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A phenomenological study on the convection heat transfer around two enclosed rotating cylinders via an immersed boundary method

Ali Ashrafizadeh [a,b,*], Ali Akbar Hosseinjani [b]

[a] On Sabbatical Leave, Department of Mechanical and Industrial Engineering, University of Toronto, Toronto, Ontario, Canada
[b] DOS Computational Lab, Faculty of Mechanical Engineering, K. N. Toosi University of Technology, Tehran, Iran

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ABSTRACT

In this paper, an extended immersed boundary method is used to study the convection of heat from two rotating hot cylinders in a square cold cavity containing air with $Pr = 0.7$. The variables in this study are the rotation scenario, Rayleigh and Richardson numbers. The computations have been carried out for three different rotation scenarios and a range of Rayleigh and Richardson numbers, i.e. $Ra = 10^4,\ 10^5$ and 10^6 and $Ri = 0.1,\ 1,\ 10,\ 100$. The pure natural convection case, i.e. $Ri \to \infty$, has also been considered. Isotherms, streamlines, local and average Nusselt numbers on all solid boundaries are reported in each test case. It is found that the Rayleigh and Richardson numbers are the dominant variables. Rotation scenario is also important and the rotation may significantly increase the heat transfer rate from the cylinders compared to the corresponding buoyancy-induced convection case. Unstable, periodic flow patterns are observed in some test cases at $Ra = 10^6$.

1. Introduction

Convection heat transfer from heated circular cylinders in a cavity with cold walls has received much attention due to its importance in fundamental heat transfer research and also its applications in the thermal design and analysis of heat exchangers, chemical and nuclear reactors, solar energy collectors and electronic cooling equipments. A large number of numerical and experimental studies have been carried out to investigate the effects of boundary conditions, fluid properties, geometry of the flow field, and the rotational status of the cylinders, on convection heat transfer.

Early studies focused on a stationary or linearly moving circular cylinder in a rectangular cavity. Cesini et al. [1] studied, both experimentally and numerically, the effects of the Rayleigh number and the cavity geometry on the heat transfer from a circular cylinder in a rectangular enclosure. Higher heat transfer rate was observed when the side walls were closer to the cylinder and oscillatory flow was observed at $Ra = 10^5$. Shu et al. [2] studied the natural convection around a hot cylinder inside a square cavity by the numerical DQ method and have shown that the position of the cylinder strongly affects the thermal field. Roychowdhury et al. [3] carried out a numerical study to determine the effects of the ratio of the cylinder and enclosure dimensions, enclosure boundary conditions and the fluid Prandtl number on the natural convection around a heated cylinder in a square enclosure. Angeli et al. [4] numerically simulated the buoyancy-induced flow regimes around a horizontal cylinder centered in a square cavity filled with air and developed a correlation for the average Nusselt number. Kim et al. [5] applied an immersed boundary method to investigate two-dimensional unsteady natural convection between a cold square enclosure and a hot inner circular cylinder. They studied the effects of the cylinder vertical location and Rayleigh number on the heat transfer. Lee et al. [6] used an immersed boundary method to model the natural heat convection around a circular cylinder in a square enclosure at different Rayleigh numbers, i.e. $Ra = 10^3$, 10^4, 10^5 and 10^6. Butler et al. [7] experimentally studied the natural convection from a heat generating horizontal cylinder enclosed in a square cavity. They reported that the available correlations failed to correctly predict the Nusselt number at high Rayleigh numbers. Hussein [8] numerically studied natural convection in a parallelogrammic cavity with a linearly moving hot circular cylinder where the upper and lower walls of the cavity were adiabatic and side walls were kept at a fixed temperature. In this research the effects of the cylinder vertical location and the direction of its motion, i.e. upward or downward movement, and the inclination angle of the cavity were studied. Kang et al. [9] numerically

* Corresponding author at: Department of Mechanical and Industrial Engineering, University of Toronto, 5 King's College Road, Toronto, Ontario M5S3G8, Canada.

E-mail addresses: ashrafizadeh@kntu.ac.ir (A. Ashrafizadeh), aahosseinjani@mail.kntu.ac.ir (A.A. Hosseinjani).

