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Combined thermal radiation and natural convection in a cavity containing a discrete heater: Effects of nature of heating and heater aspect ratio

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ABSTRACT

This paper investigates the interaction between thermal radiation and natural convection in an air filled square cavity with a discrete heater placed inside. The vertical walls of the cavity are cooled while the horizontal ones are insulated. Two types of the heater, viz., isothermal and heat generating are considered. The governing coupled nonlinear partial differential equations were solved using a finite volume method on a uniformly staggered grid system. The effects of the pertinent parameters such as the Rayleigh number, aspect ratio of the discrete heater and surface emissivity on the heat and fluid flow characteristics are investigated in detail. In general it is found that the overall heat transfer rate is enhanced with an increase of the surface emissivity and the Rayleigh number for both isothermal and heat generating heaters. Buoyancy induced flow gets augmented for the isothermal solid body whereas it is weakened for the heat generating body in the presence of radiation exchange.

1. Introduction

Cooling of electronic devices present in sealed cabins remains a great challenge to electronic and thermal designers as a result of constant miniaturization of these devices and their increased operating temperature level. The design and operation of these devices affect the cooling mechanisms that are used to reduce their own failure. In general the above said cabins are modelled as rectangular cavities with various obstructions placed inside representing the electronic devices. In view of a variety of shapes and thermal conditions of these devices the obstructions are considered in the form of partitions, partial baffles and discrete bodies and are assumed to be either isothermal or isoflux or heat generating. Among the various known cooling techniques used in such applications, natural convection cooling using air as the medium is the most widely used one as it is simple to design, cheap, noise free and highly reliable.

Several investigations, belonging to the past few decades, dealing with natural convection in enclosures with obstructions of various shapes are available in the literature (House et al., 1990; Oh et al., 1997; Sun and Emery, 1997; Barozzi and Corticelli, 2000; Deng et al., 2002; Oztop et al., 2004; Zhao et al., 2006; Bouafia and Daube, 2007; Hakeem et al., 2008). It was shown that the obstructions could significantly change the heat transfer and fluid flow phenomena. They ignored the influence of radiation based on low emissivities of cavity surfaces or shadow effects of the obstructions. However, in most of the practical situations, the radiation heat transfer plays a vital role if the emissivities of the surfaces are very high. Therefore, we cannot neglect it in comparison with natural convection, even at room temperature. Only few studies have been reported on the coupled convection and radiation heat transfer problems with obstructions (Chang et al., 1983; Mezrhab and Bchir, 1999; Mezrhab et al., 2007; Saravanan and Sivaraj, 2013; 2015; Liu and Phan-Thien, 1999; Mezrhab et al., 2006; Bouali et al., 2006; Sun et al., 2011; Saravanan and Sivaraj, 2014; Martyushev and Sheremet, 2014). Chang et al. (1983) studied numerically the interactions between natural convection and thermal radiation in a square cavity with equal vertical finite thickness partitions attached at the centers of the ceiling and floor. They analyzed the effects of partition heights at two levels of Grashof numbers for participating and nonparticipating gases. It was found that the radiation effects are much more sensitive to the presence of the partitions than the convective flows. The contribution of natural convection remained essentially the same until the partitions occupied one half of the cavity height. A numerical study of natural convection and radiation in partitioned differentially heated square cav-

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ity was presented by Mezrhab and Bchir (1999). They considered a thick partition located vertically close to the hot wall forming a narrow vertical channel in which the flow is controlled by vents at the bottom and top of the partition. The effect of radiation was discussed as a function of the widths of the vents, solid/fluid conductivity ratio and Rayleigh number. Mezrhab et al. (2007) numerically studied the combined natural convection and surface radiation in a square cavity divided by a centered thin vertical partition forming gaps for fluid flow. They investigated the effect of radiation exchange on the heat transfer and the flow field by varying the gap width, maximal temperature difference and the cavity length. They found that the radiation exchange causes a rise in the overall heat transfer. Recently we numerically studied the interaction between surface radiation and natural convection in an air filled cavity with a uniformly or nonuniformly heated plate placed at its center (Saravanan and Sivaraj, 2013; 2015). It was found that the surface radiation makes the entire cavity thermally active with a good homogenization of the temperature field for both types of heating. Moreover the heat transfer rate for a vertically placed plate was always higher than that of a horizontally oriented one. However the non-uniform heating resulted in a dual effect depending on the plate length and emissivity.

