International Journal of Heat and Mass Transfer 95 (2016) 566–578

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Three-dimensional flow instability of natural convection induced by variation in radius of inner circular cylinder inside cubic enclosure

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ARTICLE INFO

Article history:
Received 15 June 2015
Received in revised form 18 December 2015
Accepted 18 December 2015
Available online 2 January 2016

Keywords:
Natural convection
Three-dimensionality
Vortical structure

ABSTRACT

Three-dimensional numerical simulations were conducted for the natural convection phenomena around a hot inner circular cylinder positioned in a cold cubic enclosure in the Rayleigh number range of $10^3 \leqslant Ra \leqslant 10^6$ at the Prandtl number of $Pr = 0.7$. The immersed boundary method (IBM) was used to capture the virtual wall boundary of the inner cylinder, based on the finite volume method (FVM). In this study, the transition of the flow regime from the steady state to the unsteady state and consequent three-dimensionality in the system induced by the increase in the flow instability were investigated. Detailed three-dimensional vortical structures of the convection cells at a relatively high Rayleigh number of $Ra = 10^6$ were analyzed using the visualization technique, and the heat transfer characteristics in the system resulting from the change in the vortical structures were addressed.

1. Introduction

Natural convection in an enclosure has various applications, ranging from industrial fields to environmental fields, such as heat exchangers, nuclear reactors safety technologies, electronics cooling to building thermal design, solar energy systems and stratified atmospheric boundary layers. The thermo-fluid behavior of those systems also entrains the fundamental knowledge of flow stability. More generally, almost all technologies involving passive heat transfer as the main source of thermal dissipation rely upon natural convection effects. For this reason, the relevant literatures have focused on heat transfer performances [1,2]. Natural convection heat transfer exhibits a great variety of complex dynamic behaviors, which depend greatly on the geometry and thermal conditions of the enclosure. Thus, the theoretical study of the phenomenon is comparatively difficult to understand and the experimental analysis of such systems has always inherent difficulties [3,4].

For several decades many researchers have investigated the effects of various parameters on natural convection in an enclosure with an inner body as the numerical methodology was developed. The horizontal concentric cylinder geometry inside an enclosure is used in pressurized-gas underground electric transmission cables [5]. Additionally, the annulus geometry has application in solar collector receiver and thermal storage systems [6]. According to the results of these previous studies, natural convection in an enclosure depends on the size and position of an inner cylinder [7–10].

Moukalled and Acharya [7] studied the natural convection heat transfer between a heated horizontal cylinder placed concentrically inside a square enclosure. Three different diameter-to-side aspect ratios between 0.1 and 0.3 were considered. The range of the Rayleigh number is $10^4 \leqslant Ra \leqslant 10^7$. According to their research, the total heat transfer increases with increasing Rayleigh number at constant enclosure aspect ratio. At constant Rayleigh numbers, the convection contribution to the total heat transfer decreases with increasing values of aspect ratios.

Shu and Zhu [8] studied the variation in the thermal and flow fields in a square enclosure with respect to the various radii of an inner circular cylinder. They obtained the results in the Rayleigh number range of $10^4 \leqslant Ra \leqslant 10^6$ with the Prandtl number of 0.71 and the diameter-to-side aspect ratios between 1.67 and 5.0. It was found that both the diameter-to-side aspect ratio and the Rayleigh number are critical to the patterns of thermal and flow fields in the enclosure.

Angeli et al. [9] investigated the effect of the radius of an inner cylinder on the heat transfer between the cylinder and the square enclosure. The range of the Rayleigh number is $10^2 \leqslant Ra \leqslant 5 \times 10^6$, and the Prandtl number is 0.7. Four values of the diameter-to-side ratios were considered: 0.2, 0.4, 0.6, and 0.8. According to their research, stable symmetric and non-symmetric steady-state solutions as well as unsteady regimes are observed, depending on the Rayleigh number and the aspect ratio of the cavity.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.12.044
0017-9310/

Nomenclature

Symbols

A	surface area of cylinder and walls of enclosure
f_i	momentum forcing
g	gravitational acceleration
H	vertical length of enclosure
h	heat source or sink
L	edge length of enclosure
n	direction normal to the wall
Nu	Nusselt number
P	dimensionless pressure
Pr	Prandtl number
q	mass source or sink
R	radius of circular cylinder
Ra	Rayleigh number
T	temperature
t	dimensionless time
u_i	dimensionless velocity vector
x_i	Cartesian coordinates system

