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Partitioning effect on natural convection in a circular enclosure with an asymmetrically placed inclined plate

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ABSTRACT

This work presents a numerical investigation on steady-state laminar natural convection in a circular enclosure with an inner flat plate at $Ra = 10^6$. The plate is inclined placed along the radial direction but is asymmetric about the center of enclosure, with eccentricity defined as the distance between the centers of two entities. The enclosure and plate are kept at low and high temperatures, respectively. The objective of this study is to explore the effects of two significant parameters, i.e., eccentricity (r) and inclination (α) of the plate, on the flow and heat transfer characteristics of the enclosure-plate system. The numerical simulation is performed using our in-house fourth-order finite difference code which is well validated. The effects of the two parameters are analyzed by the total heat transfer rate, temperature distribution, formation and evolution of various vortices, and distribution of local heat transfer rate for $r/D = 0.00(0.05)0.20$ and $\alpha = 0^\circ(5^\circ)180^\circ$ where D is the enclosure diameter. Numerical results reveal that natural convection is weakened by the partitioning effect of nearly horizontal plate since fluid circulation is greatly constrained, while the effect is minor at low and high inclinations where fluid circulation is pronounced. Depending on the eccentricity and inclination, there could be at most two and three vortices in the left and right halves of the enclosure, respectively, whose formation and spatial evolution behaviors and intensity variations exhibit complex patterns, and are closely related with the heat transfer characteristics. For high eccentricity configurations, the heat transfer in the gap can be dominated by either convection or conduction depending on the gap size, the latter of which is characterized by the expected linear variation of circumferential position of maximum local heat transfer rate with the inclination.

1. Introduction

Natural convection in enclosures is one of the most significant and classical problems in fluid mechanics and heat transfer, and is frequently encountered in engineering circumstances such as indoor energy management and electronic cooling. The fluid is heated and moves upward due to buoyancy, which results in the fluid circulation in the enclosure and heat transfer between entities of different temperatures. Depending on the types of hot and cold entities, natural convection in enclosures can be roughly categorized into two types. The first is natural convection induced by temperature difference between different parts of the enclosure itself, such as the well-known differentially heated enclosure configuration where the two vertical sidewalls are kept at different temperatures [1], and the enclosure where the sidewalls are heated and cooled in different sections [2]. The second type is characterized by the enclosure and inner objects maintained at different temperatures, in which the fluid is heated by one and cooled by the other and circulates in the enclosure, thus heat transfer occurs between the enclosure and inner objects. The major difference between the two configurations is that in the second type, the flow circulation is also affected by the presence of inner objects in addition to the buoyancy arising from temperature difference. The inherent interaction between the fluid and inner objects complicates the flow and heat transfer characteristics.

There were a number of works on natural convection in an enclosure with inner cylinders due to its relatively simple geometrical configuration and physical model, e.g., enclosure with an inner circular [3] or square cylinder [4]. In most studies, the existence of inner cylinders reduces the fluid domain size although the cylinders are normally much smaller than the enclosure. Comparably, there were relatively less studies on the geometric configuration of enclosure with inner thin flat plates. The primary feature of the thin plate geometry is its high specific surface area, by which the fluid can be effectively heated by the large surface of the plate without noticeable reduction of fluid domain size. The presence of the plate only slightly reduces the space for fluid circulation, while its influence on the flow characteristics

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is mainly realized through the partitioning effect which roughly separates the fluid within two connected domains.

Singh & Liburdy [5] experimentally studied natural convection in a circular enclosure with a concentric thin flat plate at Rayleigh number up to $Ra = 2.8 \times 10^6$; the effect of plate inclination on flow and heat transfer characteristics were investigated. They found that the effect is minor for inclination larger than 60°. The heat transfer rate at the bottom of the plate is more affected than the top part, and the local Nusselt number decreases due to flow separation. For a square enclosure, Nag et al. [6] studied the differentially heated enclosure with one horizontal plate attached to the hot sidewall. They concluded that the heat transfer between two sidewalls is weakened for an insulated plate, while it can be intensified for a conductive plate regardless of size and position, which is also supported by the conclusions of Tasnim & Collins [7] for a curved plate in a differentially heated enclosure. Dagtekin & Oztop [8] investigated similar configuration at $Ra = 10^4$–10^6 except that the enclosure has two cooled and two insulated sidewalls, and two vertical heated plates attached to the enclosure bottom. The introduction of the plates affects the flow pattern much more significantly than the heat transfer performance, and the total heat transfer rate increases with the spacing of two plates. There are more studies on the configuration of enclosure with an isolated plate that is not attached to any of the sidewalls, in which the fluid could circulate around the plate. Wang et al. [9] numerically and experimentally studied natural convection in a square enclosure with a heated plate close to the bottom, or a cooled plate close to the enclosure top at $Ra = 10^2$–10^7. They found that the heat transfer rate almost does not vary with the plate position if the spacing between the plate and enclosure sidewall is more than 25% the enclosure length, while it increases with the decreasing spacing for spacing smaller than 20% the enclosure length. Oztop et al. [10] studied the effects of size and position of a horizontal or vertical plate in a square enclosure. The total heat transfer rate for the vertical plate configuration can be 20% higher than that of the horizontal one. The same conclusion is also obtained by Wang et al. [11] for mixed convection in a lid driven enclosure. Altaç & Kurtul [12] explored natural convection in a tilted rectangular enclosure with a centered heated plate at $Ra = 10^5$–10^7 and enclosure aspect ratio equals to one or two. They found that for the square enclosure, the total heat transfer rate reaches maximum at inclination of 22.5°, while it is not observed for enclosure of aspect ratio two. For cases of low Rayleigh number and small plate, the total heat transfer rate almost does not vary with the inclination due to negligible partitioning effect. Natural convection in a square enclosure with two orthogonally placed plates is also studied by Hakeem et al. [13] and Kandaswamy et al. [14], in which the heat transfer characteristics are primarily determined by the plate with higher temperature.

