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Fluid–structure interaction analysis of mixed convection heat transfer in a lid-driven cavity with a flexible bottom wall

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ABSTRACT

A numerical investigation of steady laminar mixed convection heat transfer in a lid driven cavity with a flexible bottom surface is analyzed. A stable thermal stratification configuration was considered by imposing a vertical temperature gradient while the vertical walls were considered to be insulated. In addition, the transport equations were solved using a finite element formulation based on the Galerkin method of weighted residuals. In essence, a fully coupled fluid–structure interaction (FSI) analysis was utilized in this investigation. Moreover, the fluid domain is described by an Arbitrary-Lagrangian–Eulerian (ALE) formulation that is fully coupled to the structure domain. Comparisons of streamlines, isotherms, bottom wall displacement and average Nusselt number were made between rigid and flexible bottom walls. The results of this investigation revealed that the elasticity of the bottom wall surface plays a significant role on the heat transfer enhancement. 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. This investigation paves the road for future research studies to consider flexible walls when augmentation of heat transfer is sought.

1. Introduction

Augmentation of flow and heat transfer in geometries with irregular surfaces is a topic of fundamental importance. This interest stems from its significance in many engineering and industrial applications such as flat-plate solar collectors, flat plate condensers in refrigerators [1], micro-electronic devices, cooling system of micro-electronic devices, and cooling of electrical components [2]. Further, all the studies on mixed convection flow and heat transfer in geometries assuming regular and irregular surfaces have been restricted to rigid walls [1–14]. For example, Al-Amiri et al. [2] conducted a study to analyze mixed convection heat transfer in a lid-driven cavity with a sinusoidal wavy bottom surface. Their results had illustrated that the average Nusselt number would increase with an increase in both the amplitude of the wavy surface and Reynolds number. Moreover, optimum heat transfer was achieved when the wavy surface was designated with two undulations while subjected to low Richardson numbers. Khanafer et al. [7] carried out a numerical study on natural convection heat transfer inside a porous cavity with a sinusoidal vertical wavy wall. Their results showed that the amplitude of the wavy surface and the number of undulations affect heat transfer characteristics inside the cavity.

Owing to the difficulties associated with machining geometries with wavy surfaces; the authors propose in this investigation the use of flexible surfaces with known elasticity to enhance heat transfer characteristics as the fluid motion will cause the deformation of the flexible solid structure. The authors have proposed a lid-driven cavity to demonstrate their case owing to its fundamental nature. The scenario of a flexible wall disturbing a fluid motion, which involves the coupling of fluid mechanics and structural mechanics, is referred to in the literature as the fluid–structure interaction (FSI). FSI approach has received a great attention in recent years and its importance is of a growing interest in mechanical, aerospace and biomedical engineering applications [15–18]. In an FSI situation, the stresses and deformations of a given structure are computed simultaneously with the fluid flow and heat transfer variables that surrounds the structure. The lid-driven cavity with a flexible bottom surface was used by several authors as a benchmark for validating their respective numerical codes for fluid–structure interaction problems [19–23]. It is worth noting that the energy transport was ignored in these cited studies as the prime motivation has been centered around proper modeling of the fluid motion in the presence of a flexible structure.

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Nomenclature

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
$\mathbf{f}_f^B$	fluid body force per unit volume
$\mathbf{f}_s^B$	solid externally applied body force vector
g	gravitational acceleration
Gr	Grashof number, $g\beta(T_H - T_C)H^3/\nu^2$
h	thickness of the flexible bottom wall
H	side length of the cavity
Nu	Nusselt number
Pr	Prandtl number, ν/α
Re	Reynolds number, U_0H/ν
S_i	interface of the fluid and solid domains
T	temperature
$\mathbf{u}$	fluid velocity vector
$\mathbf{u}_g$	moving coordinate velocity
U_0	sliding lid velocity
x, y	Cartesian coordinates
X_b, Y_b	dimensionless displacements

