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Natural convection in a square enclosure with two inner circular cylinders positioned at different vertical locations

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ABSTRACT

The present study investigates the natural convection induced by a temperature difference between a cold outer square enclosure and two hot inner circular cylinders. A two-dimensional solution for natural convection in an enclosure with inner cylinders is obtained using an accurate and efficient immersed boundary method. The immersed boundary method based on the finite volume method is used to handle inner cylinders located at different vertical centerline positions of the enclosure for different Rayleigh numbers in the range $10^3 \leqslant Ra \leqslant 10^6$. The results in the case of two cylinders are compared with those in the case of the single cylinder in order to see the effect of the interaction between the adjacent two inner hot cylinders in addition to the interaction between two hot inner cylinders and the cold walls of the enclosure. The distribution of isotherms and streamlines eventually reaches a steady state or changes its state from steady to unsteady, depending on the values of the Rayleigh number and the cylinder position in the enclosure. The distribution of the local and surface-averaged Nusselt numbers is obtained for different Rayleigh numbers and the cylinder positions.

1. Introduction

The heat transfer and flow characteristics of natural convection in an enclosure have many industrial and environmental applications, such as heat exchangers, solar collectors, nuclear safety systems, chemical reactors, electronic equipment cooling, and stratified atmosphere boundary layers. Many engineers in industrial settings wish to avoid the use of active control equipment (e.g., fans) for cooling or heating because of their additional cost, noise, and vibration problems. Therefore, it is important to fully understand the mechanism of natural convection. In this study, we investigate the effect of two cylinders at different vertical locations in the enclosure on the heat transfer and fluid flow.

For several decades, many investigations have dealt with natural convection from a heated body placed concentrically [1–6] or eccentrically [7–11] inside a cooled enclosure.

Cesini et al. [1] performed a numerical and experimental analysis of natural convection from a horizontal cylinder enclosed in a rectangular cavity. The influence of the cavity aspect ratio and the Rayleigh number on the distribution of temperature and Nusselt number was investigated. As a result, the average heat transfer coefficients increase with the increasing Rayleigh number.

Asan [2] numerically studied two-dimensional natural convection in an annulus between two isothermal concentric square ducts and obtained solutions up to a Rayleigh number (*Ra*) of 10^6. The results showed that the dimension ratio and Rayleigh number have a profound influence on the temperature and flow field.

Moukalled and Acharya [3] and Shu and Zhu [4] studied the change of the thermo-flow field between a low-temperature outer square enclosure and a high-temperature inner circular cylinder according to the radius of the inner circular cylinder. Moukalled and Acharya [3] considered three different aspect ratios, r/L, of the cylinder radius, r, to the enclosure height, L, in the range of $10^4 \leqslant Ra \leqslant 10^7$. They showed that, at a constant enclosure aspect ratio, the total heat transfer increases with increasing Rayleigh number. When the Rayleigh number is constant, the convection contribution to the total heat transfer decreases with the increasing value of the aspect ratio. Shu and Zhu [4] obtained numerical results for Rayleigh numbers ranging from 10^4 to 10^6 and aspect ratios between 1.67 and 5.0. It was found that both the aspect ratio and the Rayleigh number are critical to the patterns of the flow and thermal fields. They also suggested that a critical aspect ratio may exist at high Rayleigh numbers to distinguish between the flow and thermal patterns.

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Nomenclature

f_i	momentum forcing
g	acceleration of gravity [m/s^2]
L	length of square enclosure [m]
n	normal direction to the wall
Nu_{cyl}	local Nusselt number along the inner single circular cylinder
$\overline{Nu}_{cyl}$	surface-averaged Nusselt number along the inner single circular cylinder
$Nu_{upper\,cyl}$	local Nusselt number along the upper inner circular cylinder
$Nu_{lower\,cyl}$	local Nusselt number along the lower inner circular cylinder
Nu_{en}	local Nusselt number along the walls of the enclosure
$\overline{Nu}_{upper\,cyl}$	surface-averaged Nusselt number along the upper inner circular cylinder
$\overline{Nu}_{lower\,cyl}$	surface-averaged Nusselt number along the lower inner circular cylinder
P^*	pressure [Pa]
P	dimensionless pressure $\left(=\frac{P^*L^2}{\rho\alpha^2}\right)$
Pr	Prandtl number (= ν/α)
r	dimensionless radius of the cylinder (= R/L)
R	radius of circular cylinder [m]
Ra	Rayleigh number $\left(=\frac{g\beta L^3(T_h-T_c)}{\nu\alpha}\right)$
t^*	time [s]
t	dimensionless time $\left(=\frac{t^*\alpha}{L^2}\right)$
T	dimensional temperature [K]
T_h	hot temperature [K]
T_c	cold temperature [K]
u_i^*	velocity [m/s]
u_i	dimensionless velocity $\left(=\frac{u_i^*L}{\alpha}\right)$
x_i^*	Cartesian coordinates [m]
x_i	dimensionless Cartesian coordinates $\left(=\frac{x_i^*}{L}\right)$
y_c^*	distance between the square enclosure center to the circular cylinder center [m]
y_c	dimensionless distance between the square enclosure center to the circular cylinder center [m]

