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Full Length Article

A comparative study of mixed convection and its effect on partially active thermal zones in a two sided lid-driven cavity filled with nanofluid

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ABSTRACT

In the present study, a two sided lid-driven mixed convection nanofluid flow with discrete heat sources have been numerically investigated. A two dimensional computational visualization technique is used to study the flow behavior using four different cases; depending on the direction of moving vertical walls with fixed upper and lower walls. Two discrete heat sources of equal lengths are taken on the lower wall and the rest of it is kept insulated. The other walls are kept at constant low temperature. The effect of flow governing parameters such as Reynolds number $1 \leqslant Re \leqslant 100$, Richardson number $0.1 \leqslant Ri \leqslant 10$ and solid volume fraction $0.0 \leqslant \phi \leqslant 0.2$ with Prandtl number $Pr = 6.2$ is studied to understand the fluid flow pattern and the heat transfer effect using isotherms and average Nusselt number.

1. Introduction

Nowadays a study of mixed convection and heat transfer in enclosures is invariably encountered in many industrial heating or cooling applications including cooling of electronic devices, solar collectors, float glass production, drying technologies, chemical processing equipments, etc. and is of great interest for researchers. This type of fluid flow and heat transfer represents a complicated flow phenomena due to the movement of one or more walls which involves forced convection and the temperature difference causing secondary buoyancy driven flow. Fluid flow and heat transfer in square or rectangular cavities driven by shear and buoyancy effects have been studied extensively. In the application point of view an enormous amount of heat needs to be emitted from a considerably small surface, the coolant should have more effectual heat transfer properties. But due to the low thermal conductivity the conventional heat transfer fluids such as water, ethylene glycol mixture has foremost limitation in enhancing the heat transfer performance and the compactness of many industrial and engineering electronic devices. Heat transfer capabilities of the conventional fluids can be enhanced effectively using nanofluids, owing to their high thermal conductivity and better stability properties. To improve thermal conductivity, nano-scale metallic particles are suspended within the fluid. The resulting mixture is referred to as nanofluid that possesses a significant larger thermal conductivity compared to the conventional fluids [1].

In the last several years, an extensive numerical, analytical and experimental study has been done on the problem of natural and mixed convection heat transfer in cavities filled with nanofluid. The natural convection problem in a differentially heated square cavity is first numerically studied by Khanafer et al. [2], with the consideration of dispersion effect. In this work, a better model for nanofluids is developed by determining the dispersion coefficient experimentally. The effect of dispersion element in a nanofluid is discussed by Khaled and Vafai [3]. The volume fraction distribution is governed by the properties of dispersive elements combined with the flow parameters such as Reynolds number and Prandtl number for optimum heat transfer. In the case of uniform flow the maximum Nusselt number distribution is found to be 21% higher than that of the dispersed distributed element flow. Maiga et al. [4] numerically studied nanofluids in a uniformly heated tube for laminar and turbulent flow. They tried to correlate the numerical results with the experimental data and observed that for increase of Reynolds number, the heat transfer effect is increasing due to the presence of nanoparticles and becomes more important in the case of turbulent flow regimes. Tiwari and Das [5] numerically simulated the problem of mixed convection in two

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Nomenclature

C_p	specific heat capacity (J/K)
g	gravitational acceleration (m/s^2)
k	thermal conductivity (W/mK)
Pr	Prandtl number
Re	Reynolds number
Gr	Grashof Number $\left(\frac{g\beta\Delta(T_H-T_C)L^3}{\nu^2}\right)$
Ri	Richardson number
P	dimensionless pressure
p	pressure ($N\ m^{-2}$)
T	temperature (K)
θ	dimensionless temperature
t	time (s)
x, y	Cartesian coordinates (m)
X, Y	dimensionless Cartesian coordinates
u, v	components of velocity in x and y directions (m/s)
U, V	dimensionless of velocity components in X and Y directions
L	width of cavity (m)
V_l	left wall velocity
V_r	right wall velocity
Nu	Nusselt number
Nu_m	average Nusselt number
V_r	right wall velocity

Greek letters

τ	dimensionless time
ψ	stream function
α	thermal diffusivity ($k/(\rho C_p)$) (m^2/s)
β	coefficient of volume expansion (K^{-1})
ϕ	solid volume fraction
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)

