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Mixed convection heat transfer in a differentially heated cavity with two rotating cylinders

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ABSTRACT

Mixed convection heat transfer in a differentially heated cavity with two rotating cylinders was studied numerically for various pertinent parameters such as Richardson number, Reynolds number, non-dimensional rotation speed of the cylinder, and the location of the cylinders. The results from these simulations were validated using an open-source spectral element code, Nek5000. The results of this study were presented in terms of streamlines, isotherms, local and average Nusselt number, and temperature profiles. The results illustrated that the average Nusselt number depends strongly on the rotation speed of the cylinder, Reynolds number, and Richardson number. However, the average Nusselt number was found to be independent of the rotation speed at high Richardson number (Ri = 10). In addition, the direction of the rotation speed of the cylinders has a profound effect on the average Nusselt. The study illustrated that the magnitude and direction of the rotation speed of the cylinders have a significant effect on the flow pattern and isotherms.

1. Introduction

Mixed convection flow and heat transfer due to the interaction between the shearing action of the rotating objects (cylinders) and natural convection effect have many engineering applications such as MEMs, nuclear reactors [1], solidification process, food processing, etc. Mixing is an important process used in a variety of manufacturing processes in the food, cosmetics, chemicals, drugs and pharmaceutical industries. In many of these processes, the mixing assembly (mixer) consists of multiple cylinders rotating in opposite directions in order to enhance mixing and control shear. Additional attachments such as vanes/paddles/blades can be mounted on these rotating cylinders to move the material back towards the center of the container and/or perform simultaneous mixing and scraping operations, thus increasing throughput of the mixers. Many authors have studied shear and buoyancy-driven flow in enclosures [1–10]. For example, Khanafer and Aithal [1] numerically studied mixed convection heat transfer in a lid-driven cavity with a rotating cylinder for various parameters such as Richardson number, the non-dimensional angular velocity of the cylinder, and the direction of rotation. Their results demonstrated that the average Nusselt number was depended on angular velocity of the cylinder (magnitude and direction). Moreover, their study illustrated greater heat transfer enhancement with a rotating cylinder compared with a stationary cylinder. Enhancement of natural convection heat transfer in an enclosure by a rotating cylinder was investigated numerically by Fu et al. [2]. A penalty finite-element method with a Newton-Raphson iteration algorithm was used in their study to solve the governing equations along with the boundary conditions. The authors found that the rotation of the cylinder had a profound effect on enhancing heat transfer inside the cavity. Liao and Lin [3] conducted numerical studies of mixed convection of a heated rotating cylinder in a square enclosure for different Rayleigh number, Prandtl number, and aspect ratio between the inner cylinder and outer enclosure. Their results showed that small aspect ratio exhibited higher Nusselt number while the rotation of the cylinder reduced the average Nusselt number.

The effect of the presence of multiple cylinders on natural convection inside an enclosure has been studied by many authors both numerically [11–17] and experimentally [18–20]. Natural convection in square enclosure with hot and cold cylinders at different vertical locations was investigated by Park et al. [13]. The distributions of the flow and thermal fields were found to depend on the positions of the cylinders in the enclosure and the buoyancy-induced convection by the ascending thermal plume from the hot cylinder. The same authors [14] investigated the natural convection induced by a temperature

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Nomenclature

g	gravitational acceleration (m/s^2)
Gr	Grashof Number $= g\,\beta\,(T_h - T_C)\,H^3/\nu^2$
H	cavity side length (m)
Nu	Nusselt number
P	dimensionless fluid pressure $= pH/(\rho u_o \nu)$
Pr	Prandtl number $= \nu/\alpha$
Re	Reynolds number $= u_o\,H/\nu$
Ri	Richardson number $= Gr/Re^2$
r_o	radius of the cylinder (m)
r_o/H	non-dimensional radius of the cylinder
T	temperature (K)
t	time (s)
u	velocity in x-direction (m/s)
u_o	tangential speed of the cylinder (m/s)
U	dimensionless horizontal velocity $= u/u_o$
v	velocity in y-direction (m/s)
V	dimensionless vertical velocity $=$ v$/u_o$
x, y	cartesian coordinates (m)
X, Y	dimensionless cartesian coordinates, $(x, y)/H$