Greek symbols

α	thermal diffusivity, $k/(\rho_f c_p)$
β	volumetric expansion coefficient
ν	kinematic viscosity
ϑ	Poisson ratio
θ	dimensionless temperature, $(T - T_C)/(T_H - T_C)$
ρ	density
$\boldsymbol{\sigma}$	stress tensor

Subscript

f	fluid domain
s	solid domain

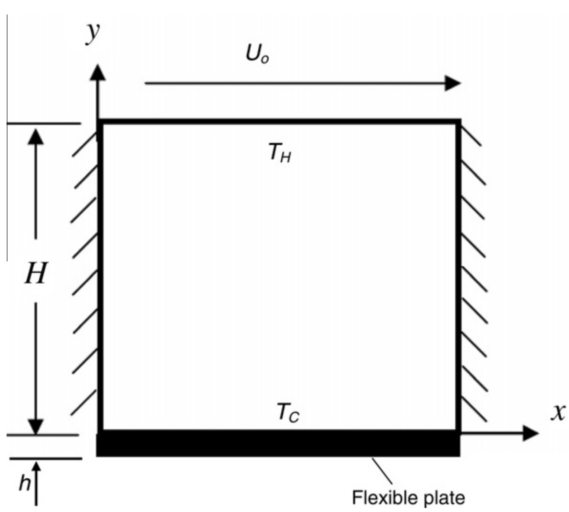

Fig. 1. Schematic diagram of the physical model.

Table 1
Comparison of the average Nusselt number at the top wall between various studies at $Gr = 10^2$.

Re	Present FEM	Ref. [32] FDM	Ref. [33] FVM	Ref. [34]	Ref. [35] FVM	Ref. [36] FDM	Ref. [37] FVM
100	**2.02**	1.94	2.01	1.99	NA	2.03	2.01
400	**4.05**	3.84	3.91	3.88	4.05	4.02	3.91
1000	**6.45**	6.33	6.33	6.35	6.55	6.48	6.33

Table 2
Comparison of the average Nusselt number at the top wall between various studies at $Gr = 10^4$ and 10^6.

Re	$Gr = 10^4$			$Gr = 10^6$		
	Present	Ref. [32]	Ref. [35]	Present	Ref. [32]	Ref. [35]
100	**1.38**	1.34	–	**1.02**	1.02	–
400	**3.76**	3.62	3.82	**1.17**	1.22	1.17
1000	**6.56**	6.29	6.50	**1.72**	1.77	1.81

*FEM: finite element method; FDM: finite difference method; FVM: finite volume method.

There are many studies reported in the literature on investigating the effect of moving boundaries on the flow and heat transfer characteristics [24–28]. These studies involved boundaries that move with a prescribed motion (e.g., displacement, pressure, or velocity). For example, Khaled and Vafai [24] studied the effects of both external squeezing and internal pressure pulsations on

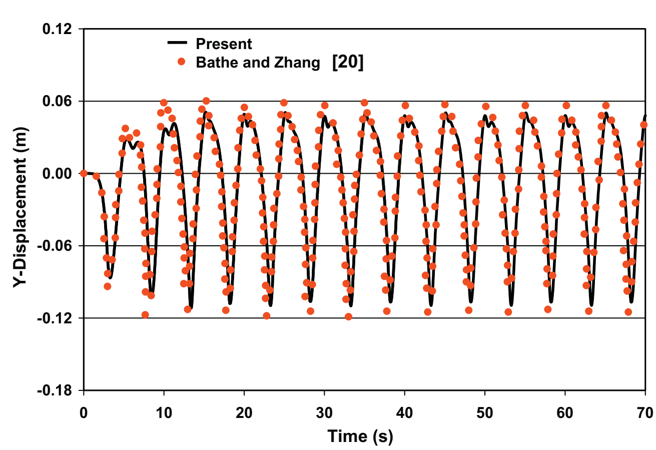

Fig. 2. Comparison of the *y*-displacement between the present results and that of Bathe and Zhang [20] in the absence of heat transfer.