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Effects of thermal boundary conditions on natural convection in a square enclosure with an inner circular cylinder locally heated from the bottom wall

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ABSTRACT

Two-dimensional numerical simulations are conducted for natural convection in an enclosure with an hot inner cylinder located at the center of a cold enclosure for four Rayleigh numbers of 10^3, 10^4, 10^5, and 10^6. The study focuses on the effects of the locally heated bottom wall of the enclosure on thermal and flow structures of natural convection. The results indicate negligible changes in thermal and flow structures based on variations in the size of the local heating zone on the bottom wall at $Ra = 10^3$ and 10^4, although there is a small variation in the convection velocity in the enclosure. At $Ra = 10^5$, small inner vortices formed in the lower part of the cylinder show significant changes in their size with increases in the size of the local heating zone. At $Ra = 10^6$, secondary vortices are generated in the lower part of the cylinder because of flow separation from the side wall. The generation and dissolution of vortices are dependent mainly on the size of the local heating zone.

1. Introduction

Natural convection in an enclosure is relevant to environmental, practical, and engineering applications such as cooling and heating in rooms, the cooling of electronic equipment, and the cooling of nuclear reactor systems. Therefore, many studies have examined natural convection in enclosures under a diverse range of thermal boundary conditions, including Rayleigh-Bénard convection [1–12]. However, the geometries that arise in practical are more complicated than a simple enclosure filled with a convective fluid. A geometric configuration of interest is coupled with the presence of bodies embedded within the enclosure. Some previous studies have explored the characteristics of thermal and flow structures of natural convection caused by the presence of an inner body in the enclosure.

Moukalled and Acharya [13] investigated the change in the thermo-flow field between an outer square enclosure with a low temperature and an inner circular cylinder with a high temperature by considering three different aspect ratios of the cylinder radius to the enclosure height for the Rayleigh number range $10^4 \leqslant Ra \leqslant 10^7$ and demonstrate that for a constant aspect ratio, total heat transfer increases as the Rayleigh number increases. For a constant Rayleigh number, the contribution of convection to total heat transfer decreases as the aspect ratio increases. Shu and Zhu [14] provided numerical analysis of natural convection in a concentric annulus between a cold outer square cylinder and a heated inner circular cylinder and present Rayleigh numbers ranging from 10^4 to 10^6 and aspect ratios of the width of the enclosure to its height ranging from 1.67 to 5.0. They find that both the aspect ratio and the Rayleigh number have significant effects on patterns of thermal and flow fields and suggest the existence of a critical aspect ratio at a high Rayleigh number that can distinguish between flow and thermal patterns. Kim et al. [15] investigated natural convection induced by temperature differences between a cold outer enclosure and a hot inner circular cylinder for Rayleigh numbers ranging from 10^3 to 10^6 by considering the vertical movement of the inner cylinder as a main simulation parameter and showed that thermal and flow fields reach a steady state and have a symmetric shape about the vertical center line through the center of the enclosure for all Rayleigh numbers considered. The number, size, and formation of convection cells depended heavily on the Rayleigh number as well as on the position of the inner circular cylinder. Saha et al. [16] performed two-dimensional numerical simulations for natural convection in a square enclosure with an adiabatic cylinder at the center of the enclosure for Grashof numbers ranging from 10^3 to 10^6 by using the finite element method. They maintained two vertical walls at constant low temperatures and imposed an adiabatic boundary condition on the top wall. They provided a local heat source with constant heat flux on the bottom wall and imposed an adiabatic

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Nomenclature

f_i	momentum forcing
g	gravitational acceleration
Gr	Grashof number
h	heat source or sink
H	enclosure height
L	enclosure width
n	direction normal to the wall
Nu	Nusselt number
P	pressure
Pr	Prandtl number
q	mass source or sink
r	radius of the circular cylinder
Ra	Rayleigh number
t	time
T	temperature
T_h	high temperature
T_c	low temperature
u, v	velocity components in x- and y-directions
w	dimensionless length of the local heating zone
W	length of the local heating zone
x, y	Cartesian coordinates

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
δ_{ij}	Kronecker delta
ρ	fluid density
ν	kinematic viscosity of the fluid
φ	angle (deg)
θ	dimensionless temperature