Subscripts

f	fluid
m	average
nf	nanofluid
o	reference state
s	solid
C	cold
H	hot

sided lid-driven differentially heated square cavity filled with copper–water nanofluid. They observed that the average Nusselt number increased substantially with the increase of the volume fraction of the nanoparticles, for a fixed Richardson number. The effect of nanoparticle concentration and the viscosity effects are found experimentally by Nguyen et al. [6] and Angue Minsta et al. [7] for various temperature values. It is found that on increment of concentration of the nanoparticles, the viscosity and temperature decrease sharply. Recently, Selimefendigil and Oztop [13] studied natural convection of nanofluid flow with different shaped obstacles including diamond, square and circular and discussed the affect of solid volume fraction and obstacle shapes on thermal patterns. In another study, Selimefendigil et al. [14] investigated the heat transfer and fluid flow in the presence of magnetic dipole in a partially heated cavity. They observed that the averaged heat transfer along the heat source is found to be minimum when magnetic dipole source is placed at the middle of the vertical wall.

Muthtamilselvan et al. [8] numerically investigated the mixed convection and heat transfer in a lid-driven enclosure filled with copper–water nanofluid, and observed that the heat transfer has a large effect on solid volume fraction and aspect ratio of the enclosure. Abu-Nada et al. [9] studied the heat transfer effect in a differentially heated enclosure using variable properties of CuO–water and Al_2O_3–water nanofluids due to natural convection. They found that for high Rayleigh number variation of average heat transfer is less sensitive in the case of thermal conductivity model than that of the viscosity model. Abbasian et al. [10] numerically studied the mixed convection with Cu–water nanofluid in a lid-driven cavity, where the horizontal walls are kept insulated and vertical walls are heated sinusoidally. They observed that with a decrease of Richardson number and an increase of volume fraction of nanoparticles there is an increase of heat transfer. Also, it is found that for a constant Reynolds number, the rate of heat transfer increases with the increase of Richardson number. Talebi et al. [11] numerically studied the problem of mixed convection flow of copper–water nanofluid in a lid-driven cavity with differentially heated vertical walls and shown the increment of average Nusselt number with the solid volume fraction over constant Reynolds and Rayleigh numbers. Mahmoudi et al. [12] studied the problem of mixed convection in a vented square cavity filled with copperwater nanofluid. It is observed that for higher Reynolds and Richardson number the presence of nanoparticles have more effect on increasing the heat transfer performance. A extensive study of mixed convection has been conducted by Selimefendigil et al. [15–23] for various geometries.

A finite volume approach is used by Sebdani et al. [25] to investigate the fluid flow and heat transfer in a square cavity filled with Al_2O_3–water nanofluid with a bottom wall heated source. Both the vertical walls of the cavity are maintained at cold temperature and moving downward with constant velocity whereas the horizontal walls are taken to be adiabatic and fixed. On addition of nanoparticles it is observed that heat transfer effect is enhanced with increase of Reynolds number, for a fixed Rayleigh number. Garoosi et al. [26,27] applied finite volume approach based on SIMPLE algorithm for simulation of mixed convection of nanofluid and concluded that at low Richardson number the nanoparticle distribution remains almost uniform. Moumni et al. [31] studied the heat transfer characteristics of various water-based nanofluids in a two-sided square lid driven cavity, using a pair of discrete heat sources with different locations at the bottom wall of the cavity. The heat transfer rate increases with an increase in Reynolds number, Richardson number and solid volume fraction, and rate of heat transfer increment is found to be higher in the case of Cu–water and Ag–water nanofluids as compared to Al_2O_3–water and TiO_2–water nanofluids.

Generally, two approaches are employed for the numerical study of the velocity field, heat transfer and temperature distribution in nanofluids namely; single phase and two phase models. In the former approach, it is assumed that the nanoparticles and the continuum phase are in thermal equilibrium and have the same velocity. Many researchers oppose the validity of single phase models as the slip velocity between the base fluid and nanoparticles may not be zero. Therefore, they encouraged the two phase model which is a more complex approach. For nanoparticles having higher thermal conductivity such as Cu ($K = 400$) which have also been used in the present study, Garoosi et al. [24,32] validated the use of a single-phase model, showing that for the nanoparticles with higher thermal conductivity the thermophoretic effect is negligible. Moreover, in another study Garoosi et al. [33] stated that for a low Richardson number the effect of drag, gravity and buoyancy

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