Previous studies, some of which were reviewed above, undoubtedly demonstrate the complexities of the physics of natural convection in an enclosure with inner plates. The flow and heat transfer characteristics are greatly determined by a multitude parameter space, including the geometry and inclination of both the enclosure and inner plate, and Prandtl and Rayleigh numbers. The heat transfer performance of the plate-enclosure system is dependent on the flow pattern in that whether the fluid is intensely circulating in the enclosure without noticeable interference from the plate. The deep understanding of the physical mechanism is beneficial for both fundamental research and engineering application in similar configurations. However, it is concluded from the above review that most of the current studies only focused on the horizontal or vertical thin flat plate in the enclosure, while there is relatively less work on the inclined plate configuration to reveal the effects of inclination and position of the plate although they are confirmed to be deterministic on the flow and heat transfer characteristics of the plate-enclosure system. The present work performs a systematic and comprehensive numerical investigation on natural convection in a circular enclosure with an inclined thin flat plate which is eccentrically placed in the enclosure. The enclosure and plate are kept at low and high temperatures, respectively. The objective of this work is to study the effects of inclination and eccentricity of the plate on the flow and heat transfer characteristics, with emphasis on the partitioning effect brought by the plate that weakens fluid circulation and degrades heat transfer. The numerical results are presented from various aspects, including the total heat transfer rate, and spatial distributions of temperature, stream function and local Nusselt number. The formation, spatial evolution and vanishing of various vortices are emphasized along with the trajectory of vortex center.

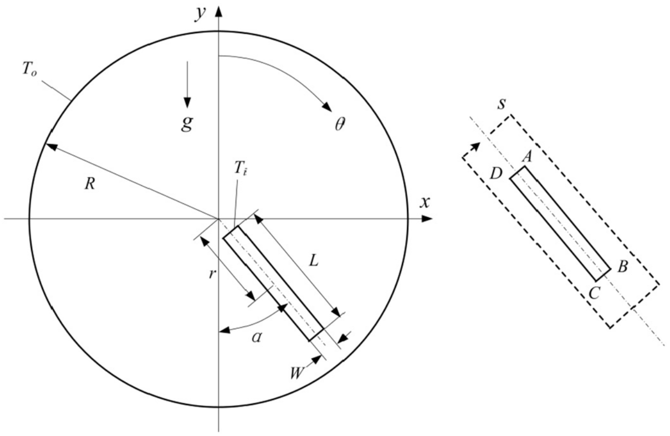

Fig. 1. Schematic of the physical model.

The paper is organized as follows. Section 2 is a general description of the targeted physical problem, the employed numerical methods and the code validation. Section 3 presents and discusses the numerical results for the effects of inclination and eccentricity of the plate. Some conclusions are drawn in Section 4.

2. Numerical setup

2.1. Physical model

The physical model is schematically given in Fig. 1. The model is defined in the Cartesian coordinate system, labeled as (x, y) in the figure, and the gravitational direction is along the negative y-direction. A thin flat plate is eccentrically placed in a circular enclosure of radius R. The length of the plate is L and the width is W, and the distance between the centers of two entities is r. A local coordinate s is defined wrapping around the plate and the perimeter is defined as s_0. The inclination angle between the major axis of the plate and the gravitational direction is α. Both the plate and enclosure are assumed sufficiently long in the axial direction, thus the end effects are neglected and only two-dimensional simulation is performed here. The two geometries are isothermal, with constant temperature T_o and T_i on the surfaces of the enclosure and plate, respectively. This rational approximation is consistent with the fact that the thermal conductivity of solid is several orders of magnitude that of fluid. The enclosure is filled with air ($Pr = 0.71$) whose thermophysical properties are considered constant in the present numerical simulations, except for the density variation that follows the Boussinesq approximation. Since the problem is governed by a large multitude parameter space (Ra, L, W, r, α), some of the parameters are fixed at representative constant values in the present study, including $Ra = 10^6$, $L/D = 0.4$ and $W/D = 0.02$ in which D is the diameter of circular enclosure ($= 2R$). The magnitudes of length and width well define a thin flat plate with high specific surface area, thus the fluid can be effectively heated without noticeable reduction of fluid domain size. We mainly study the effects of eccentricity and inclination of the plate on the flow and heat transfer characteristics, with the scope of the values at $r/D = 0.0(0.05)0.2$ and $\alpha = 0°(5°)180°$ due to the symmetry of the geometries.