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A numerical study on natural convection in an inclined square enclosure with a circular cylinder

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ABSTRACT

This study examined numerically the natural convection induced by a temperature difference between a cold outer inclined square enclosure and a hot inner circular cylinder. A two-dimensional solution for natural convection was obtained using the finite volume method with second-order accuracy and the immersed boundary method to handle efficiently the inner circular cylinder within an inclined square enclosure. The present study considered the effects of the following parameters on fluid flow and heat transfer in an enclosure: Rayleigh number from 10^3 to 10^6, the dimensionless cylinder radii from 0.1 to 0.3 and tilted angle of the enclosure from 0° to 45°. The results showed that the distribution of isotherms, streamlines, local and surface-averaged Nusselt numbers are determined by the combined effects of convection and the distance between the cylinder and walls of the enclosure, which are a function of the Rayleigh number, dimensionless cylinder radius and tilted angle of the enclosure.

1. Introduction

Natural convection in an enclosure, whose flow is caused by temperature-induced density variations, has been studied over the latest few decades because it is relevant to many industrial and environment applications, such as heat exchanger, nuclear and chemical reactors, cooling of electronic equipment and stratified atmospheric boundary layers. Although a range of configurations of the enclosure problem are possible, one of the most studied cases involves the natural convection in the square enclosure with the presence of bodies embedded.

Asan [1] numerically investigated the steady-state, laminar, two-dimensional natural convection in an annulus between two isothermal concentric square ducts considering three different dimension ratios and Rayleigh numbers up to 10^6. The results showed that a multiple cell solution is developed between the upper sides of the square ducts as the dimension ratio is increased (decreasing the gap between squares) depending on the Rayleigh numbers.

Kumar De and Dalal [2] studied natural convection around a tilted square cylinder kept in an enclosure in the range of $10^3 \leqslant Ra \leqslant 10^6$. The results reported the effects of the enclosure geometry using three different aspect ratios placing the square cylinder at different heights from the bottom. As a result, it was found that the function of aspect ratio affected the flow pattern and thermal stratification and consequently changed overall heat transfer.

Cesini et al. [3] performed a numerical and experimental analysis for natural convection heat transfer from a horizontal cylinder enclosure in a rectangular cavity. The influence of the Rayleigh number and the geometry of the cavity on the heat transfer are investigated and as a result the average heat transfer coefficient increases when the Rayleigh number increases.

Moulalled and Acharya [4] and Shu and Zhu [5] examined natural convection between the low temperature outer square enclosure and high temperature inner circular cylinder according to the radius of the inner circular cylinder. Moukalled and Acharya [4] considered three different aspect ratios of the cylinder radius to the enclosure height in the range of $10^4 \leqslant Ra \leqslant 10^7$. They reported that at a constant enclosure aspect ratio, the total heat transfer rate increases with increasing Rayleigh number. When the Rayleigh number is constant, the convection contribution to the total heat transfer rate decreases with increasing aspect ratio. Shu and Zhu [5] obtained the numerical results for different Rayleigh numbers ranging from 10^4 to 10^6 and aspect ratios ranging from 1.67 to 5.0. Both the aspect ratio and Rayleigh number are critical to the distribution of flow and thermal fields. They also suggested that there may be a critical aspect ratio to distinguish the fluid flow and thermal fields into different patterns at high Rayleigh numbers.

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Nomenclature

f_i	momentum forcing
g	gravitational acceleration
h	heat source or sink
L	length of square enclosure
n	normal direction to the wall
Nu_{cyl}	local Nusselt number along the circular cylinder
Nu_{en}	local Nusselt number along the walls of the enclosure
$\overline{Nu}_b$	surface-averaged Nusselt number along the bottom wall of the enclosure
$\overline{Nu}_{en}$	surface-averaged Nusselt number along the square enclosure
$\overline{Nu}_l$	surface-averaged Nusselt number along the top wall of the enclosure
$\overline{Nu}_t$	surface-averaged Nusselt number along the top wall of the enclosure
$\overline{Nu}_r$	surface-averaged Nusselt number along the right wall of the enclosure
P	pressure
Pr	Prandtl number
q	mass source or sink
R	dimensionless radius of circular cylinder
Ra	Rayleigh number
S	distance along the square enclosure
t	dimensionless time
T	dimensional temperature
W	surface area of walls
T_h	hot temperature
T_c	cold temperature
u_i	dimensionless velocity vector
x_i	Cartesian coordinates system

