International Journal of Thermal Sciences 134 (2018) 242–257

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Heat transfer and entropy generation of laminar mixed convection in an inclined lid driven enclosure with a circular porous cylinder

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ARTICLE INFO

Keywords:
Lid driven enclosure
Mixed convection
Circular porous cylinder
Inclination angle
Entropy generation

ABSTRACT

Convective heat transfer and entropy generation in an inclined lid driven square enclosure with a circular porous cylinder positioned at the center have been investigated numerically. The governing transport equations within the porous media are treated according to the volume-average theory while the transport phenomena in the rest of the enclosure are represented with Navier–Stokes equations. The bottom wall of the enclosure is assumed to have higher temperature than the top wall and the sidewalls are insulated. In addition, the top horizontal wall is moving in its own plane with a constant speed while all other walls remain stationary. Computations have been conducted over a wide range of pertinent parameters: Richardson number ($Ri = 0.01$, 1, 5 and 10), Darcy number ($Da = 10^{-5}$, 10^{-4}, 10^{-3} and 10^{-2}), and inclination angle ($\alpha = 0$, 30, 45, 75 and 90). Results revealed that the effects of Darcy number and inclination angle on heat transfer depends on the Richardson number. The effect of the inclination angle on the heat transfer and entropy generation inside the enclosure is more noticeable at high Richardson numbers. Second law analysis also indicated that the proportion of the irreversibilities due to the fluid friction and heat transfer varies as the scrutinized parameters change.

1. Introduction

Due to its practical importance, mixed convection flow and the associated heat transfer behavior in enclosures with a moving boundary continues to be widely investigated theoretically, numerically, and experimentally. The problem of mixed convection with lid driven flows occurs in most of environmental and engineering applications such as, electronic device cooling, food processing, heat exchanger, solar energy collector, thermal storage, chemical processing equipment, high performance building insulations, furnace, lubrication systems, drying or geophysics technologies and others [1–4]. In the mixed convection type of heat transfer, there is a significant interaction between natural and forced convection and it happens when shear driven force caused by the movement of wall (walls) and the gravity driven buoyancy force due to the presence of gravitational field and density gradient (temperature gradients) are of comparable magnitude and coupling of these forces makes the analysis more complicated. The ratio of the Grashof number to square of the Reynolds number ($Ri = Gr/Re^2$) which is called Richardson number, characterizes the mixed convection regime and it is on the order of one for mixed convection flows.

Number of investigations on lid driven cavity and mixed convection involving different combinations of cavity configurations and various pertinent parameters such as Rayleigh number, Richardson number and Grashof number have been grown rapidly in recent years. Additionally, obstacles, partitions and fins of varying shapes are utilized inside the enclosures to impact the flow field and heat transfer characteristics. Dagtekin and Oztop [5] studied mixed convection heat transfer in a lid driven cavity with an isothermally heated rectangular block inserted at different positions. They observed that the dimension of rectangular block inside the cavity has significant effect on heat transfer. Shi and Khodadai [6–8] reported that the mixed convection heat transfer and fluid flow can be controlled by utilizing thin fin in lid driven enclosures. Oztop et al. [9] numerically investigated mixed convection heat transfer in a lid driven differentially heated cavity with a cylindrical body inside. They considered different thermal boundary conditions for the inner cylinder and performed the simulations for a wide range of Richardson number, location of the cylinder and cylinder diameter. They observed that the fluid flow and temperature characteristics of the enclosure is mostly influenced by the direction of the moving wall. The mixed convection heat transfer in a lid driven cavity with a heated circular hollow cylinder in the center is investigated numerically by Billah et al. [10]. They reported that flow field and temperature distribution inside the enclosure is mostly affected by diameter of the cylinder and solid–fluid thermal conductivity. Islam et al. [11]

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https://doi.org/10.1016/j.ijthermalsci.2018.08.018
Received 8 March 2017; Received in revised form 30 July 2018; Accepted 7 August 2018

numerically studied the impacts of the Richardson number, blockage ratio and blockage placement eccentricities on heat transfer in a lid driven cavity with an isothermally heated square body. The effect of the exit port location on heat transfer and irreversibility generation inside the cavity is numerically explored in a square enclosure with heat generating rectangular body by Shuja et al. [12]. Rahman et al. [13] employed finite element technique to numerically study mixed convection heat transfer in a rectangular cavity with a heat conducting horizontal circular cylinder inside. Khanafer and Aithal [14] numerically analyzed the effects of Rayleigh number, radius and location of the cylinder and type of boundary condition on heat transfer rate in a lid driven enclosure with a circular body. Gangawane [15] numerically studied mixed convection heat transfer in a lid driven enclosure with heated triangular body inside for a wide range of pertinent non-dimensional parameters. Several studies dealing with enhancing natural convection heat transfer in obstructed and finned enclosures have been reported in previous works [16–18].

