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Conjugate natural convection heat transfer in a partitioned differentially-heated square cavity

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ABSTRACT

In this study numerical results for conjugate natural convection flow and heat transfer in a differentially-heated square cavity divided by a partition with finite thickness and thermal conductivity are presented. A series of numerical simulation is carried out using the finite volume method over a wide range of the Rayleigh number (10^5–10^9), with three dimensionless partition thicknesses (0.05, 0.1 and 0.2) and three dimensionless partition positions (0.25, 0.5 and 0.75), both are non-dimensionalized by the cavity width. The results show that the average Nusselt number increases with the Rayleigh number but decreases with partition thickness. It is also found that the partition position has a negligible effect on the average Nusselt number for the whole range of Rayleigh number considered.

1. Introduction

Conjugate natural convection in a differentially-heated, partitioned cavity with heat-conducting partition wall is present in various situations in nature and engineering, such as in solar thermal systems, electronic equipment, chemical reactors and buildings, and has attracted extensive research interest (see, *e.g.*,[1–6]). The majority of the early studies have focused on the steady-state behaviour and assumed either a very thin partition (in particular a partition without thickness) or a partition with infinite thermal conductivity. The neglect of or the over-simplified assumptions about the coupling of the fluids on either side of the heat-conducting partition have been shown to lead to significant inaccuracy in prediction of the heat transfer coefficients (see, *e.g.*, [7, 8]).

The numerical results of Ho and Yih [9] show that heat transfer in an air-filled partitioned rectangular cavity is considerably lower than that in a non-partitioned cavity, while the numerical study of Acharya and Tsang [10] shows that inclination angle also has a strong influence on the maximum Nusselt number. Turkoglu and Yücel [11] numerically simulated the flow and conjugate natural convection heat transfer in cavities with multiple conducting partitions and conducting side walls and found that the increase of number of partitions leads to the decrease of heat transfer whereas on the other hand the increase of the Rayleigh number results in increased heat transfer. However, they also found that the cavity aspect ratio has no significant bearing on heat transfer within the range considered. Cuckovic-Dzodzo et al. [12] made a numerical and experimental study on the laminar conjugate natural convection flow and heat transfer in a cubic enclosure with and without a heat conducting partition with glycerol as the working medium and the partition placed in the middle of the enclosure. Their results also show that the convective heat transfer in the partitioned cavity is reduced in comparison to that in the cavity without a partition, from 59.1% to 63.6% for the Rayleigh number in the range of 38,000 to 369,000. Similarly, Nishimura et al. [13] conducted a numerical and experimental study on the laminar conjugate natural convection in a rectangular enclosure divided by multiple vertical partitions. In this study, the thickness of the partitions was neglected in the numerical simulation and the partitions were equally spaced in the enclosure. Their numerical results reveal that the Nusselt number was inversely proportional to $(1 + N)$, where N is the number of partitions, which was in agreement with their experimental results as well as the results obtained by Cuckovic-Dzodzo et al. [12].

Transient laminar natural convection in a partitioned enclosure with an adiabatic baffle and with the enclosure heated by uniform heat flux from left wall and cooled from right wall has been studied numerically by Fu et al. [14, 15]. They observed that for the Rayleigh number in the range of 10^4 to 10^6 the adiabatic baffle and the

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Rayleigh number have significant influence on the transient heat transfer mechanism, with the largest effect occurring mainly in the first one-third of the transient stage, regardless of the presence or location of a baffle. A numerical simulation of unsteady natural convection in a differentially heated cavity with a thin fin of different lengths on a sidewall at the Rayleigh number of 3.8×10^9 was performed by Xu et al. [16]. They reported that the fin length significantly influences the transient thermal flow around the fin and heat transfer through the finned sidewall in the early stage. Xu [17] also investigated the unsteady coupled thermal boundary layers induced by a fin on the partition of a differentially heated cavity and demonstrated that the fin may induce a transition to unsteady coupled thermal boundary layers and the critical Rayleigh number for the occurrence of the transition was between 3.5×10^8–3.6×10^8.

Xu et al. [18] classified unsteady natural convection flows in a partitioned cavity into three distinct stages: the initial, transient and steady-state stages. They examined the transient start-up characteristics of unsteady natural convection flows on both sides of the partition, and found that the temperature distribution on the partition surrounded by the coupled convection boundary layers is like that in a differentially heated cavity with isothermal side walls. However, due to the presence of the partition, the volumetric flow rate and heat transfer is reduced by 37% and 50%, respectively. A numerical study on the natural convection heat transfer in an isosceles triangular enclosure having a vertical infinite conductivity wall at the center was carried out by Saha and Gu [19]. Their results support the flow classification of Xu et al. [18], and show that the temperature distribution on the partition is similar to the isothermal cavity case at the transition stage and to the isoflux cavity case at the steady state stage. Williamson et al. [20] investigated the time-dependent oscillatory flow in a differentially heated rectangular cavity with an infinitely conducting vertical partition. They found that the critical Rayleigh number for flow to become unstable is dependent on the aspect ratio.