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
γ	tilted angle
δ_{i2}	Kronecker delta
ρ	density
ν	kinematic viscosity
φ	angle in the circumferential direction along the cylinder surface
θ	dimensionless temperature

Sub/Superscripts

*	dimensional value
–	surface-averaged quantity
cyl	cylinder
en	enclosure
c	cold
h	hot
t	top wall
r	right wall
b	bottom wall
l	left wall

The effect of the location of the inner circular cylinder on natural convection between the low temperature outer square enclosure and high temperature inner circular cylinder was also investigated. Shu et al. [6] studied numerically the natural convection between an outer square enclosure and inner circular cylinder for different eccentricity values and angular positions of the outer cylinder at a Rayleigh number of 3×10^5. They reported that the global circulation, flow separation and the top space between the square outer enclosure and inner circular cylinder have significant effects on the plume inclination. The changes in natural convection between a hot inner cylinder and cold outer square cylinder according to the location of the inner circular cylinder moving vertically along the centerline of the square enclosure were investigated by Kim et al. [7] and Yoon et al. [8] at Rayleigh numbers from 10^4 to 10^6 and a Rayleigh number of 10^7, respectively. When the Rayleigh number was varied from 10^4 to 10^6, Kim et al. [4] reported that the flow and thermal fields eventually reach a steady state with a symmetric shape about the vertical centerline of the enclosure and their pattern depends strongly on the vertical position of the inner cylinder in the enclosure. When the Rayleigh number is high (10^7), Yoon et al. [8] reported that the flow and thermal fields depend more strongly on the location of the inner cylinder in the enclosure than when the low Rayleigh number ranged from 10^4 to 10^6 and change their shape from an unsteady state to a steady one at two critical points.

Lee et al. [9] also investigated the effect of the location of the inner circular cylinder on natural convection between the low temperature outer square enclosure and high temperature inner circular cylinder. Lee et al. [9] studied the natural convection for the Rayleigh numbers ranged from 10^3 to 10^6 when the location of the inner cylinder was changed horizontally along the center of square enclosure or diagonally along a diagonal line of the square enclosure. Lee et al. [9] reported that the existence of local peaks of the Nusselt number along the surfaces of the cylinder and the enclosure is determined by the gap and the thermal plume governed by the conduction and the convection, respectively.

Some studies have examined numerically [10,11] and experimentally [12] the effect of the cavity orientation on the natural convection inside a square enclosure without an inner cylinder. They reported that the flow and thermal fields in the square enclosure depend strongly on the cavity orientation because the buoyancy force components vary as a function of the cavity orientation. Therefore, the inclination of the square enclosure will also have some influence on the natural convection inside the square enclosure in the presence of the embedded inner cylinder.

Xu et al. [13] investigated numerically the natural convection heat transfer from a heated horizontal cylinder that was placed concentrically inside a cooled inclined triangular enclosure. They considered the effect of the Rayleigh number, the aspect ratio of the cylinder diameter to the triangle height and the inclination angle of the enclosure on the distribution of fluid flow, temperature and Nusselt number. They reported that at a specified constant aspect ratio, both the inclination angle and geometry of the cross-section have significant effects on the flow and thermal field distribution.

As shown above, most studies examined natural convection between the inner cylinder and the outer square cylinder when the outer square cylinder was upright. On the other hand, no study has examined natural convection between the inner cylinder and outer square enclosure when the outer square enclosure is tilted. This is despite the fact that such a study on the tilting effect of the outer enclosure on the distribution of the fluid flow and thermal fields is some interest for different science and engineering applications. From an academic perspective, it enriches our understanding on the flow physics and heat transfer characteristics in similar but more complex configurations. For an engineering application, the tilted angle of roof affects the air circulation in the room. Similar situations also exist in the cooling of electric