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Effect of a circular cylinder's location on natural convection in a rhombus enclosure

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ABSTRACT

Based on numerical simulations using the immersed boundary method (IBM), results for natural convection in a rhombus enclosure with an inner circular cylinder and a Prandtl number $Pr = 0.7$ are presented. This simulation spans four decades of Rayleigh number Ra, from 10^3 to 10^7. The inner circular cylinder's location is vertically changed along the rhombus enclosure's centerline. We investigate the effects of both the inner cylinder's location in the rhombus enclosure and buoyancy-induced convection on heat transfer and fluid flow. With respect to the cylinder's location and the Rayleigh number, the thermal and flow field is categorized into three regimes: steady-symmetric, steady-asymmetric, and unsteady-asymmetric. The map of thermal and flow regimes is presented as a function of the cylinder's location and of the Rayleigh number. Detailed analysis results for the distribution of streamlines, isotherms, and Nusselt numbers are also presented in this paper.

1. Introduction

Phenomena involving natural convection in fluid-filled enclosures have received considerable attention because natural convection plays important roles in many engineering applications, such as nuclear reactors, heat exchangers, thermal insulation of pipes buried in the ground, and solar collector receivers. Many researchers have investigated the parameters that affect natural convection in an enclosure. Their findings have indicated that natural convection in an enclosure is influenced by the thermal conditions of the enclosure, the existence of a body in the enclosure, the shape of the enclosure, and the inner body's position in the enclosure [1–26].

Among the thermal conditions for natural convection in an enclosure are horizontally imposed temperature differences on the enclosure wall [1–6]. Another thermal condition influencing natural convection in an enclosure is vertically imposed temperature differences [7–11]. The fluid flow and heat transfer in the enclosure depend on thermal conditions, even when the Rayleigh number and Prandtl number are unchanged.

For a body within an enclosure, its effect on natural convection in that enclosure has been investigated by many researchers who have studied the influence of various body shapes, such as a cylinder with a circular, square, or triangular cross-section, a cube, or a sphere. Lee et al. [3] investigated the effect of an inner square cylinder on natural convection in an enclosure for various Rayleigh numbers. They compared the natural convection results for the enclosure with an inner square cylinder to the results for the enclosure without an inner body. They reported that the existence of the inner body affects fluid flow and heat transfer in the enclosure. Xu et al. [12] and Asan et al. [13], Moukalled and Acharya [14], Shu and Zhu [15], Tasnim et al. [16] and Angeli et al. [17] have considered inner bodies of various shapes and sizes to determine how the inner body affects natural convection in an enclosure. They reported that natural convection in the enclosure is strongly influenced by the shape and size of the inner body.

The effect of the enclosure's shape on natural convection within the enclosure has been studied by changing the rectangular enclosure's aspect ratio or changing the shape of the enclosure's cross-section. Kumar De and Dalal [18] have investigated the effect of a rectangular enclosure's aspect ratio. When the aspect ratio of the enclosure is varied, the patterns of flow and thermal stratification in the enclosure change. When the Rayleigh number is constant, the convection's effect on total heat transfer decreases as the enclosure's aspect ratio increases. Warrington et al. [19] have examined the effect of the shape of an enclosure's cross-section on natural convection in the enclosure. They have considered spherical and cubical enclosures. They have reported

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Nomenclature

f_i	momentum forcing
g	gravitational acceleration [m/s^2]
L	length of rhombus enclosure [m]
n	normal direction to the wall
Nu	local Nusselt number
p	dimensionless pressure
Pr	Prandtl number
q	mass source or sink
R	radius of circular cylinder [m]
Ra	Rayleigh number
S	distance along rhombus enclosure
t	dimensionless time
T	temperature [K]
u_i	dimensionless velocity vector
x_i	Cartesian coordinates system
Greek symbols	
α	thermal diffusivity [m^2/s]
β	thermal expansion coefficient [K^{-1}]
δ	dimensionless off-center distance
δ_{i2}	Kronecker delta
ρ	density [kg/m^3]
ν	kinematic viscosity [m^2/s]
φ	angle of circular cylinder [°]
θ	dimensionless temperature
Sub/superscripts	
$*$	dimensional value
$-$	surface-averaged quantity
cyl	cylinder
en	enclosure
c	cold
h	hot
upper	*Wall* 1 and *Wall* 4 of enclosure
lower	*Wall* 2 and *Wall* 3 of enclosure
right	*Wall* 1 and *Wall* 2 of enclosure
left	*Wall* 3 and *Wall* 4 of enclosure

that the temperature profile and heat transfer characteristics are highly dependent on the cross-sectional shape of the enclosure.