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
θ	dimensionless temperature
λ_2	lambda-2 criteria for vortical structure
ν	kinematic viscosity
ξ	volume averaged orthogonal enstrophy
ρ	density
τ_p	period of the fluctuation of thermal and flow fields
φ	angle (degrees)
Ω	volume of fluid
ω	orthogonal enstrophy

Sub/superscripts

B	bottom wall
c	cold
C	cylinder
EN	enclosure
i, j	tensor notation
h	hot
T	top wall
$*$	dimensional variable

Mathematical symbol

$< >$	surface-averaged value

Kim et al. [10] studied on the natural convection in the square enclosure with respect to the position of the inner circular cylinder. The range of the Rayleigh number is $10^3 \leqslant Ra \leqslant 10^6$, and the Prandtl number is 0.7. The inner circular cylinder moved along the vertical centerline of the enclosure in the range of $-0.25 \leqslant \delta \leqslant 0.25$. They reported that the number, size and formation of convection cells in the enclosure depend on the location of the inner cylinder as well as the Rayleigh number.

In this study, therefore, authors consider three-dimensional configuration of the system having a cubic enclosure and an inner circular cylinder in order to investigate the transition of the flow regime from the steady state to the unsteady state due to the flow instability in the Rayleigh number range of $10^3 \leqslant Ra \leqslant 10^6$ when the radius of the inner circular cylinder varies in $0.1L \leqslant R \leqslant 0.4L$ as well as the consequent three-dimensionality in the system. Detailed three-dimensional vortical structures of the convection cells at a relatively high Rayleigh number of $Ra = 10^6$ were analyzed using the visualization technique, and the heat transfer characteristics in the system resulting from the change in the vortical structures were addressed.

2. Computational details

2.1. Numerical methods

In this study, the immersed boundary method based on the finite volume method is used to capture the virtual wall boundary of an inner circular cylinder positioned in the cubic enclosure. The immersed boundary method has a benefit to handle more easily an inner object having a complex geometry in the Cartesian coordinate system. Further details on the immersed boundary method are described in Kim et al. [11] and Kim and Choi [12].

The governing equations for mass, momentum, and energy conservation using the immersed boundary method are defined in their non-dimensional forms as follows:

$$\frac{\partial u_i}{\partial x_i} - q = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + Pr \frac{\partial^2 u_i}{\partial x_j \partial x_j} + Ra\ Pr\ \theta\ \delta_{i2} + f_i \tag{2}$$

$$\frac{\partial \theta}{\partial t} + u_j \frac{\partial \theta}{\partial x_j} = \frac{\partial^2 \theta}{\partial x_j \partial x_j} + h \tag{3}$$

The dimensionless variables in the above equations are defined as:

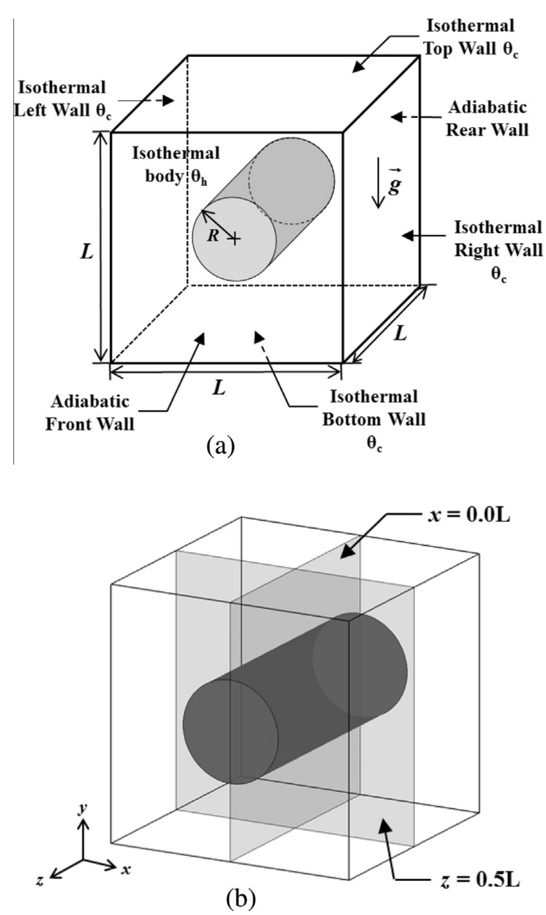

Fig. 1. (a) Computational domain and coordinate system along with boundary conditions and (b) definition of planes for cross-sectional view.