Greek symbols

α	thermal diffusivity [m^2/s]
β	thermal expansion coefficient [K^{-1}]
δ^*	vertical distance between the centers of two circular cylinders [m]
δ	dimensionless vertical distance between the centers of two circular cylinders
ρ	density [kg/m^3]
ν	kinematic viscosity [m^2/s]
φ	angle from the top of the circular cylinder
θ	dimensionless temperature $\left(=\frac{T-T_c}{T_h-T_c}\right)$

Subscripts/superscripts

*	dimensional value
–	surface-averaged quantity

Kim et al. [7] and Yoon et al. [8] conducted numerical investigations on the natural convection induced by the temperature difference between a cold outer square enclosure and a hot inner circular cylinder for different Rayleigh numbers varying over the range $10^3 \leqslant Ra \leqslant 10^7$. The location of the inner circular cylinder (δ) was changed vertically along the centerline of the square enclosure. The number, size, and formation of the cells strongly depended on the Rayleigh number and position of the inner circular cylinder within the enclosure. At $Ra = 10^7$, the bifurcation of natural convection from the unsteady to the steady state depended on δ. They showed that the flow and heat transfer at $Ra = 10^7$ became unsteady at $\delta \leqslant \delta_{C,L}$ and $\delta \geqslant \delta_{C,U}$, where $\delta_{C,L} = 0.05$ and $\delta_{C,U} = 0.18$.

However, natural convection in the presence of an array of cylinders inside an enclosure is quite different from that in the presence of a single cylinder in the enclosure. This is because of the mutual interaction among the buoyant plumes generated by an array of cylinders, in addition to the interaction between the array and the enclosure. Several researchers have considered the effect of the presence of an array of cylinders on natural convection numerically [12–17] or experimentally [18–20].

Lacroix [12] numerically studied the natural convection heat transfer from two vertically separated heated cylinders to a rectangular cavity cooled from above. Two cavity widths and three top cylinder positions were investigated over Rayleigh numbers in the range $10^4 \leqslant Ra \leqslant 10^6$. The results showed the complexity of convective motion in different geometric configurations and the effects of the cylinder positions and Rayleigh number on the local and overall heat transfer rates.

Lacroix and Joyeux [13] conducted a numerical study of natural convection heat transfer from two horizontal heated cylinders confined to a rectangular enclosure having conducting vertical walls of finite thicknesses and horizontal walls at the heat sink temperature. They focused on investigating the interaction between convection in the fluid-filled cavity and conduction in the vertical walls, indicating that heat transfer is strongly influenced by the coupling effect between solid wall conduction and fluid convection.

Chae and Chung [18] conducted an experimental investigation of the natural convection heat transfer for two parallel horizontal cylinders. They considered various pitch-to-diameter ratios (P/D) from 1.02 to 9, Prandtl numbers from 2014 to 8334, and Rayleigh numbers varying over the range $7.3 \times 10^7 \leqslant Ra \leqslant 4.5 \times 10^{10}$. They measured the mass transfer rate from the cylinders and obtained the heat transfer rate (Nusselt number) on the basis of the analogy concept. Their results showed that the Nusselt number ratios of the upper to lower cylinders, which increased with P/D, were less than 1 at P/D values of less than about 1.5 for laminar flows, and were almost 1 at P/D values very close to 1 for turbulent flows. The Nusselt number ratios of the upper to lower cylinders also depended on the Prandtl number, showing a steep variation with P/D at higher Prandtl numbers.

Although many researchers have studied on the natural convection, there is little information about natural convection processes within a cooled square enclosure containing two hot circular cylinders located at different vertical positions along the center of the enclosure. In this situation, the flow and heat transfer characteristics are largely affected by the location of two cylinders and the buoyancy-induced convection at different Rayleigh numbers. The aim of this study is to examine the effects of the locations of two hot inner circular cylinders in the enclosure and the buoyancy-induced convection on heat transfer and fluid flow in the enclosure when two circular cylinders are located at different vertical positions along the center of the enclosure at different Rayleigh numbers. The results in the case of two cylinders are compared with those in the case of the single cylinder in order to investigate the effect of the interaction between two adjacent hot cylinders on the fluid flow and heat transfer in the enclosure, in addition to the interaction between the two hot cylinders and the cold enclosure walls.