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Natural convection in square enclosure with hot and cold cylinders at different vertical locations

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ABSTRACT

This study investigates the natural convection in a square enclosure with hot and cold cylinders, induced by the temperature difference between a cold enclosure and the hot and cold circular cylinders contained within it. The immersed boundary method is used to model the two enclosed cylinders, based on the finite volume method, and two-dimensional natural convection was studied for different Rayleigh numbers in the range $10^3 \leqslant Ra \leqslant 10^6$. Additionally, the study investigates the effect the presence of the hot and cold cylinders at different locations within the enclosure have on the heat transfer and fluid flow. The locations of the hot and cold circular cylinders are varied vertically along the centerline at the left and right parts of the enclosure, respectively. The existence of local peaks for the Nusselt numbers along the surfaces of the cylinders and enclosure is determined by the gap between the cylinders and the enclosure and thermal plume governed by the convection, respectively. Detailed analysis results for the distributions of the streamlines, isotherms, and Nusselt numbers are presented in this paper.

1. Introduction

The heat transfer and flow characteristics of the natural convection in an enclosure has many industrial and environmental applications, including heat exchangers, nuclear and chemical reactors, electronic equipment cooling, and stratified atmosphere boundary layers. The geometries that arise in engineering applications are more complicated than a simple enclosure filled with a convective fluid. The geometric configuration of interest is coupled with the presence of bodies embedded within the enclosure. This study investigated the effect the presence of the hot and cold cylinders at different locations in the enclosure had on the heat transfer and fluid flow.

For several decades, research has been conducted on the effect the presence of a body under different thermal conditions within an enclosure has on natural convection. In these studies, the thermal boundary condition applied to the square enclosure has been either a horizontally imposed temperature difference or a heat flux condition [1–5], or a vertically imposed temperature difference or a heat flux condition [6–11].

Kim et al. [12] and Yoon et al. [13] carried out 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 cell 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 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 $\delta_{C,U} = 0.18$.

Lee et al. [14] conducted a numerical investigation on the natural convection within a square enclosure containing a circular cylinder placed at different horizontal and diagonal locations for different Rayleigh numbers varying in the range $10^3 \leqslant Ra \leqslant 10^6$. Regardless of the Rayleigh number, when the inner cylinder was placed closer to the side wall or corner of the enclosure by a horizontal or diagonal movement, respectively, the two inner eddies were separated and located at the upper and lower parts of the enclosure in the narrow region facing the cylinder movement. Otherwise, one large circulation was formed in the opposite region.

The natural convection around an array of cylinders is different from those around a single cylinder because of the mutual interaction of the buoyant plumes generated by the cylinders.

Reymond et al. [15] carried out an experimental investigation on the natural convection heat transfer from a pair of vertically

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Nomenclature

Nu	local Nusselt number $\left(Nu = \frac{\partial\theta}{\partial n}\big\|_{wall}\right)$
Nu_{hotcyl}	local Nusselt number along the hot inner circular cylinder
$Nu_{coldcyl}$	local Nusselt number along the cold inner circular cylinder
Nu_{en}	local Nusselt number along the walls of the enclosure
$\overline{Nu}$	surface-averaged Nusselt number $\left(\overline{Nu} = \frac{1}{W}\int_0^W NudS\right)$
$\overline{Nu}_T$	surface-averaged Nusselt number along the top wall of the enclosure
$\overline{Nu}_B$	surface-averaged Nusselt number along the bottom wall of the enclosure
$\overline{Nu}_R$	surface-averaged Nusselt number along the right wall of the enclosure
$\overline{Nu}_L$	surface-averaged Nusselt number along the left wall of the enclosure
$\overline{Nu}_{en}$	surface-averaged Nusselt number along the square enclosure
P	dimensionless pressure
Pr	Prandtl number ($Pr = \nu\alpha$)
R	radius of circular cylinder
Ra	Rayleigh number $\left(Ra = \frac{g\beta L^3 (T_h - T_c)}{\nu\alpha}\right)$
t	dimensionless time
T	dimensional temperature
T_h	hot temperature
T_c	cold temperature
u_i	dimensionless velocity
x_i	dimensionless Cartesian coordinates
f_i	momentum forcing
g	gravity
L	length of square enclosure
n	normal direction to the wall
W	surface area of the wall

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
δ	vertical distance from center of square cylinder to circular cylinder center
δ_{i2}	Kronecker delta
ρ	density
ν	kinematic viscosity
φ	angle from the top of circular cylinder
θ	dimensionless temperature

Sub/Superscripts

*	dimensional value
-	surface-averaged quantity

aligned horizontal cylinders for different Rayleigh numbers (2×10^6, 4×10^6, and 6×10^6) and for different lengths of cylinder spacing (1.5, 2, and 3 cylinder diameters). Their results showed that the fluid flow and heat transfer around the lower cylinder were unaffected by the presence of an unheated lower cylinder, and those around the heated upper cylinder were likewise unaffected by the presence of the unheated lower cylinder. However, when both the lower and upper cylinders were heated, the fluid flow and heat transfer around the upper heated cylinder was strongly affected by the presence of the heated lower cylinder because a plume rising from the heated lower cylinder interacted with the heated upper cylinder.

Chae and Chung [16] carried out an experimental investigation on 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 from 7.3×10^7 to 4.5×10^{10}. They measured the mass transfer rate from the cylinders and obtained the heat transfer rate (Nusselt number) based upon the analogy concept. Their results showed that the Nusselt number ratios of the upper to lower cylinders that 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 natural convection in the absence or presence of a body within an enclosure, few studies have considered natural convection in the presence of a pair of cylinders within an enclosure. In the present study, hot and cold cylinders were placed at different locations within a cold enclosure to investigate the effect the locations of the hot and cold cylinders within the enclosure has on the fluid flow and heat transfer because a plume rising from the hot cylinder interacts with the cold cylinder and enclosure. We also considered different Rayleigh numbers to investigate the effect the buoyancy-induced convection caused by the temperature difference has on the fluid flow and heat transfer in the enclosure in the presence of the cylinders.

2. Numerical methodology

Fig. 1 shows the computational domain and coordinate system along with the boundary conditions considered in the present study. The system consisted of a square enclosure with sides of length *L*, within which hot and cold cylinders with radius *R*

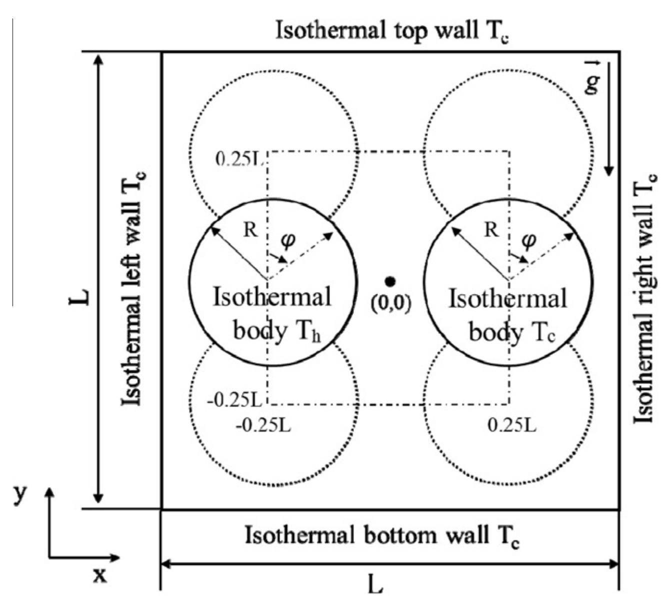

Fig. 1. Computational domain and coordinate system along with boundary conditions.