Greek symbols

α	thermal diffusivity of the fluid
β	coefficient of thermal expansion of fluid
ω	angular speed of the cylinder (rad/s)
ν	kinematic viscosity (m^2/s)
θ	dimensionless temperature $= (T - T_C)/(T_h - T_C)$
ρ	density (kg/m^3)
Ψ	dimensionless stream function

Subscripts

c	Cold
h	Hot

difference between a cold outer square enclosure and two hot inner circular cylinders. The immersed boundary method based on the finite volume method was used to study the effect of the cylinders located at different positions along the vertical centerline of the enclosure for different Rayleigh numbers in the range 10^3 to 10^6. Their results illustrated that the values of average Nusselt number along the walls of the enclosure were larger for the case of two cylinders than in the case of a single cylinder for all Rayleigh numbers and cylinder positions considered.

Reymond et al. [21] conducted experiments of natural convection heat transfer from a single horizontal cylinder and a pair of vertically aligned horizontal cylinders. Surface heat transfer distributions around the circumference of the cylinders were presented for Rayleigh numbers of 2 × 10^6, 4 × 10^6 and 6 × 10^6 and a range of cylinder spacing of 1.5, 2 and 3 diameters, respectively. With a cylinder pairing, the lower cylinder was found unaffected by the presence of the second cylinder; the same was true of the upper cylinder if the lower one was not heated. However, when both cylinders were heated it was found

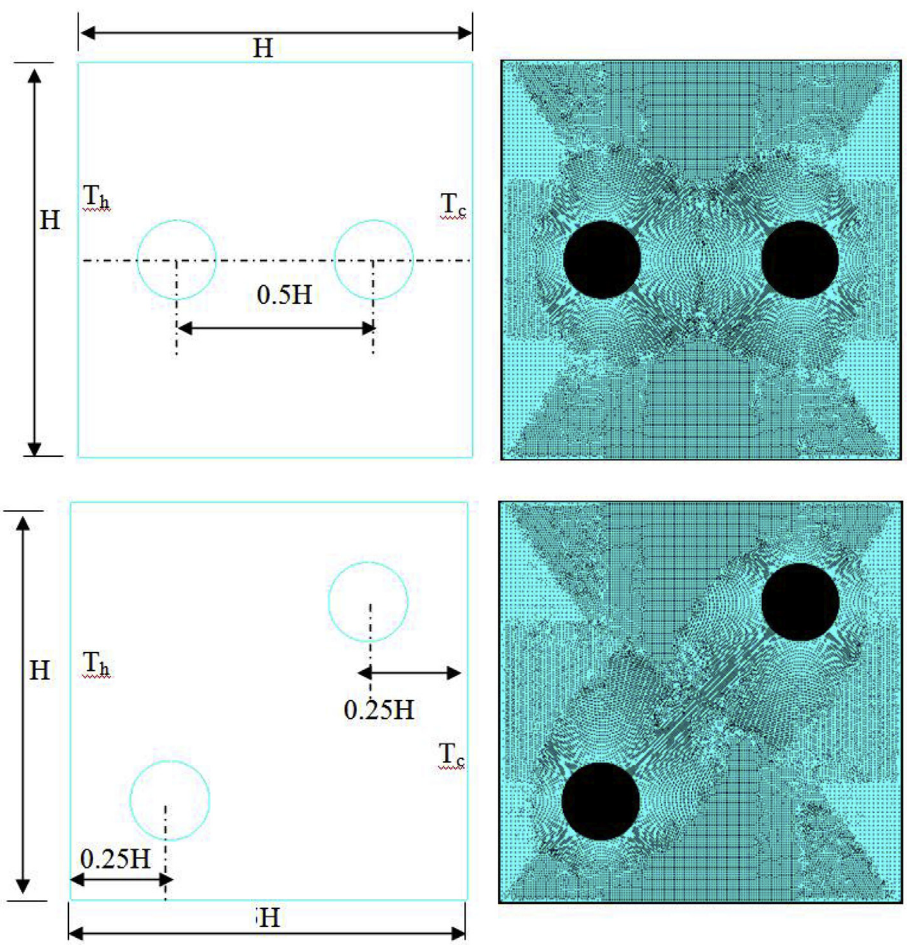

Fig. 1. (a) Schematic configuration of the considered model with coordinates and boundary conditions, (b) Grid distributions.