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Comparison of flow and heat transfer characteristics in a lid-driven cavity between flexible and modified geometry of a heated bottom wall

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ABSTRACT

A numerical investigation of steady laminar mixed convection flow and heat transfer in a lid driven cavity with a flexible heated bottom surface is investigated. Moreover, the heated bottom wall is characterized by rectangular and sinusoidal wavy profiles for a rigid wall analysis. A stable thermal stratification configuration was considered by imposing a vertical temperature gradient while the vertical walls were considered to be insulated. The transport equations are solved using a finite element formulation based on the Galerkin method of weighted residuals. For a flexible bottom wall case, a fully coupled fluid–structure interaction (FSI) analysis is utilized and the fluid domain is described by an Arbitrary-Lagrangian–Eulerian (ALE) formulation that is fully coupled to the structure domain. The results of this investigation revealed that the heat transfer enhancement is noticed in all the studied cases compared with a flat bottom wall case. Furthermore, the contribution of the forced convection heat transfer to that offered by natural convection heat transfer has a profound effect on the behavior of the flexible wall as well as the momentum and energy transport processes within the cavity. Flexible bottom wall case is found to exhibit significant heat transfer enhancement (61.4%) compared with a flat bottom wall case at Grashof number of 10^4 and $Re < 400$. However, rectangular wavy profile exhibits higher heat transfer enhancement (maximum: 14.4% at $Re = 200$) than sinusoidal wavy profile (9.6% at $Re = 200$) and flexible bottom wall (12.3% at $Re = 200$) at a low Grashof number of 10^2. This investigation shows the benefits of using flexible walls when augmentation of heat transfer is sought at high Grashof numbers.

1. Introduction

Mixed convection flow and heat transfer characteristics in a lid-driven cavity have received a considerable attention in the past decades [1–7]. This interest stems from its importance in wide industrial and engineering applications such as cooling of electronic devices, drying technologies, lubrication technologies, food processing, flow and heat transfer in solar ponds and thermal-hydraulics of nuclear reactors [8–12]. Giving the popularity of the lid-driven cavity problem, it is also widely used as a benchmark tool for the evaluation of different numerical schemes [13–16]. Flow and heat transfer from irregular surfaces are often encountered in many engineering applications to enhance heat transfer such as micro-electronic devices, electric machinery, cooling system of microelectronic devices, cooling of electrical components [17], and flat-plate solar collectors and flat-plate condensers in refrigerators [18].

It is worth noting that most of the previous studies on enclosures with a form of wavy surfaces were concerned with natural convection. For example, Adjlout et al. [19] studied numerically the effect of a hot wavy wall in an inclined differentially heated square cavity for different inclination angles, amplitudes and Rayleigh numbers while the Prandtl number was kept constant. Their results concluded that the wavy wall affected the flow and heat transfer rate in the enclosure. Mahmud et al. [20] investigated numerically flow and heat transfer characteristics inside an isothermal vertical wavy-walled enclosure bounded by two adiabatic straight walls. Simulation was carried out for a range of wave ratio (defined by amplitude/average width) 0.0–0.4, aspect ratio (defined by height/average width) 1.0–2.0, Grashof number $Gr = 10^0–10^7$ for a fluid having Prandtl number 0.7. Das and Mahmud [21] studied the hydrodynamic and thermal behaviors of fluid inside two wavy and two straight walls enclosure. The top and the bottom walls were wavy and kept isothermal while the vertical straight walls were considered adiabatic. Results were presented

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Nomenclature

A	dimensionless amplitude of the wavy surface
c_p	specific heat
$\ddot{\mathbf{d}}_s$	local acceleration of the solid region
$\mathbf{d_f}$	displacement vector of the fluid domain
$\mathbf{d_s}$	displacement vector of the solid domain
E	Young's modulus
$\mathbf{f}$	fluid body force per unit volume
$\mathbf{f_s}$	solid externally applied body force vector
g	gravitational acceleration
Gr	Grashof number, $Gr = g\beta(T_\mathrm{H} - T_\mathrm{C})H^3/\nu^2$
H	side length of the enclosure
h	thickness of the flexible bottom wall
k	thermal conductivity
Nu	Nusselt number
$\overline{Nu}$	average Nusselt number
$\overline{Nu}_0$	average Nusselt number of a flat wall case
p	pressure
Pr	Prandtl number, ν/α
Re	Reynolds number, U_0H/ν
Ri	Richardson number, Gr/Re^2
S	total length of the wall
S_i	interface of the fluid and solid domains
T	temperature
$\mathbf{u}$	fluid velocity vector
$\mathbf{w}$	moving coordinate velocity
u, v	velocity components along x- and y-axes
U, V	dimensionless velocity components
U_0	sliding top wall velocity
x, y	Cartesian coordinates
X, Y	dimensionless coordinates

