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Mixed convection characteristics in rectangular enclosure containing heated elliptical block: Effect of direction of moving wall

Krunal M. Gangawane*,[1], Siddharth Gupta

Department of Chemical Engineering, School of Engineering, University of Petroleum and Energy Studies, Dehradun-248007, Uttrakhand, India

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ABSTRACT

The present research numerically explores the hydrodynamic and thermal characteristics due to mixed convection in the rectangular enclosure with one of the vertical wall moving and containing centrally placed heated elliptical block for steady state condition. In particular, the influence of different flow pertaining parameters, such as, the direction of moving vertical wall (either in positive –y or negative –y coordinate directions), aspect ratio of an elliptical cylinder (E_r = 0.5, 1 and 2) are studied for the broad range of dimensionless parameters (Reynolds number: $1 \le Re \le 5000$; Prandtl number: $1 \le Pr \le 100$ and Grashof number: $0 \le Gr \le 10^5$) by using finite volume method (FVM) and SIMPLE numerical approach. The analysis of physical insights of an enclosure is accomplished by systematic evaluation of the streamlines as well as isotherms profiles. In order to compare mean heat transfer from an elliptical cylinder with that of circular shape, normalized Nusselt number (Nu^N) is estimated. Heat transfer characteristics are more predominantly affected due to the direction of moving lid than the aspect ratio of the elliptical cylinder. Also, the enclosure with moving wall along positive –y direction tends to enhance heat transfer rate. Rather than a pure circular shape, the enclosure with heated elliptical block ($Er \neq 1$) shows a higher rate of convective heat transfer.

1. Introduction

Convective heat transfer from cylinders of an elliptical cross section has received huge consideration in recent years because of its numerous engineering applications as well as pragmatic relevance. The development of high-performance heat exchanger devices for making effective use of energy is a very crucial and pressing problem nowadays. For an instance, the process heat transfer equipment, such as heat exchangers made of tubes of circular cross-section are widely used in many chemical/process, automobile or like industries (probes and sensors, hot wire anemometry, RTM process of producing fiber composites, filters of aerosol, screens of filtration process, etc.). The flow circulation over such tubes, however, is not necessarily normal to the tube axis which makes the tube cross-section in the direction of flow to have an elliptical shape. In general, the elliptical geometry can represent the circular cylinder as well as very thin plate depending on the value of the axis ratio [1,2]. The heat transfer characteristics from an elliptical tube/block depend on its geometry (i.e. aspect ratio, surface roughness, etc.), fluid properties, flow approaching condition, and the block/tube surface temperature variation. Moreover, the study of heat transfer from an elliptical body inside a channel/enclosure is of great theoretical significance as elliptical shape can be considered as a prototype for modeling heat transfer from a broad range of bluff bodies (as it can used to the elaborate the influence of both angle of attack and thickness). The different modes of convective heat transfer modes may significantly take place ranging from forced convection dominated regime to natural convection one inside above mentioned systems. The mixed convection (combined free and forced) heat transfer occurs when both inertial and buoyancy forces are of comparable magnitude. The basic parameters which govern the forced and natural convection are Reynolds number (Re) and Grashof number (Gr), respectively [1–3].

On the account of fundamental and pragmatic implication, the experimental and numerical investigations within square/rectangular enclosures have been extensively studied and very well documented. The reason for the overwhelming popularity of such constellations is due to the simple domain with the ability to explore the broad varieties of fluid flow and heat transfer fundamentals (multiplicity of steady solutions, boundary layer, vortex size and location, circulation of fluid, etc.). Typical examples which can be idealized as an enclosure are cooling systems of electronic gadgets, high performance building insulation, multi-shed structures, furnace, food processing (heating of various foodstuffs like beans, carrot and potato chips, etc.), lubrication

* Corresponding author.
E-mail addresses: krunalgangawane@gmail.com, gangawanek@nitrkl.ac.in (K.M. Gangawane).
[1] Current address: Department of Chemical Engineering, National Institute of Technology Rourkela, Rourkela 769008, Orissa, India.

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Nomenclature

E_R	aspect ratio of elliptical cylinder (E_r = radius along x-direction/radius along –y-direction), dimensionless
C_p	heat capacity, J/(kg.K)
CWT	constant wall temperature, K
Gr	Grashof number, dimensionless
H	height of cavity (Characteristic length), m
h	heat transfer coefficient, W/(m^2.K)
k	thermal conductivity, W/(m.K)
L	width of cavity, m
Nu	local nusselt number, dimensionless
$\overline{Nu}$	average nusselt number, dimensionless
Nu^N	normalized nusselt number, dimensionless
P	Pressure, N/m^2
Pe	Peclet number, dimensionless
Pr	Prandtl number, dimensionless
q_w	heat flux, W/m^2
Ra	Rayleigh number, dimensionless
Re	Reynolds number, dimensionless
Ri	Richardson number, dimensionless
$\overline{T}$	Temperature, K
U_w	velocity of moving wall, m/s
$\overline{u_x}$, $\overline{u_y}$	velocity components, m/s
u_x, u_y	velocity components, dimensionless
$\overline{x}$, $\overline{y}$	co-ordinates, m
x,y	co-ordinates, dimensionless
$\Delta\theta$	normalized temperature difference, dimensionless

