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Numerical simulation of natural convection in a horizontal enclosure: Part I. On the effect of adiabatic obstacle in middle

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A B S T R A C T

In this study, an effect of a three-dimensional obstacle of natural convection in a horizontal enclosure was discussed. Geometry which was taken into account was horizontal enclosure with unit aspect ratio and length of π along spanwise direction. The enclosure was heated from the bottom wall, and then was cooled down from above. An obstacle was located in the middle of the enclosure to examine its effect. A three-dimensional solution was obtained using Chebyshev spectral multi-domain methodology for different Rayleigh number at which the thermal behavior was evolved from a steady state to a chaotic pattern. As the geometry was elongated in conjunction with periodic boundary conditions to allow lateral freedom for the convection cells, longitudinal geometry along spanwise direction was discretized through a Fourier series expansion with a uniform mesh configuration. An adiabatic obstacle played a different role in determining the thermal behavior: No-slip condition of the surface of the obstacle disturbed the overall plume behavior in terms of the momentum transfer, whereas the adiabatic boundary condition did not influence significantly in terms of energy transfer. At a low Rayleigh number, thermal behavior in three-dimensional enclosure showed steady invariant solution along spanwise direction which is identical to two-dimensional result. With increasing buoyant force, spanwise invariance of longitudinal roll cell was collapsed and three-dimensional mode was obtained following flow regime transition. After undergoing periodically oscillatory phase, a chaotic flow transition occurred. At a high Rayleigh number, three-dimensional thermal plume oscillates freely in elongated geometry and consequently yields higher heat transfer rate. In addition, the thermal flow field was captured by visualizing the three-dimensional vortical structure. The chaotic three-dimensional flow behavior was quantitatively examined by obtaining the turbulent statistics.

1. Introduction

Rayleigh-Bénard convection (RBC) with a vertical thermal gradient in the horizontal layer confined between the heated bottom plate and cooled top plate has been a topic of interest in the thermal fluid dynamics [1]. RBC shows various flow regimes from conduction to hard turbulence. Global statistics and flow dynamics have been investigated throughout various regimes [2–4]. Due to the characteristics of RBC as one of the examples for canonical turbulent flows, thermal structures in turbulent flow regime have been widely investigated and correspondingly heat transfer coefficients have been proposed for wide range of Rayleigh number and aspect ratios [5–7]. For mid-range of Rayleigh number, Flow behaviors with respect to thermal boundary layer has been studied [8].

One of the reasons why the RBC has been investigated for decades is that vast flow regimes can be obtained despite simple geometric configuration. Contrast to a cylindrical container which has been mostly taken into account as a fundamental configuration for the RBC, A rectangular enclosure configuration has been also utilized especially owing to invariance along longitudinal direction. With respect to numerical approach, Numerical models of this problem typically employ a finite computational domain along the horizontal directions. Various aspect ratios have been taken into account to investigate the nature of fluid motion. Flow instability and consequent transition of convection mode were studied in limited aspect ratio of computational geometry. Stability analyses can be one of the measures to investigate the flow transition. In three-dimensional natural convection flow, a flow instability is reported to be characterized by the large scale rotating vortices [9]. Two-dimensional natural convection have been also studied by applying two- and three-dimensional perturbation [10]. Cubic enclosure is a representatively simple geometry to investigate the convection mode and corresponding flow behavior [11]. Long

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rectangular cavity has been selected to investigate a variation of large-scale thermal flow behavior for turbulent flow regime [12–14]. The quantitative results such as rms temperature fluctuation and skewness show that the flow behavior in large-scale convection can have strong spatial degree of freedom. An effect of aspect ratio for RBC has been considered by varying an aspect ratio of a rectangular cavity in conjunction with Rayleigh number and revealed that the aspect ratio influenced an onset of unsteady motion and corresponding global flow structure, and became significant for small Rayleigh number [15].

Plume behaviors and corresponding heat transfer enhancement mechanisms are investigated with respect to practical geometry such as obstacle in the cavity. Recently, numerous researches for a limited aspect ratio of en enclosure with obstacles have been investigated to examine the effect of the existence of obstacles. A conducting body in a rectangular enclosure with an obstacle inside was first numerically considered in [16], which was followed by other analogous researches as a benchmark example. To take into account a complicated geometry in a horizontal enclosure, complicated geometries have been employed to evaluate an effect of the existence of the obstacle on the natural convection in conjunction with a series of cases: a single obstacle in the middle [17]; a single obstacle at an arbitrary location within an enclosure [18]; and arbitrary formation of multiple obstacles [19]. They examined the effect of obstacles by obtaining the local Nusselt number and dominant frequency of the plume behavior. An array of bluff bodies was considered in a wide horizontal fluid layer [20,21]. They investigated the plume behavior for various thermal boundary conditions of bodies and examined the periodicity of the roll cell when increasing the aspect ratio of a horizontal fluid layer by obtaining the wavelength of a roll cell.

