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Numerical simulation of three-dimensional natural convection in a cubic enclosure induced by an isothermally-heated circular cylinder at different inclinations

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ABSTRACT

This study numerically examines three-dimensional natural convection of air induced by temperature difference between a cold outer cubic enclosure and a hot inner cylinder. Simulations have been carried out for Rayleigh numbers ranging from 10^3 to 10^7 and a titled angle of the enclosure varying from 0° to 90°. The developed mathematical model is governed by the coupled equations of continuity, momentum and energy and is solved by finite volume method. The effects of cylinder inclination and Rayleigh number on fluid flow and heat transfer are presented. The distribution of isocontours of temperature, components of velocity and streamtraces eventually reaches a steady state for Rayleigh numbers ranging from 10^3 to 10^7 for titled inclination of 90°. However, for the remaining inclinations, Rayleigh numbers must be in the range 10^3–10^6 to avoid unsteady state which is manifested by the subdivision of the area, containing the maximum local heat transfer rate, into three parts for a Rayleigh number equal to 10^7 and an inclination of 90°. We mention that instability study is not included in the present paper which is solely devoted to three dimensional calculations. Results indicate also that optimal average heat transfer rate is obtained for Rayleigh number set to 10^6 and an inclination of 90° for both cases of the inner cylinder and lateral walls of cubical enclosure.

1. Introduction

Cooling is the key of challenges in development of effective equipment. So, natural convection in cavities is used to design much equipment such as heat exchanger, nuclear safety systems, cooling of electronic equipment and stratified atmospheric boundary layers. Natural convection heat transfer exhibits a great variety of complex dynamic behaviors which depend heavily on the geometry and thermal conditions of the enclosure. For several decades, classical boundary condition was started by DeVahl Davies [1] who proposed the problem of differentially heated cavity. Due to the temperature difference, natural convection develops in the enclosure. The geometries that arise in engineering applications are more complicated than a simple differentially heated enclosure, so attention has shifted to enclosures with hot immersed bodies within [2–4].

The effects of eccentric positions ($\varepsilon = 0.5$ and -0.5) and concentric position ($\varepsilon = 0.0$) in a square enclosure have been studied for a particular aspect ratio ($L/D = 2$) by Tasnim et al. [5]. They found that heat transfer rate at eccentric positions is comparatively higher than the heat transfer at concentric ones. It was concluded that at all values of eccentric position, circulatory zone with one core is observed near the upper part of the cylinder. Again for $\varepsilon = 0.0$; a critical range of Grashof number is identified below which heat transfer is higher for lower L/D ratio and above which heat transfer is lower for lower L/D ratio.

Natural convection heat transfer of heated horizontal cylinders placed concentrically inside a square enclosure, has continued to be a very active area for scientists during the past few decades. For example, Moukalled and Acharya [6] and Shu and Zhu [7] studied numerically the change of the thermo-flow field between a low-temperature outer square enclosure and a high-temperature inner circular cylinder according to the radius of the inner circular cylinder. Shu and Zhu [7] presented numerical results for Rayleigh numbers range from 10^4 to 10^6 and aspect ratios between 1.67 and 5.0. It is shown that for both the aspect ratio and the Rayleigh number are critical to the patterns of flow and thermal fields. It is suggested that a critical aspect ratio may exist at high Rayleigh

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Nomenclature

G	acceleration of gravity (m/s^2)
C_p	specific heat capacity (J/kg K)
K	thermal conductivity (W/mK)
P_0	pressure scale, ρu_0^2
u_0	velocity scale, $\sqrt{g\beta\Delta TL}$
Pr	Prandtl number, $Pr = \nu/a$
Ra	Rayleigh number $g\beta L^3(T_h - T_c)/(\nu a)$
$\overline{Nu}$	average Nusselt number
Nu_{loc}	local Nusselt number
Nu_{mp}	Nusselt number at the mid-plane
Nu_{corr}	correlated Nusselt number
L	length of the cubical enclosure and the cylinder (m)
T_c	cold wall temperature (K)
T_h	hot wall temperature (K)
T	temperature (K)
A	thermal diffusivity (m^2/s)
N	normal direction
u, v, w	dimensionless velocity components
x, y, z	dimensionless Cartesian coordinates
t	dimensionless time

Greek symbols

θ	dimensionless temperature, $\theta = (T-T_c)/(T_h-T_c)$
ν	kinematics viscosity (m^2/s)
μ	dynamic viscosity (kg/(m s))
ρ	fluid density (kg/m^3)
α	inclination angle
β	coefficient of thermal expansion (K^{-1})

Subscripts

max	maximum
c	cold
h	hot

number to distinguish the flow and thermal patterns.

