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Three-dimensional analysis of natural convection in a partially-open cavity with internal heat source

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ABSTRACT

In this study a three-dimensional model was employed to numerically investigate the natural convection inside a partially-open cubic cavity with internal heat source. The boundary conditions are set so that two opposite vertical walls are maintained at different constant temperatures while the others walls are considered adiabatic. An opening occupying half of the entire area is placed in the right cold wall, allowing the fluid input and output of the cavity. The temperature difference between the non-adiabatic walls was defined using the external Rayleigh number within the range $Ra_e = 10^3$–10^5. The intensity of the internal heat source was evaluated through the relation $R = Ra_i/Ra_e$, investigated between 0 and 2000. The results show a significant influence of three-dimensional effects, in special for high Ra_e and R values, affecting the energy and flow distribution inside the cavity. In many cases the heat transfer between the fluid and the walls, measured by the Nusselt number, shows a rather different pattern even at the central part of the cavity when compared with results obtained with a two-dimensional model. Moreover, different Prandtl numbers were analyzed to consider the effect of the thermal and momentum diffusion proprieties of the fluid. It was observed that the main effect of the Prandtl number is on the heat exchange at the hot wall, while the maximum dimensionless temperature and the heat exchange at the cold wall are less dependent on the Prandtl number.

1. Introduction

Natural convection in cavities is a widely studied problem of relevance to many environmental and industrial applications, such as electronic cooling devices, solar thermal receivers, thermal design of buildings, construction and operation of nuclear and chemical reactors, crystal growth, solar collectors with insulated strips [1], etc. In practical engineering applications the system configurations are more complex than a simple enclosure filled by a fluid, and the presence of baffles, openings and internal heat sources should be considered due to their great impact on the flow pattern and energy distribution inside the cavity [2,3].

Many studies have focused on the effect of openings or bodies placed inside the cavity on the natural convection induced by the temperature difference between walls, considering several cavity shapes, for example, rectangular [2–12], trapezoidal [13–16] and triangular [17–19]. Lee et al. [3] evaluated numerically the natural convection in a square cavity induced by the temperature difference between cold walls and a hot cylinder placed inside the cavity. Different Ra_e values between 10^3 and 10^6 and different cylinder positions were considered. The authors reported local peaks in the Nusselt number on the surface of the cylinder in points closer to the walls. Merrikh and Lage [6] performed a numerical study of natural convection induced by a temperature difference between vertical walls in a cavity with solid square conducting blocks. They proposed an expression to predict the minimum number of blocks necessary to switch the flow pattern. Oztop et al. [9] evaluated a partially-open cavity filled with a porous medium, examining the effect of the Grashof and Darcy numbers, the length of heated wall and the location of the opening on the natural convection. A similar geometry was investigated by Fontana et al. [11], but the two-dimensional cavity was filled with air and an internal heat source was positioned on the bottom wall. The authors evaluated the effect of Ra_e (external) and Ra_i (internal) Rayleigh numbers and the opening size on the flow pattern and energy distribution inside the cavity and in the opening. That study demonstrated a strong influence of the opening size on the energy exchange between the system and the surroundings.

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Nomenclature

A_s	superficial area [m^2]
g	gravity acceleration [$m\ s^{-2}$]
H	height of cavity [m]
H^*	height of the opening [m]
k	thermal conductivity [$W\ m^{-1}\ K^{-1}$]
L	length of cavity [m]
Nu_C	Nusselt number at the cold wall
$\overline{Nu}_C$	average Nusselt number at the cold wall
Nu_H	Nusselt number at the hot wall
$\overline{Nu}_H$	average Nusselt number at the hot wall
Nu_{MP}	average Nusselt number at the cavity middle-plane
p	pressure [Pa]
Pr	Prandtl number
$\dot{q}$	volumetric heat-generation rate [$W\ m^{-3}$]
R	internal to external Rayleigh numbers ratio
Ra_e	external Rayleigh number
Ra_i	internal Rayleigh number
T	temperature [K]
T_C	right (cold) wall temperature [K]
T_H	left (hot) wall temperature [K]
$\vec{u}$	velocity vector (u, v, w) [$m\ s^{-1}$]
u_{max}	dimensionless maximum velocity in x direction
v_{max}	dimensionless maximum velocity in y direction
V_s	volume of the internal heat source [m^3]
W	width of cavity [m]
w_{max}	dimensionless maximum velocity in z direction
X^*	dimensionless width
Y^*	dimensionless height
x, y, z	cartesian coordinates