Subscripts/superscripts

$*$	dimensional variable
c	cold
cyl	cylinder
h	hot
top	top wall
$bottom$	bottom wall
p	period

Mathematical symbols

$\langle\,\rangle$	surface-averaged value
$-$	time-averaged value
$\langle \bar{\ } \rangle$	surface- and time-averaged value

boundary condition on the rest of the bottom wall. Then they analyzed the effects of the length of the heat source on the flow and heat transfer in the enclosure and reported that an increase in the Nusselt number reduces the maximum temperature on the heated surface on the bottom wall. Jami et al. [17] investigated laminar natural convection in a partially heated square enclosure with a heat-conducting cylinder at the center of the enclosure for the Rayleigh number range $10^3 \leqslant Ra \leqslant 10^6$ by using the lattice Boltzmann equation and the finite difference method through a suitable coupling and reported that the surface-averaged Nusselt number for hot and cold walls is linearly proportional to the temperature difference for a constant Rayleigh number. Ha et al. [18] examined two-dimensional and unsteady natural convection in a square enclosure with a square body at the center of the enclosure by using the Chevyshev spectral collocation method and found that the fluid flow and temperature fields depend on the thermal boundary condition of the body, demonstrating different patterns of streamlines and isothermals. They revealed the critical Rayleigh numbers for the onset of asymmetric thermal and flow structures as well as for the unsteadiness of the flow.

The present paper conducts two-dimensional numerical simulations for natural convection in a square enclosure with a hot inner circular cylinder for a wide range of Rayleigh numbers ($10^3 \leqslant Ra \leqslant 10^6$) and examines the effects of the locally heated bottom wall of the enclosure on thermal and flow structures of natural convection. For this, the paper provides an in-depth analysis of the structures of thermal and flow fields in the enclosure caused by local heating based on variations in the size of the local heating zone. In addition, the paper provides a quantitative analysis of the heat transfer characteristics based on the convective flow.

2. Numerical methodology

Fig. 1 shows the computational domain of the enclosure considered in this paper and its coordinate system. Here L and H represent the width and height of the enclosure, respectively. The aspect ratio of the length of the enclosure to its height is unity, representing a square enclosure. In addition, R represents the radius of the inner cylinder ($R = 0.2L$). The cylinder is located at the center of the enclosure. W represents the length of the local heating zone placed on the bottom wall of the enclosure. This paper selects w ($w = W/L$) as a main simulation parameter and varies it from 0 to 1. The top wall of the enclosure and the cylinder surface are kept at a constant low temperature T_c and a constant high temperature T_h, respectively, and an adiabatic condition is imposed on the side wall of the enclosure. A local heat source with a constant high temperature T_h is placed on the bottom wall of the enclosure, and an adiabatic condition is imposed on the rest of the bottom wall. A

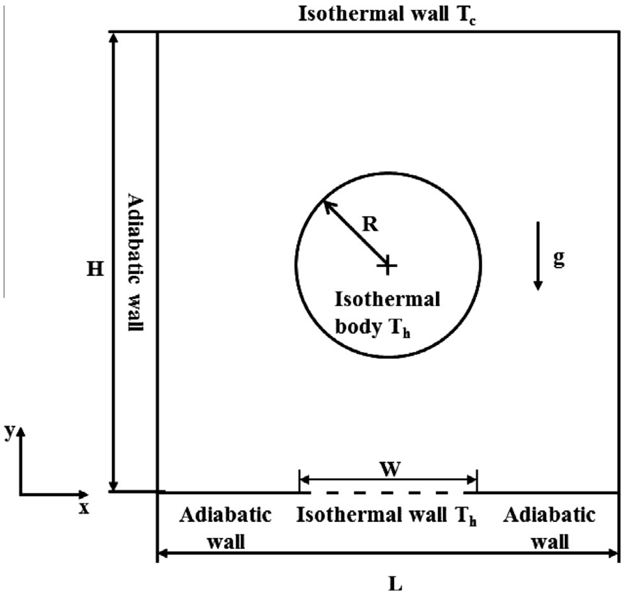

Fig. 1. Computational domain and boundary conditions.