The effect of partition characteristics have been examined in some previous studies. Ghosh et al. [21] examined the effect of the partition position on the flow structure and heat transfer in a rectangular cavity with a single thin partition, and found that for the Rayleigh number in the range of 10^3–10^7, the partition location does not have a significant effect on the heat transfer. Tong and Gerner [22] investigated the effect of the position of vertical partition in an air-filled rectangular enclosure. In the study, the partition was assumed to have negligible thermal resistance and the Rayleigh number was in the range of 10^4–10^5. The results show that placing the partition in the middle will result in the largest reduction in heat transfer. Kahveci [23] extended the investigation by making more realistic assumptions on the conducting partitions and examined the effect of partition thickness, conductivity and position on the Nusselt number of the steady-state laminar natural convection heat transfer at relatively low Rayleigh numbers, over the range of 10^4–10^6. It is found that when the distance of the partition is increased from the left wall towards the middle of the cavity, the average Nusselt number decreases asymptotically towards a constant value and the partition thickness has negligible effect on the heat transfer. It is also found that the variation of the thermal resistance of the partition leads to substantially different heat transfer changes, which was also found by Kangni et al. [24], who studied the effect of the thermal resistance of the partition in a divided tall cavity with a finite thickness partition. Additionally, Kahveci [25] examined the effect of aspect ratio on natural convection heat transfer in a partitioned cavity and reported that the increase in the aspect ratio will result in enhanced heat transfer.

From the literature review, it is revealed that the studies on the effect of the partition on natural convection have been focused on the centrally placed or thin partition or partition with infinite thermal conductivity and at relatively low Rayleigh numbers over narrow ranges. This motivates the current study which aims to examine the effects of partition position and thickness on the unsteady conjugate natural convection heat transfer in a differentially heated partitioned enclosure over a wide range of Rayleigh numbers.

The remainder of this paper is organized as follows. The physical system under consideration, the computational domain, the governing equations, the initial and boundary conditions, the numerical solution technique, and the benchmark results of the numerical solutions against the available solutions are briefly described in Section 2. In Section 3, the major results of this study and the pertinent discussion are detailed. Finally, the conclusions are drawn in Section 4.

2. Numerical methodology

The physical system under consideration is a two-dimensional partitioned rectangular cavity (with height H and width L and the aspect ratio $A = H/L$), as illustrated in Fig. 1. The top and bottom walls of the cavity are adiabatic and the left and right vertical walls are isothermal fixed at T_h and T_c respectively ($T_h > T_c$, with the dimensionless temperatures $\theta = 1.0$ and $\theta = 0.0$, respectively, where $\theta = (T - T_c)/(T_h - T_c)$). A partition of thickness T_p is placed at the location X_p from the left wall (both T_p and X_p are dimensionless, made dimensionless by L). The working fluid is assumed to be air (Pr = 0.71, where Pr is the Prandtl number as will be defined by Eq. (5)), which is initially quiescent and at a temperature of $(T_h + T_c)/2$ (*i.e.*, at the dimensionless temperature $\theta = 0.5$). All the interior walls and the partition surfaces are rigid and no-slip. The partition wall is heat conducting, with finite thermal conductivity k_s.

The transient flow of fluid within the cavity is governed by the two-dimensional Navier-Stokes equations with the Boussinesq approximation for buoyancy which, together with the temperature equation, can be written in dimensionless forms in Cartesian coordinates as follows,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (1)$$

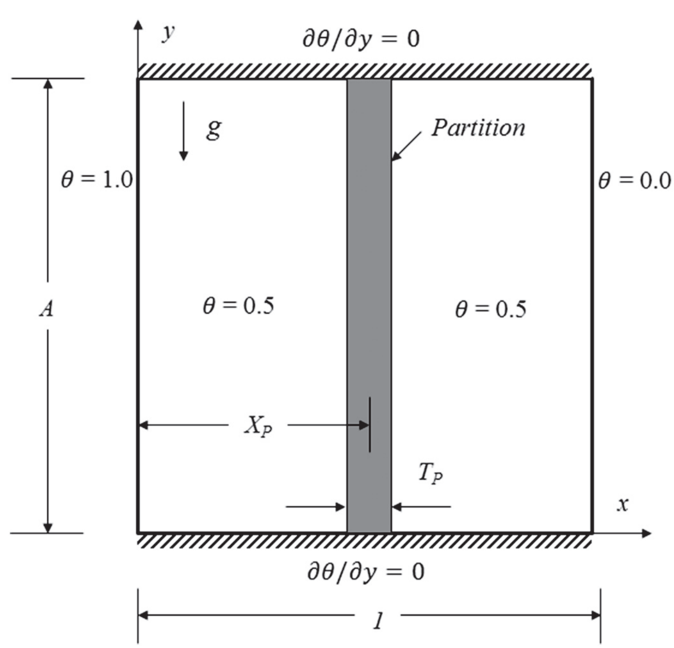

Fig. 1. Schematic of the physical system under consideration, the computational domain and the initial and boundary conditions.

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