Greek symbols

α	thermal diffusivity
β	volumetric expansion coefficient
λ	number of undulation.
ν	fluid kinematic viscosity
θ	dimensionless temperature, $(T - T_H)/(T_H - T_C)$
ρ	fluid density
ϑ	Poisson's ratio
$\boldsymbol{\sigma}$	stress tensor

Subscript

f	fluid domain
s	solid domain

in the form of local and global Nusselt number distributions for a selected range of Grashof number (10^3–10^7). They reported that the amplitude-wavelength ratio affected local heat transfer rate, but it had no significant influence on average heat transfer rate. Dalal and Das [22] studied numerically natural convection inside a two-dimensional cavity with a wavy right vertical wall. The bottom wall was heated by a spatially varying temperature and other three walls were kept at constant lower temperature. Results were presented in the form of local and average Nusselt number distribution for a selected range of Rayleigh number (10^0–10^6). Their results showed that the presence of undulation in the right wall affected local heat transfer rate and flow field as well as thermal field.

Our literature survey showed that mixed convection flow and heat transfer in enclosures having irregular walls have received little attention. Al-Amiri et al. [17] studied mixed convection heat transfer in a lid-driven cavity with a sinusoidal wavy bottom surface for various Richardson number, number of wavy surface, and the amplitude of the wavy surface. Their results illustrated that the average Nusselt number increased with an increase in both the amplitude of the wavy surface and Reynolds number. Optimum heat transfer was designated with two undulations while subjected to low Richardson numbers. Nasrin and Parvin [23] studied numerically mixed convection flow and heat transfer in a lid-driven cavity with sinusoidal wavy bottom surface in presence of transverse magnetic field for various pertinent parameters. The enclosure is saturated with electrically conducting fluid. The cavity vertical walls were insulated while the wavy bottom surface was maintained at a uniform temperature higher than the top lid. Their results illustrated that the average Nusselt number at the heated surface increased with an increase of the number of waves as well as the Reynolds number, while decreased with increasing Hartmann number. A numerical study was performed by Mekroussi et al. [24] to analyze mixed convection flow and heat transfer in a lid-driven cavity with sinusoidal wavy bottom surface. The cavity vertical walls were insulated while the wavy bottom surface was maintained at a uniform temperature higher than the top lid. The numerical tests were carried out for various inclination angles ranging to 0° from 180° and number of undulation varied from 4 to 6, while the Prandtl number was kept constant $Pr = 0.71$. The results of this investigation illustrated that the average Nusselt number at the heated surface increased with an increase of the number of undulations as well as the angle of inclination. Cho et al. [25] investigated numerically mixed convection heat transfer characteristics of water-based nanofluids confined within a lid-driven cavity. In modeling the cavity, it was assumed that the left and right walls have a wavy surface, while the upper and lower walls were both flat. The results of this investigation showed that for a given nanofluid, the mean Nusselt number could be optimized via an appropriate tuning of the wavy surface geometry parameters. Recently, Al-Amiri and Khanafer [26] investigated numerically laminar mixed convection heat transfer in a lid-driven cavity with a flexible bottom surface. Their results revealed that the elasticity of the bottom surface played a significant role on the heat transfer enhancement.

One can note from above that no investigations have discussed in details the advantages of using flexible wall on the heat transfer enhancement compared to modified geometries. Therefore, the main objective of this investigation is to compare flow and heat transfer characteristics in a lid-driven cavity between flexible and modified geometry of the heated bottom wall (rectangular and sinusoidal wavy profiles) for various pertinent parameters.

2. Mathematical formulation

A two-dimensional square cavity is considered in the present study with the physical dimensions shown in Fig. 1. The cavity side length is considered to be H while the thickness of the flexible bottom wall was set to be $0.002H$ of the side length. The working fluid is assumed to be an incompressible Newtonian fluid with a Prandtl number of 0.71 that is operating under steady-state laminar heat transfer regime. Furthermore, the thermophysical properties of the working fluid are taken to be constant except for the density variation, which is modeled according to the Boussinesq approximation. The mechanically induced lid motion (top wall) is