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Nomenclature

c_p	constant pressure specific heat
$\mathrm{D}(\Phi)$	distribution operator
$\vec{f}$	external momentum source
$\vec{\mathrm{f}}$	non-dimensional external momentum source
$\vec{\mathrm{F}}$	non-dimensional external momentum source on *IB* point
$\mathrm{f_x, f_y}$	non-dimensional external momentum source components
g	gravitational acceleration
h	external heat source
h	non-dimensional external heat source
$\mathrm{I}(\phi)$	interpolation operator
k	thermal conductivity
L_0	problem-dependent length scales
L_s	the side of enclosure
$\mathbf{n}$	normal vector at on immersed boundary point
$\mathbf{n}_x, \mathbf{n}_y$	normal vector components at on immersed boundary point
N_{IB}	number of immersed boundary points
Nu	Nusselt number
P	pressure term
P	non-dimensional pressure term
Pr	Prandtl number
Q_Γ	specified heat flux
Re	Reynolds number
Ri	Richardson number
Ra	Rayleigh number
t	time
t	non-dimensional time
T	temperature
T_H, T_C	hot and cold reference temperatures
u_0	problem-dependent velocity scale
$\vec{\mathrm{u}}^*$	intermediate velocity
$\vec{\mathrm{u}}$	non-dimensional velocity vector
$\vec{\mathrm{U}}$	non-dimensional velocity at on immersed boundary point
$\mathrm{u, v}$	non-dimensional velocity components
$\vec{\mathrm{U}}_\mathrm{B}$	specified non-dimensional fluid velocity at the boundary
$\vec{\mathrm{V}}_\Gamma$	non-dimensional boundary velocity
$\vec{x}$	Eulerian point coordinate vector
$\vec{\mathrm{x}}$	Eulerian point non-dimensional coordinate vector
$\vec{\mathrm{X}}_{IB}$	Coordinate vector of an immersed boundary point
$\mathrm{x, y}$	Eulerian point non-dimensional coordinate vector components
$\mathrm{X}_{IB}, \mathrm{Y}_{IB}$	immersed boundary point coordinate vector components

Greek letters

α	thermal diffusivity
β	coefficient of thermal expansion
δ	discrete delta function
Θ	non-dimensional temperature
Θ^*	non-dimensional intermediate temperature
Θ_Γ	non-dimensional boundary temperature
$\bar{\Theta}$	non-dimensional temperature at on immersed boundary point
Θ_B	specified non-dimensional fluid temperature at the boundary
ρ_0	density at the reference temperature
ν	kinematic viscosity
ω	rotational speed of the cylinder

Superscripts

n	time step
i	inner loop iteration index
k	outer loop iteration index

Subscripts

IB	immersed boundary point

investigated the bifurcation of the unsteady natural convection and the effects of the location of an inner heated cylinder along a horizontal or diagonal line in a cooled enclosure on upwelling and downwelling thermal plumes at $\mathrm{Ra} = 10^7$. Park et al. [10] numerically studied the natural convection from a heated cylinder in an inclined square enclosure. Choi et al. [11] numerically studied the effect of a circular cylinder's vertical location on natural convection in a rhombus enclosure and reported three different flow patterns, i.e. steady-symmetric, steady-asymmetric and unsteady-asymmetric flow regimes.

Another natural convection flow situation of significant interest has been the convection of heat around two stationary hot circular cylinders in a cold enclosure. In this case the interactions between the buoyant plumes result in interesting and rather complex flow patterns and phenomena. Lacroix and Joyeux [12] studied a pair of vertically aligned hot circular cylinders in a rectangular enclosure with insulated side walls. Reymond et al. [13] experimentally studied convection of heat around single and also a pair of vertically aligned cylinders in an enclosure filled with water. Chae and Chung [14] used heat and mass transfer analogy and experimentally investigated the mass transfer rate from vertically aligned cylinders to determine the effects of pitch-to-diameter ratio, Prandtl number and Rayleigh number on the heat transfer. Flow bifurcation and natural convection from a pair of circular cylinders aligned horizontally have been studied by park et al. [15]. Karimi et al. [16] have also studied two horizontally aligned circular cylinders in a square enclosure via a finite volume-based commercial CFD package and have reported the occurrence of both steady and unsteady flow regimes. Park et al. [17] investigated natural convection phenomena in a square enclosure with two inner circular cylinders positioned at different vertical locations.

The effect of the rotation of a cylinder inside an enclosure on heat convection has also been studied. Ghaddar and Thiele [18] modeled the heat convection around a constant heat flux rotating cylinder within an isothermal rectangular enclosure via a spectral element method. They found that the heat transfer was enhanced at low Rayleigh numbers and noticeably hampered at high Rayleigh numbers due to the rotational motion of the cylinder. Costa and Raimundo [19] studied the effects of the cylinder diameter, its rotational speed, thermal conductivity and thermal capacity of the cylinder on the mixed convection in a square enclosure. Hussain and Hussein [20] investigated the mixed convection in a cavity with an inner rotating cylinder via the finite volume method. Their results show that the Richardson and Reynolds numbers have significant effects on the flow and temperature fields and the rotating cylinder position strongly affects the heat convection. Liao and Lin [21] studied mixed convection within domains with a stationary or rotating cylinder using an immersed-boundary method. The effects of the Rayleigh number, Prandtl number and the aspect ratio between the inner cylinder and the outer enclosure on the flow