Greek alphabet

α	thermal diffusivity [$m^2\ s^{-1}$]
β	thermal expansion coefficient [K^{-1}]
θ	dimensionless temperature
ν	kinematic viscosity [$m^2\ s^{-1}$]
ρ	density [$kg\ m^{-3}$]
Ψ	stream function [$m^2\ s^{-1}$]
Ψ	dimensionless stream function

In the above-cited studies two-dimensional models were used to analyze natural convection inside the cavities. However, depending on the dimensions of the cavity, significant three-dimensional effects can arise. In this context, some authors analyzed the natural convection in three-dimensional structures [20–27]. Beya and Lili [22] analyzed the natural convection in a cubic enclosure heated and cooled from two opposite walls while the remaining walls were kept adiabatic, considering different values for the Rayleigh and Prandtl numbers and several cavity inclinations. The authors reported an oscillatory behavior after a Hopf bifurcation, for $Ra_e = 8.5 \times 10^4$ and an inclination of 45°, demonstrating the existence of time-dependent stable solutions. Lo [24] performed a similar study but using a square cavity with one heated and one cooled opposite vertical wall. Different Ra_e numbers and cavity widths were analyzed and a significant influence of the six walls on the energy distribution was observed. Stiriba et al. [26] investigated mixed convection in an open cubic enclosure, with a laminar current flowing over the opening. Due to the large difference in the velocity of the fluids, Kelvin–Helmholtz instability arises in a transition region, causing the flow instability and increasing the heat transfer between the fluid and the hot walls. Yu and Joshi [27] performed a study on natural convection in a partially-open cavity, evaluating the position and size of the opening and the Rayleigh number. The authors highlighted very pronounced three-dimensional effects and a significant influence of the vent location and size on the flow structure.

The aim of the present study is evaluate the natural convection inside a partially-open cavity with an internal heat source and vertical walls maintained at different temperatures, using a three-dimensional model to capture the influence of the back and front adiabatic walls on the flow structure and heat transfer. The external Rayleigh number was varied from 10^3 to 10^5, and four values for the ratio between the internal and external Rayleigh numbers were investigated (0, 400, 1000 and 2000). The physical proprieties of the fluids have a significant importance in terms of the natural convection. In particular, it is well known that the Prandtl number (ratio between momentum and heat diffusivity) is an important dimensionless parameter to be considered, and so different values for the Prandtl number of the fluid were considered to evaluate its effect on the energy distribution and heat exchange inside the cavity.

The article is structured as follows. In Section 2, the governing equations for mass, momentum and energy conservation are defined. Section 3 describes the numerical methodology used and the code validation. In Section 4 the main results are discussed. The results for the flow structure and energy distribution are presented in form of isotherms, streamlines and maximum temperature, while the local and average Nusselt number is used to quantify the heat exchange between the fluid and the non-adiabatic walls. In Section 5 concluding remarks finalize the paper.

2. Physical problem and governing equations

A schematic diagram of the computational domain used in this study is shown in Fig. 1. The system consists of a cubic enclosure, where the width (W), the length (L) and the height (H) are assumed to be identical. The opening is placed on the right vertical wall of the cavity occupying 50% of the wall height and the entire length, so that the height of the opening is defined as $H^* = H/2$. The internal heat source is positioned on the center of the bottom horizontal wall, occupying 1% of the total volume of the cavity. The length

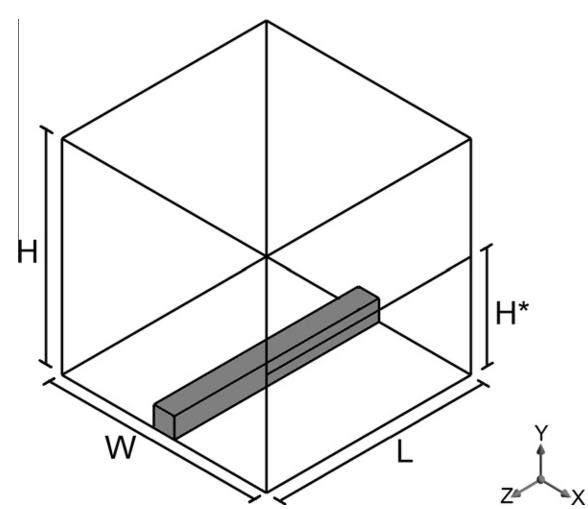

Fig. 1. Sketch of the computational domain.