Greek

μ	dynamic viscosity, N.s/m^2
α	thermal diffusivity, m^2/s
β	coefficient of thermal expansion, 1/K
θ	normalized temperature, dimensionless
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
$\overline{\rho}$	average density determined at T_{ref}, K
Ψ	stream function, m^2/s
Ω	angular rotational speed, RPM

Subscripts

c	cold
w	wall or surface
ref	reference value

technologies, fluidized bed drying of fibrous substances, solar heat collectors, drying, etc. [4–11]. Moreover, there are few industrial processes (crystal growth, solidification, etc.) in which convection currents should be minimized/restricted. This can be accomplished by placing obstacle/object/cylinder (of any shape circular, elliptical square, triangular, etc.) is used for controlling fluid flow due to convection [12] in enclosure. Ample literature is available for convection heat transfer in lid-driven enclosures [13–18]. Most of the literature have explored the lid-driven cavity with one of the walls exposed to higher temperature/heat source. Few studies have covered enclosure with one or two-sided moving lid. However, very limited information on the lid-driven rectangular enclosure containing obstacle for a wide range of Prandtl numbers is documented. Few studies [19–21] have provided the benchmarking of results for hydrodynamics in the lid-driven enclosure. Many studies [22–30] have revealed the natural/forced/mixed convection characteristics in enclosure with adiabatic/isothermal obstacle of varying shape. Abu-Nada et al. [31] delineated the influence of the presence of horizontal circular cylinder on mixed convection characteristics for nanofluids. Oztop et al. [32] investigated the fluid flow due to mixed convection in the lid-driven enclosure containing two-dimensional body for a wide range of Richardson numbers. They reported the presence of a circular body can be considered as a control parameter for heat and fluid flow in enclosures or likes structures. Billah et al. [33] presented the numerical study of combined convection in the lid-driven cavity having heated circular hollow cylinder. They found the significant impact of the cylinder diameter on overall fluid flow and heat transfer behavior. Subsequently, Rahman et al. [34] studied mixed convection in the double lid-driven cavity under the influence of magnetic field having heat generating a square block for a wide range of Ri. Moreover, Błasiak and Kolasinski [35] computationally modeled two-dimensional mixed convection in the lid-driven cavity with a constant heat flux boundary condition for a wide range of pertinent parameters. Increase in Ri causes the decrease in average surface averaged Nu. Recently, natural convection from the heated hexagonal block for non-Newtonian power-law fluids is reported by Gangawane and Manikandan [36]. They observed remarkable influence of thermal boundary conditions on the overall structure of fluid flow in the cavity. More recently, Gangawane [37] identified the critical Reynolds number in top lid-driven containing heated triangular block for the laminar condition due to mixed convection. Convection rate increases only up to Re_{cr} = 190–220 for lower Grashof number values (Gr ≤ 10^2).

In recent years, the studies delineating heat and fluid flow characteristics from heated elliptical cylinder have seen remarkable growth. For an instance, Badr [38] presented numerical study of mixed convection from straight elliptical tube for laminar range of Re (Re = 50–200) and Grashof number (Gr = 0-10^6). It is observed that, for given Re, augmentation in Gr tends to suppress the vortex shedding. Kondjoyan and Daudin [39] studied the effect of free stream turbulence intensity (1.5–40%) on the heat and mass transfer from the surface of elliptical as well as the circular cylinder. Later, the heat transfer including an optimization study for comparison of the staggered circular and elliptical tubes for forced convection is reported by Matos et al. [40]. This research concluded that the elliptical arrangement can enhance heat transfer up to 13%. Chen [41] presented the numerical simulation study for pressure melting ice around the horizontal elliptical cylinder by solving Reynolds equation ($\mu\partial^2 u/\partial s^2 = dp/dh$, where '$s$' and '$h$' are the distances in normal and tangential directions, respectively). Meng et al. [42] experimentally analyzed the convective heat transfer in an alternating elliptical axis tubes. The cross-sectional change in the alternating elliptical axis tubes strongly affects the heat transfer characteristics. Subsequently, Faruquee et al. [43] elucidated the influence of axis ratio on heat and fluid flow properties around the elliptical cylinder for laminar flow condition. The wake size and the drag coefficient show linear variation with an axis ratio of the cylinder. Later, Bharti et al. [44] presented an extensive study of forced convection heat transfer from channel built-in an elliptical cylinder for non-Newtonian power-law fluids. They reported the similar influence of elliptical cylinder on flow governing parameters as that of the circular one. Cheng [45] numerically investigated the natural convection boundary layer flow with temperature-dependent viscosity from a horizontal elliptical cylinder with constant surface heat flux thermal condition. Local Nusselt number of the elliptical cylinder increases with the Prandtl number. Chandra and Chhabra [46] presented detailed analysis of forced convection from semi-circular cylinder in unconfined flow condition. This study identified the critical values of Reynolds number for wake formation and onset of vortex shedding. Subsequently, the heat transfer characteristics across a pair of confined elliptical cylinders in the line array for non-Newtonian power-law fluids is studied by Nejat et al. [47] for different aspect ratio of elliptical cylinder (E_r = 0.25–2). They observed that the elliptical cylinder with E_r = 0.5 can be more efficient