Researches for natural convection with the obstacles introduced above have been limited to a two-dimensional approach, in which the plume behavior at a relatively low Rayleigh number was investigated. Since a two-dimensional simulation shows asymptotically different flow pattern with respect to unsteadiness with increasing of buoyant force, the necessity to investigate a three-dimensional thermal behavior affected by the existence of an obstacle has been raised. Thus, three-dimensional enclosure heated from below and cooled from above is considered in this study. An aspect ratio (width to height) of unity for an enclosure is taken into account, and a periodic boundary condition along the spanwise direction is employed to allow lateral freedom for the convection cells. An adiabatic obstacle is located in the middle and elongated through the spanwise direction. For comparison, the natural convection in an enclosure without an obstacle is also simulated and the differences due to the obstacle are discussed. The three-dimensional flow behavior is examined by comparing two-dimensional results from previous researches [20–22], and extends to a further buoyant force at $Ra = 10^7$. The impact of the existence of an adiabatic body on the turbulent flow structure, dynamics, and overall heat transfer is evaluated by obtaining quantitative turbulent statistics such as the power spectra and autocorrelation. In addition, vortical structures are visualized by adopting the swirl strength.

2. Numerical methodology

2.1. Governing equation and numerical discretization

The system consists of a horizontal enclosure heated from the bottom and cooled from above. A schematic of the geometry is shown in Fig. 1. The enclosure has height L and the aspect ratio is unity. The obstacle in middle has a height of one-third of the enclosure height, 0.33L. The bottom wall of the enclosure is kept at a constant high temperature of T_h, whereas the top wall is kept

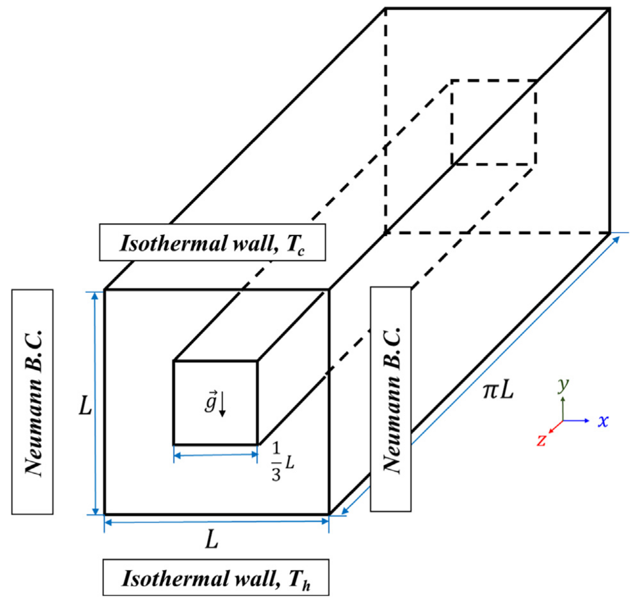

Fig. 1. Schematics of the computational geometry.

at a constant low temperature of T_c. The length along the longitudinal direction is assigned to be π. As the geometry is elongated in conjunction with periodic boundary conditions to allow lateral freedom for the convection cells, longitudinal direction was discretized through a Fourier serious expansion with a uniform mesh configuration. The fluid properties are also assumed to be constant, except for the fluid density in the buoyancy term, which follows the Boussinesq approximation. The gravitational acceleration acts in the negative y-axis.

The continuity, Navier-Stokes, and energy equations in their non-dimensional forms are taken into account as:

$$\nabla \cdot \mathbf{u} = 0 \tag{1a}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + Pr \nabla^2 \mathbf{u} + Ra\ Pr\ \boldsymbol{\theta}\ \mathbf{k}_2 \tag{1b}$$

$$\frac{\partial \theta}{\partial t} + \mathbf{u} \cdot \nabla \theta = \nabla^2 \theta \tag{1c}$$

The dimensionless variables in the above equations are defined as:

$$t = \frac{t^* \alpha}{L^2}, \quad \mathrm{x} = \frac{\mathrm{x}^*}{L}, \quad \mathbf{u} = \frac{\mathbf{u}^* \mathrm{L}}{\alpha}, \quad P = \frac{P^* L^2}{\rho \alpha^2}, \quad \theta = \frac{T - T_c}{T_h - T_c} \tag{2}$$

In the above equations, ρ represents the dimensional density, and α is the thermal diffusivity. The superscript $*$ in Eq. (2) represents the dimensional variables. In addition, $\mathbf{u}$, P, t, and θ are the non-dimensional velocity, pressure, time and temperature. A conventional non-dimensional parameter can be obtained in momentum Eq. (1b) as follows:

$$Pr = \frac{\nu}{\alpha} \text{ and } Ra = \frac{g \beta L^3 (T_h - T_c)}{\nu \alpha} \tag{3}$$

where ν, g, and β are the kinematic viscosity, gravitational acceleration, and volume expansion coefficient, respectively.

For the boundary conditions, $\theta = 1$ at bottom wall and $\theta = 0$ at top wall of the enclosure. At the lateral wall, adiabatic boundary condition is assigned as follows:

$$\frac{\partial \theta}{\partial \mathbf{n}} = 0 \tag{4}$$