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Fluid–solid interaction in natural convection heat transfer in a square cavity with a perfectly thermal-conductive flexible diagonal partition

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ABSTRACT

The unsteady natural convective heat transfer of an incompressible fluid is studied in a square cavity divided into two triangles using a flexible thermal conductive membrane. The temperature difference in the cavity induces buoyancy forces and natural convective flows. The membrane is adopted to be very flexible and thin, and hence, the interaction of the fluid and solid structure interaction (FSI) could change the shape of the membrane. An arbitrary Lagrangian–Eulerian (ALE) formulation associated with an unstructured grid is utilized to formulate the motion of the membrane. The solid and fluid governing equations are formulated and written in a non-dimensional form and the behavior of the membrane and the convective heat transfer of the cavity for various non-dimensional parameters are examined. The effects of the stiffness of the membrane and the fluid parameters on the shape of the membrane and the convective heat transfer in the cavity are studied.

1. Introduction

The natural convective heat transfer has been the subject of many studies due to its prime importance in various industrial and natural processes. Some of the practical applications of natural convection in enclosures are solar collectors, cooling of electronic equipment, energy storage systems, air conditioned system in buildings, thermal insulation and fire propensity control in buildings [1–3].

Giving the popularity of the natural convection heat transfer in a differentially heated cavity, this problem has been addressed as a benchmark study in many of the previous studies [3,5–15].

Earlier investigators have theoretically and experimentally addressed many aspects of convective heat transfer in cavity enclosures involving conjugate heat transfer effects [16], nanofluids and entropy generation [17], magnetic field effects [18], cavity filled with porous media [19] and the presence of a solid partition [20].

Many researchers have studied different geometry aspects of convective heat transfer in simple enclosures, such as the geometry of triangular shape [21], C-shape [22], concentric annulus [23], hemispherical shape [24–26], and parallelogrammic shape [27].

Modeling of real systems may differ distinctly from a simple enclosure. For example, a box containing electronic units is divided into partitions using thermal conductive plates. Some of sensitive electronic equipment should be insulated from the surrounding using a conductive metallic cover. In many cases, a chemical reactor should be divided in sections in which each section contains different chemical species, but the heat transfer could be occurred between the species through partitions. In a solar collector, the convection in the two adjacent air layers is coupled at the glazing. There are applications in which two fluids or containment gases are separated by a very thin flexible layer. In building insulation applications, the cavity in the walls is filled with a layer of polyethylene to prevent heat loss. For the case of a very thin membrane layer, the membrane is completely flexible and can go under deflection through the interaction of the structure with the free convection flow. Hence, the practical application of partitions in enclosures has encouraged researchers to examine the effect of the presence of partitions on convective heat transfer in cavities.

Tatsuo et al. [20] have experimentally studied the effect of the presence of a partition on the steady-state natural convective heat transfer in a cavity with a differential difference temperature at the sidewalls. Acharya and Jetli [28] have numerically studied the effect of the presence of a vertical partition on the natural convective heat transfer in a cavity with differentially difference sidewalls temperature. Nishimura et al. [14] have addressed the effect of the presence of multiple vertical partitions on the convective heat

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Nomenclature

Latin symbols

d	displacement
E	Young's modulus
E_τ	dimensionless flexibility
f_i	dimensionless body force
f_p	dimensionless body force
F_v	dimensionless body force
g	gravitational acceleration vector
Gr	Grashof number
k	thermal conductivity
L	cavity size
Nu	Nusselt number
p	dimensionless pressure
Pr	Prandtl number
Ra	thermal Rayleigh number
t	dimensionless time
T	temperature
T_0	initial average of the temperature in the enclosure
U	dimensionless velocity magnitude
u, v	dimensionless velocity vector
u_p	moving coordinate velocity
W_s	strain energy density
x, y	Cartesian coordinates

Greek symbols

μ_l	Lamé parameter
α	thermal diffusivity
β	thermal expansion coefficient
ε	strain
θ	dimensionless temperature
κ	solid-to-fluid thermal conductivity ratio
λ	Lamé parameters
ν	kinematic viscosity
ρ	density
σ	stress tensor
υ	Poisson's ratio
τ	Dimensionless time

Subscripts

c	cold
f	fluid
h	hot
p	partition
R	ratio

Superscripts

*	dimensional

transfer in a rectangular enclosure. Kahveci [4] has examined the effect of the presence of a vertical partition with finite thermal conductivity on the natural convective heat transfer in a square cavity. Chamkha and Ben-Nakhi [12,29,30] and Cheikh et al. [31] have numerically examined the effect of partial partitions (fins) on the convective heat transfer in cavities. All of the mentioned studies have addressed the effect of the presence of a partition on the steady state convective heat transfer in an enclosure.