Utilization of porous medium is one of the efficient ways to control the heat transfer performance in enclosures. It increases heat transfer surface and provides an effective interaction between convective heat transfer inside pores and heat conduction in a solid matrix [19–21]. Thus, heat transfer and fluid flow analysis in complex domains including clear fluid and porous regions is very useful for an optimization of various engineering devices. Heat transfer and fluid flow analysis in porous structures and their applications are extensively documented in the literature [22–24]. Dixon and Kulacki [25] numerically studied mixed convection heat transfer and laminar fluid flow in horizontal fluid saturated porous layers. In the second part of their work, they reported the experimental mixed convection heat transfer coefficients for the same conditions [26]. The effects of surface thermal radiation on natural convection heat transfer in a locally heated enclosure with a horizontal porous layer is numerically studied by Wang et al. [27]. Alloi et al. [28] numerically examined the effects of the inclination angle, aspect ratio of the enclosure and the form drag parameter on the natural convection heat transfer in a tilted enclosure filled with a fluid-saturated porous medium. Hu et al. [29] numerically studied the natural convection heat transfer in a square cavity with a cylinder covered by a porous layer. They found that the addition of a porous layer can alter the flow field and increase the heat transfer rate. In the case of enclosures filled with a porous medium saturated by nanofluid, some interesting results can be found in Refs. [30,31].

On the basis of above literature review and author's knowledge, the utilization of a porous body inside a tilted lid driven enclosure has received minimal attention. Moreover, most of the previous studies are based on the first law analysis, which is not sufficient to clarify the energy efficacy of thermal systems. Irreversibilities due to the fluid friction and the heat transfer process that cause energy loss, are present in all thermofluidic processes. Entropy generation can be utilized as a gauge to determine the extent of these irreversibilities. In designing practical thermal systems, it is appropriate to minimize the rate of entropy generation so as to maximize the available energy, which can be achieved by utilizing the Entropy Generation Minimization (EGM) method [32,33]. The objective of the current investigation is to closely study the mixed convection heat transfer and entropy generation in a tilted square enclosure with a circular porous cylinder placed in the center of the enclosure at different pertinent parameters. The results are shown by streamlines, isotherms, average Nusselt number, local and average entropy generations and Bejan number.

2. Mathematical modeling

This work intends to numerically explore the mixed convection heat transfer and entropy generation inside a two-dimensional inclined square enclosure (with sides of length L) in the presence of a centered circular porous cylinder with radius r_o ($= 0.2\,L$) and thermal conductivity of k_p. Fig. 1 illustrates the schematic diagram of the enclosure with the circular porous cylinder, the coordinate system and related parameters. The top horizontal wall of the enclosure moves in $+x$ direction with a uniform velocity U_0, while all other walls remain

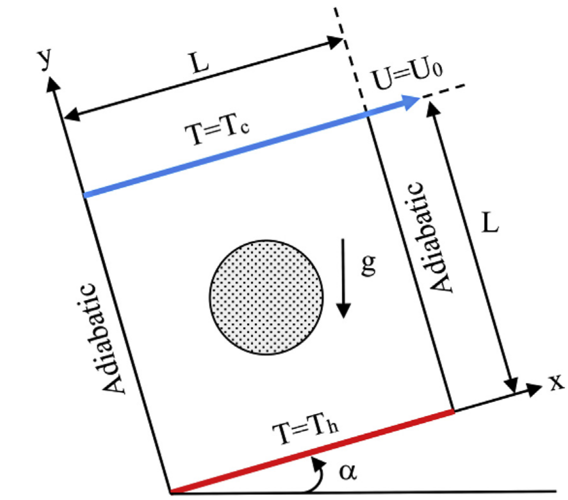

Fig. 1. Physical model with coordinates and boundary conditions.

Table 1
Grid refinement test at $Ri = 1$, $Da = 10^{-2}$ and $\alpha = 0$.

Mesh size	Nu_{Avg}
4100	2.9876
7200	3.0042
11,200	3.0243
22,000	3.0931

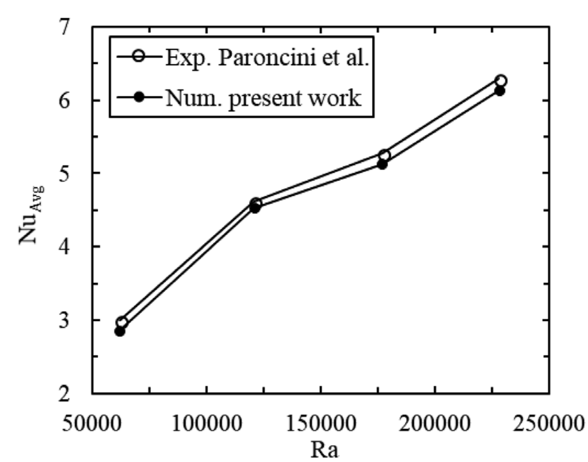

Fig. 2. Comparison of the average Nusselt number obtained in the present work and experiments [43] at different Rayleigh numbers.

Table 2
Comparison of the average Nusselt number between the results obtained in present work and Singh et al. [44].

Da	Pr = 0.015			Pr = 1000		
	Present work	Ref. [44]	Relative Error (%)	Present work	Ref. [44]	Relative Error (%)
10^{-2}	9.18	9.16	0.21	14.13	14.78	4.39
10^{-3}	7.98	7.98	0	12.51	12.58	0.55
10^{-4}	6.53	6.47	0.92	7.63	7.36	3.66
10^{-5}	5.91	5.82	1.50	5.66	5.39	5.01