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Mixed convection heat transfer in a lid-driven trapezoidal enclosure filled with nanofluids☆

Ali Khaleel Kareem [a,b,*], H.A. Mohammed [c], Ahmed Kadhim Hussein [d], Shian Gao [a]

[a] Department of Engineering, University of Leicester, Leicester LE1 7RH, United Kingdom
[b] Engineering Department, University of Thi-Qar, Nassiriya, Iraq
[c] Department of Thermofluids, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia
[d] Department of Mechanical Engineering, College of Engineering, Babylon University, Babylon City, Iraq

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ABSTRACT

Mixed convection heat transfer in a two-dimensional trapezoidal lid-driven enclosure filled with nanofluids heated from below is numerically studied. The governing equations for both fluid flow and heat transfer are solved by using the finite volume method (FVM). The bottom wall of the enclosure is heated while the upper wall is cooled at lower temperature and the other two sidewalls are adiabatic. Four types of nanofluids (Al_2O_3, CuO, SiO_2, and TiO_2 with pure water) with nanoparticle volume fraction (ϕ) in the range of 1–4% and nanoparticle diameter in the range 25–70 nm were used. This investigation covers Richardson number and Reynolds number in the ranges of 0.1–10 and 100–1200, respectively. The trapezoidal lid-driven enclosure was studied for different rotational angles (Φ) in the range of 30°–60°, different inclination sidewalls angles (γ) in the range of 30°–60° and various aspect ratios (A) ranged from 0.5 to 2. This investigation is also examined the opposing and aiding flow conditions. The results show that all types of nanofluids have higher Nusselt number compared with pure water. It is found that SiO_2–water has the highest Nusselt number followed by Al_2O_3–water, TiO_2–water, and CuO–water. The Nusselt number increases as the volume fraction increases but it decreases as the diameter of the nanoparticles of nanofluids increases. The Nusselt number increases with the decrease of rotational angle and inclination angle from 30° to 60° and with the increase of aspect ratio. The results of flow direction show that the aiding flow gives higher Nusselt number than the opposing flow.

1. Introduction

Mixed convection heat transfer in a lid-driven enclosure had been a subject of interest in many research studies. Mixed convection flow in lid-driven cavities or enclosures occurs as a result of two competing mechanisms. The first one is due to shear flow which caused by the movement of one of the walls of the cavity while the second one is due to buoyancy flow produced by non-homogeneity of the cavity thermal boundaries. Understanding these mechanisms is of a great significance from technical and engineering standpoints. There were many geometric shapes of the lid-driven enclosures that had been studied in the past decades considering various combinations of the imposed temperature gradients and cavity configurations. The common geometric shapes are circle, square, rectangular and triangular. However, little studies on a two-dimensional trapezoidal lid-driven enclosure have been carried out to investigate the heat transfer enhancement. These types of lid-driven enclosures are used in many engineering applications such as food processing, lubrication technologies, thermal-hydraulics of nuclear reactors, electronic cooling, crystal growth, flow and heat transfer in solar ponds, dynamics of lakes, and float glass production [1].

The mixed convection heat transfer in trapezoidal lid-driven enclosures occurred in many industrial devices using conventional fluids such as water, propylene glycol or ethylene glycol. However, the low thermal conductivity has always been the primary limitation in the development of energy-efficient heat transfer fluids, performance and compactness of many engineering equipment such as electronic devices and heat exchanger. In order to overcome this limitation, there is a strong motivation to improve advanced heat transfer fluids with substantially higher thermal conductivity. Hence, in recent years, nanofluids have attracted more attention for cooling in various industrial applications. This new generation of heat transfer fluids consists of suspended nanoparticles, which have a better suspension stability compared to millimeter or micrometer size ones. Various types of powders such as polymeric particles, non-metallic, and metallic can be added into base fluids to form slurries. Thus, the heat transfer characteristics will be enhanced by using class of fluids called nanofluids. The convective heat transfer

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* Corresponding author at: Department of Engineering, University of Leicester, Leicester LE1 7RH, United Kingdom.
E-mail addresses: akkak2@le.ac.uk, alikhaleel17@yahoo.com (A.K. Kareem), Hussein.dash@yahoo.com (H.A. Mohammed).

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Nomenclature

A	Aspect ratio, H/W
C_p	Specific heat at constant pressure (J/kg K)
d_p	Diameter of nanofluid particles (nm)
G	Gravitational acceleration (m/s^2)
Gr	Grashof number ($g\,\beta\Delta TW^3/\nu^2$)
H	Convective heat transfer coefficient (W/m^2 K)
K	Thermal conductivity of the fluid (W/m K)
Nu	Nusselt number (hW/k)
Pr	Prandtl number (ν/α)
q"	Heat flux (W/m^2)
R	Length of the inclined sidewalls (m)
Ra	Rayleigh number ($g\,\beta\Delta TH^3/\alpha\nu$)
Re	Reynolds number (uW/ν)
Ri	Richardson number (Gr/Re^2)
T	Temperature of the fluid (K)
U	Velocity component at x-direction (m/s)
U	Dimensionless velocity component at x-direction (u/U_o)
V	Velocity component at y-direction (m/s)
V	Dimensionless velocity component at y-direction (v/U_o)
W	Length of the cavity (m)
X	Distance along the x-coordinate, m
X	Distance along the non-dimensional x-coordinate (x/W)
Y	Distance along the non-dimensional y-coordinate (y/W)

