furthermore, they noticed that

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