Recently, there are few studies which have addressed the unsteady convective heat transfer in portioned enclosures. Suvash and Gu [32], Suvash et al. [33] have studied the unsteady natural convective heat transfer in a triangular cavity. Xu et al. [13] have examined the unsteady natural convective heat transfer of air in a square cavity with a highly conductive vertical partition.

In all of the studies mentioned in the literature, the partition has been considered as rigid. However, in many of real world problems, the partition can be flexible and the fluid-structure interaction (FSI) can change the shape of the partition. Consequently, the shape of the partition can affect the flow and heat transfer in the cavity. In the transient case, the motion of the flexible partition, the fluid flow and the heat transfer are coupled.

To the best of authors' knowledge, the effect of the presence of a flexible partition in a cavity on the natural convective heat transfer neither in the steady state nor in the unsteady state has been addressed yet. The present study aims to examine the effect of the presence of a perfectly conductive flexible partition on the natural convective heat transfer in a square cavity.

2. Mathematical formulation

Consider the laminar flow steady-state natural convection heat transfer of a Newtonian fluid in a square cavity of size L (height H and length L where $L \approx H$). The cavity is divided into two triangular partitions using a diagonal thin flexible membrane of thickness t_p^*. The membrane is flexible with the Young's modulus of E, Poison's ratio v and density ρ. The vertical walls of the cavity are isothermal of temperature difference ΔT while the top and bottom walls are perfectly insulated. There is a very small open boundary with the relative pressure of zero in each partition, allowing fluid entrance or ejection due to movement of the membrane and the change of volume of the partitions. The size of the open boundary is 0.1% of the height of the cavity. It is assumed that the membrane is very thin and perfectly thermally conductive with very low thermal capacity. Hence, the effect of temperature gradients and transient energy storage in the plate are neglected. It is assumed that the temperature difference between the cavity sidewalls is limited, and hence, the thermo-physical properties are independent of temperature variation and the Boussinesq approximation is applicable. The body force due to the weight of the membrane and the buoyancy forces are taken into account. A schematic representation of the cavity, coordinate system and the physical model are depicted in Fig. 1.

The governing equations for the geometrically nonlinear elasto-dynamic structural displacement of the membrane can be written as:

$$\rho_s \frac{d^2 \boldsymbol{d}_s^*}{dt^2} - \nabla \boldsymbol{\sigma}^* = \boldsymbol{F}_v^* \tag{1}$$

The governing equations of the conservation of mass, momentum and energy in arbitrary Lagrangian–Eulerian (ALE) formulation are written as:

$$\nabla \cdot \boldsymbol{u}^* = 0 \tag{2}$$

$$\frac{\partial \boldsymbol{u}^*}{\partial t} + (\boldsymbol{u}^* - \boldsymbol{w}^*).\nabla \boldsymbol{u}^* = -\frac{1}{\rho_f}\nabla P^* + \nu_f \nabla^2 \boldsymbol{u}^* + \beta \boldsymbol{g}(T - T_c) \tag{3}$$

$$\frac{\partial T}{\partial t} + (\boldsymbol{u}^* - \boldsymbol{w}^*).\nabla T = \alpha_f \nabla^2 T^* \tag{4}$$

where $\boldsymbol{\sigma}^*$ is the stress tensor, $\boldsymbol{d}_s^*$ is the solid displacement vector, $\boldsymbol{F}_v^*$ is the applied body force per unit of area, including the weight of the membrane and the buoyancy forces acting on the flexible membrane, $\boldsymbol{u}^*$ is the fluid velocity vector, $\boldsymbol{w}^*$ is the moving coordinate velocity, P^* is the fluid pressure and T is the fluid temperature.