Lee et al. [8] analyzed the effects of the presence of hot inner cylinder located at different locations along the horizontal or diagonal line of the cold square enclosure on the fluid flow and heat transfer for Rayleigh numbers ranging from 10^3 to 6.10^6. They demonstrated that, when $Ra = 10^3$ and 10^4, the profile of local Nusselt number along the walls of the enclosure Nu_{en} on the diagonal location of the cylinder ζ shows almost the symmetric distribution to the center of the enclosure $\zeta = 0$. However, when $Ra = 10^5$ and 10^6, the profile of $\overline{Nu}_{en}$ along the ζ shows the weak asymmetric distribution to $\zeta = 0$. Thus authors approved that, for the same absolute values of ζ at $Ra = 10^5$ and 10^6, the value of $\overline{Nu}_{en}$ at $0.25 \le \zeta \le 0$ is slightly larger than that at $0 \le \zeta \le 0.25$, due to the increased buoyancy-induced convection effect when the inner cylinder is located at the lower diagonal line of the enclosure.

A marginally related publication was done by Salam Hadi Hussain et al. [9] who reported the numerical results of natural convection in a square enclosure with isothermal walls (T_c) and heated by a concentric internal circular isoflux cylinder wall changed vertically along the centerline of the enclosure from −0.25 L to 0.25 L for Rayleigh numbers in the range 10^3–10^6. These authors found that values of the average Nusselt number of the cold square enclosure is smaller than the corresponding values of the hot inner cylinder for all distances from the center of square cylinder to circular cylinder center because the isotherms have a slight effect and almost symmetrical.

In the above-cited studies two-dimensional models were used to analyze natural convection inside the cavities. However, there is little information about three-dimensional natural convection when a heated cylinder exists within the cooled cubical enclosure.

The literature survey shows that the three-dimensional enclosures induced by a heat generating conducting body have not been considered so far. Almost only one work has dealing with this kind of flow and carried out by Ha and Jung [10]. Authors showed that the presence of a cubic conducting body in a cubic enclosure results in a larger variation of the local Nusselt number at the hot and cold walls in the z-direction, compared to cases without a cubic conducting body in the cubic enclosure, indicating the existence of strong three-dimensionalities of natural convection with a conducting body.

A numerical study of steady natural convection in a cooled cubic enclosure containing a heated circular and elliptical cylinder has been carried out lately by Ravnik et Škerget [11]; Rayleigh number values are considered in the range ($Ra \le 10^6$), while Al_2O_3, Cu and TiO_2 nanofluids are used as well as water and air. The authors concluded that nanofluid enhances heat transfer when heat is dominated by conduction, whereas the convection becomes preponderant in case the use of nanofluid is low. Furthermore, they concluded also that the comparison of circular and elliptical cylinder conducted to a slight difference between levels of heat transfer which is better in the case of elliptical cylinder. Authors showed also that elliptical cylinder inclination against gravity increases the heat transfer rate and modifies the structure of the flow. This strengthening was seen to be low when conduction dominates and enhanced in the case of convection. As a conclusion, when they make a comparison between 2D and 3D simulations, authors found that there is a slight difference between them in the case of conduction. The authors hence concluded that 2D simulations can be used for these problems.

Among the studies mentioned above, several works refer to obstructed cavities depending on the shape and position of the inner body. However, some works revealed that location of the inner body has effect on the flow and heat transfer rates in a cavity. For example, Yoon et al. [12] studied the influence of the position of an inner sphere on natural convection in a cubical enclosure. They investigated the effect of the location of the inner sphere on the heat transfer and fluid flow in a cubical enclosure for Rayleigh numbers in the range of$10^3 \le Ra \le 10^6$ and they observed that the distribution of the local Nusselt number of the cylinder depends greatly on the location of the inner sphere as well as the Rayleigh number. Changyoung Choi et al. [13] analyzed numerically the natural convection in a cubical enclosure with an isothermal inner circular cylinder. They approved that the location of the inner cylinder affects fluid flow and heat transfer, their works disclosed that for a Rayleigh number $Ra = 10^3$, the end wall of the cubical enclosure has a negligible effect on the thermal and flow fields in the enclosure, however, in the range $10^4 \le Ra \le 10^6$, the effect of the end wall on heat transfer and fluid flow in the enclosure depends on both the location of the inner cylinder and the Rayleigh number.

Some studies have examined numerically [14] and experimentally [15,16] the effect of the cavity orientation on the natural convection inside a cubical enclosure without an inner cylinder. They revealed that the flow and thermal fields in the cubical enclosure depend strongly on the cavity orientation because the buoyancy force components vary as a function because the cavity orientation.