Greek symbols

A	thermal diffusivity of the fluid (m^2/s)
B	volumetric coefficient of thermal expansion (1/K)
Γ	inclination angle of the sidewalls of the cavity
Θ	dimensionless temperature ($(T_H - T_C)/\Delta T$)
μ	dynamic viscosity of the fluid (Pa s)
N	kinematic viscosity of the fluid (m^2/s)
P	density of the fluid (kg/m^2)
Φ	rotational angle of the cavity
ϕ	volume fraction
E	nondimensional length of the heat source (l/L)
φ	volume fraction (%)

Subscripts

av	average value
bf	base fluid
C	cold temperature
dp	nanoparticle diameter
f	fluid
H	hot temperature
nf	nanofluid
p	nanoparticles
W	wall

characteristics of nanofluids depend on the thermophysical properties of the base fluid and the ultrafine particles, the flow structure, the volume fraction of suspended particles, the dimensions and the shape of these particles. Because the prospect of nanofluid is very promising, many studies on convective heat transfer using nanofluid have been reported in the recent years [2–5].

Understanding the phenomena of the recirculating flow within the cavity is treated as one of the fundamental studies to fluid-dynamics researchers and hence has been pursued extensively. Abu-Nada and Chamkha [1] studied numerically steady laminar mixed convection flow in a lid-driven inclined square enclosure filled with Al_2O_3–water nanofluid. It was concluded that the heat transfer mechanisms and the flow characteristics inside the cavity were strongly dependent on the Richardson number. The mixed convection heat transfer in a two-dimensional enclosure trapezoidal cavity filled with air was studied numerically by Mamun, et al. [6]. It was observed that the average Nusselt number increases with increasing the aspect ratio for all rotational angles. The average Nusselt number was also sensitive to rotational angle. Yang [7] studied numerically laminar mixed convection of air in a shear-and buoyancy-driven cavity having a locally heated lower wall and moving cooled sidewalls. It was observed that the flow and temperature fields were symmetrical about the midlength of the enclosure because of the symmetry of the boundary conditions in the vertical direction.

The mixed convection heat transfer characteristics in a lid-driven 2-D square cavity with various Richardson and Prandtl numbers were studied by Cheng [8]. It was concluded that the heat transfer increases continuously with increasing both Re and Gr numbers for Ri = 0.01 but it was not for 0.5 ≤ Ri ≤ 100. Basak, et al. [9] studied numerically mixed convection flows in a lid-driven square cavity filled with porous medium by using penalty finite element analysis. It was concluded that the average Nusselt numbers were almost invariant with Gr number for Pr = 0.7 with all Da number for linearly heated side walls or cooled right wall. Basak, et al. [10] performed a numerical analysis to study the influence of linearly heated side walls or cooled right wall on mixed convection lid-driven flows in a square cavity. It was shown that (Nu_b) was equal to zero on the left edge of the bottom wall but it increases towards the right edge of the bottom wall in the cooled right wall case.

Basak, et al. [11] investigated the influence of uniform and non-uniform heating of bottom wall on mixed convection lid-driven flows in a square cavity using finite element method. It was concluded that the heat transfer rate for uniform heating was always more as compared to the non-uniform heating. Pingan, et al. [12] employed numerical method to investigate 2D laminar natural convection in a square cavity containing a circular pipe. It was concluded that the original distribution of temperature in square cavity was influenced by the quantity of heat transfer through the pipe surface. Kandaswamy, et al. [13] studied numerically the buoyancy driven convection in a square cavity induced by two mutually orthogonal and arbitrarily located baffles. It was concluded that the net heat transfer in the cavity can be enhanced by increasing the vertical baffle length regardless of its position.

Cianfrini, et al. [14] studied numerically natural convection in air-filled, tilted square enclosures. It was concluded that for a sufficiently wide range of γ around 135° the overall amount of heat transferred along the x-direction across the cavity is larger than that corresponding to the untilted case. Al-Amiri, et al. [15] studied numerically steady mixed convection in a square lid-driven cavity under the combined buoyancy effects of thermal and mass diffusion. It was found that Lewis number has an insignificant effect on the isotherms and streamlines for small Richardson numbers. Ho, et al. [16] studied numerically the effects due to uncertainties in effective dynamic viscosity and thermal conductivity of the Al_2O_3–water nanofluid on laminar natural convection heat transfer in a square enclosure. It was observed that the uncertainties associated with different formulas adopted for the effective thermal conductivity and dynamic viscosity of the nanofluid have a strong bearing on the natural convection heat transfer characteristics in the enclosure.

Basak, et al. [17] studied numerically the steady laminar natural convection flow in a square cavity with uniformly and non-uniformly heated bottom wall using finite element method. The local Nusselt number at the bottom wall was least at the center for uniform heating and there were two minimum heat transfer zones at the center and the corner points for non-uniform heating. Moallemi and Jang [18] investigated numerically the flow and heat transfer in a lid driven square cavity. It was found that the influence of buoyancy force on the flow and heat transfer in the cavity is more pronounced for higher values of Pr number, if Re and Gr numbers are kept constant. Reima, et al. [19] studied numerically the flow of a viscous thermally-stratified fluid in a square container. It was observed that when the frequency parameter (ω′) is