The effect of an inner body's position on natural convection in an enclosure has been reported by Tasnim et al. [16], Shu et al. [20], Lee et al. [21], Kang et al. [22], Ding et al. [23], Kim et al. [24], Yoon et al. [25], Husain et al. [26], and Park et al. [27]. They have investigated the influence of the inner body's position by changing the location of the body vertically [16,20–23] and horizontally [24–27] in the enclosure. They have observed that the heat transfer and fluid flow characteristics are strongly dependent on the position of the inner body as well as the Rayleigh number.

As summarized in previous research, many researchers have reported the effect of the thermal conditions of the enclosure, of the existence of a body in the enclosure, of the shape of the enclosure, and of an inner body's position in the enclosure on natural convection in the enclosure. However, there are few studies exploring how natural convection in the enclosure varies depending on both the enclosure's shape and an inner body's position simultaneously. Thus, in this study, natural convection in a rhombus enclosure with an inner circular cylinder has been investigated by changing both the cylinder's position and the Rayleigh number. The flow and heat transfer characteristics in the rhombus enclosure for different positions of the cylinder and different values of the Rayleigh number have been analyzed by observing the streamlines in the rhombus enclosure and the Nusselt number on the surface of the circular cylinder and the enclosure.

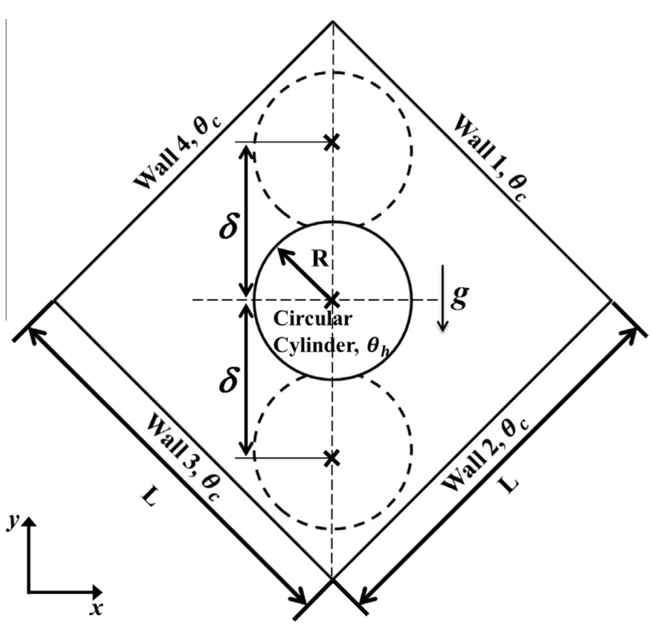

Fig. 1. Computational domain and coordinate system.

2. Computational details

2.1. Numerical methods

To investigate the effect of an inner cylinder's position on natural convection in an enclosure, Lee et al. [21], Kang et al. [22], Kim et al.

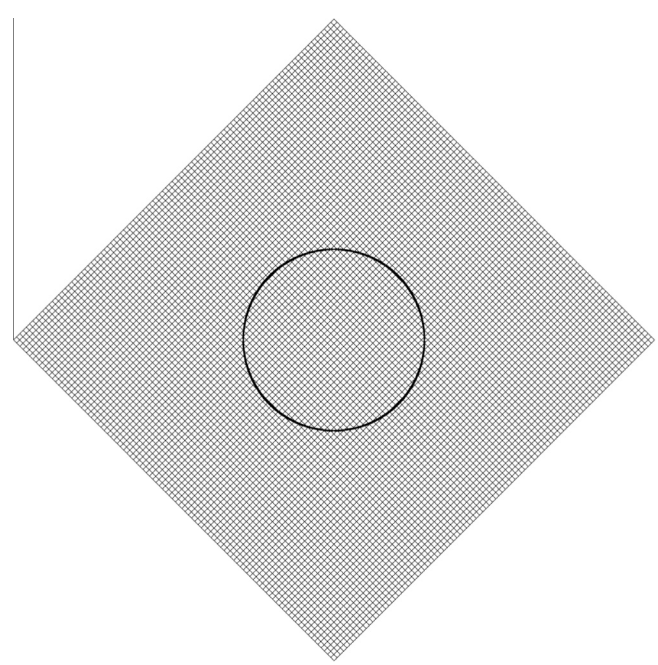

Fig. 2. A typical grid distribution for $\delta = 0$.