Several studies dealing with the combined effect of natural convection and surface radiation have considered cavities with a square inner body. Liu and Phan-Thien (1999) numerically studied the conjugate conduction, convection and radiation problem in a vertical differentially heated square cavity with a heated square body inside. They concluded that radiation had a strong influence on temperature and velocity distributions and the emissivity had a significant influence on the global flow when more heat is generated in the block. Mezrhab et al. (2006) performed a numerical study of the radiation and natural convection interactions in a differentially heated square cavity with a centered square body. They found that the radiation exchange homogenizes the temperature inside the cavity and produces an increase in the average Nusselt number, particularly when the solid/fluid conductivity ratio and the Rayleigh number are high. Moreover, the average Nusselt number increases with increasing emissivity of the radiative surfaces, particularly at high Rayleigh numbers. The effects of surface radiation and inclination angle on heat transfer and flow structures in an inclined rectangular cavity with or without a centered conducting body was studied numerically by Bouali et al. (2006). The vertical walls of the cavity were maintained at different but uniform temperatures and the others were kept insulated. It was found that the inner body and the increase of the inclination angle reduce the total heat transfer in the cavity especially when the radiation exchange is taken care of. Sun et al. (2011) have investigated the effect of surface radiation on the stability properties of natural convective flows in a square air filled cavity cooled from below and above, with a hot isothermal square body located at the cavity center. They predicted that the Rayleigh number for the transition to unsteady flows is considerably increased under the influence of radiation. Saravanan and Sivaraj (2014) considered the influence of surface radiation on transient natural convection in a square enclosure purely driven by a discrete heater placed at its center. It was found that surface radiation shows its effect only for higher values of the Rayleigh number and hence the net radiative fluxes at the top and bottom walls become quite distinct. Transient natural convection and surface radiation in a closed cavity with heat conducting solid walls of finite thickness and a local heat source of constant temperature which is in convective heat exchange with the environment have been studied by Martyushev and Sheremet (2014). It has been found that regardless of the considered solid-fluid interface the average convective Nusselt number increases with the Rayleigh number and thermal conductivity ratio, and decreases with the surface emissivity and ratio of solid wall thickness to cavity spacing. Correlations of the average convective and radiative Nusselt numbers along the solid-fluid interfaces have been obtained depending on the Rayleigh number, surface emissivity, thermal conductivity ratio and ratio of solid wall thickness to cavity spacing.

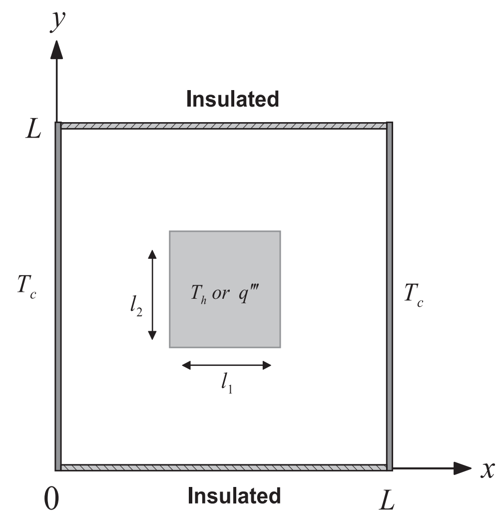

Fig. 1. Physical configuration.

The objective of the present work is to analyse the effect of aspect ratio of the obstructions on the combined radiation and natural convection in cavities as it has not been given due attention in the past literature. The only known available work addressing this issue is that of Shuja et al. (2001) who considered natural convection due to a protruding solid body of variable aspect ratio. Though the present configuration to be discussed in this work is often encountered in electronic industry as discussed earlier, nuclear and chemical energy production systems and solar energy collection systems also employ similar basic designs.

2. Mathematical analysis

The physical model considered here is a two dimensional square cavity of length L containing a rectangular solid body of length l_1 and height l_2 at its center (see Fig. 1). Two types of thermal conditions are imposed on the solid body. The body is either isothermal at a higher temperature T_h (Case I) or generating heat at a uniform rate q'' (Case II). The area of the solid body is maintained to be $L^2/9$. The vertical walls are cooled at a constant temperature T_c while the horizontal walls are insulated. The cavity is filled with air which acts as the working fluid. Air is non-emitting and non-absorbing under moderate temperatures which makes it a radiatively non-participating medium. All cavity walls and solid body surfaces are assumed to be opaque, gray and diffuse emitters and reflectors of radiation with a constant emissivity ε. The Cartesian coordinates (x, y) are chosen with (u, v) as the corresponding velocity components. The gravity $\bar{g}$ acts downward normal to the x direction. The flow is assumed to be laminar, incompressible and the fluid properties are assumed to be constant except the density in the buoyancy term, following the Boussinesq approximation. Then the governing equations for the laminar flow of the incompressible fluid are

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$