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Transient combined natural convection and radiation in a double space cavity with conducting walls

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A B S T R A C T

Two-dimensional numerical analysis of transient conjugate heat transfer in a double space gas filled enclosure with conducting solid walls has been carried out. This configuration can be found in cooling process of some electronic equipment in which the generated heat must be removed to avoid failure. Natural convection equations in the enclosures are solved in terms of the dimensionless stream function and vorticity using finite-difference technique. The discrete ordinates method (DOM) is used to solve the radiative transfer equation (RTE) in the filling gases which are considered to be absorbing, emitting and scattering. The effects of Rayleigh number and optical thickness of two radiating media in transient cooling process from the hot surface toward the cold one are investigated. The transient results show that when the optical thickness of the gas layer closed to the heat source is lower than the second layer, more heat penetrates into the enclosure which consequently leads to higher cooling performance and lower rates of thermal failure.

1. Introduction

Combined natural convection and radiation in differentially heated enclosures is important in many engineering applications such as building systems, fire spreading, cooling process in electronic equipment and etc. Since the current flow through a resistance is accompanied by heat generation, thermal control by the mechanisms of convection, conduction and radiation has become increasingly important in the design and operation of electronic equipment because the failure rate of these devices increases exponentially with temperature [1]. From engineering point of view, natural convections is the most dominant heat transfer mechanism in storage, transport or low velocity applications. Therefore, it has been of great concern to scientists and engineers. The number of numerical and experimental studies [2–8] during the past several decades shows the importance of this topic. In many engineering applications, radiation heat transfer mechanism plays an important role in thermal behavior of the system. Radiation heat transfer coupled with natural convection has a great influence on the thermal and flow field, especially when the fluid is treated as an absorbing, emitting, and scattering medium.

In reviewing the preceding investigations, several works are found for problem of combined radiation and natural convection in participating media. Chang et al. [9] investigated combined radiation and natural convection in square enclosures with partitions mounted at the midpoint of the ceiling and floor. Webb and Viskanta [10] carried out numerical study of coupled heat transfer problem involving both convection and radiation in a rectangular cavity. The combined natural convection with radiation heat transfer in enclosures was studied by Yang [11]. Ycel et al. [12] used the discrete ordinate method to study combined natural convection and radiation heat transfer in a rectangular participating medium. Lauriat [13,14] computed interaction between natural convection and radiation in rectangular enclosures using the P-1 differential approximation to represent radiative heat transfer. Tan and Howell [15] studied the benchmark problem of square cavity for solving combined radiation and thermal convection in a two-dimensional square participating medium. A numerical investigation of combined natural convection and radiation heat transfer with a gray and scattering medium has been performed using the hybrid thermal Lattice Boltzmann method by Moufekkir et al. [16]. Lari et al. [17] analyzed the effect of radiative heat transfer on natural convection heat transfer in a square cavity under normal room conditions. It was reported that neglecting radiation effect on this combined heat transfer introduces considerable error in computing temperature distribution. Colomer et al. [18] have studied the combined natural convection and radiation in a three-dimensional heated cavity by using DOM to solve the RTE. Capdevila et al. [19–21] and Ibrahim et al. [22] analyzed the effect of surface and gas radiation on turbulent natural convection in two- and three-dimensional cavities. In addition to thermal radiation, some geometrical parameters, such as the enclosure inclination angle have a great influence on natural heat transfer and cooling of

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engineering application. Hence, many studies have been carried out to investigate the effect of enclosure inclination angle [23–32] on thermal behavior of the system.

In many applications, transient natural convection flow is also of great concern due to different thermal behavior in the initial developing period before the steady-state condition. So, many researchers have been interested in analyzing both numerically and experimentally the natural convection problems of different geometries under unsteady and steady-state conditions with considering thermal radiation effect. Two-Dimensional investigation of time-dependent natural convection in a square cavity was done by Aydm [33]. The results showed that for sufficiently high Rayleigh numbers, an oscillatory approach to the steady-state is detected. A two-dimensional unsteady natural convection in a square cavity was studied by Baek and Kim [34] in which only surface radiation was considered in the calculations. The results showed that with the presence of radiation, steady-state condition is established faster. Zhu and Yang [35] studied both numerically and experimentally an unsteady laminar natural convection of air flow in a tall cavity. It was found that in case of suddenly heating mode, the multicellular flow pattern occurs for a specific range of Rayleigh numbers. Two-dimensional time-dependent laminar natural convection of air flow was studied numerically in a vertical rectangular cavity by Bae and Hyun [36]. Three discrete flush-mounted heaters were placed on one side wall and were abruptly switched on-off. Effect of different Rayleigh numbers on thermal behavior and air cooling was studied. Three-dimensional numerical and experimental study of transient natural convection of passive heating room using values of hourly averaged radiation during winter was carried out by Kurtbas and Durmus [37]. In order to verify the numerical results, experiments were carried out manufacturing a model room. It was shown that the overall heat transfer coefficient for low Rayleigh number affects the average Nusselt number more than that of high Rayleigh number. Sheremet et al. [38] analyzed unsteady natural convection of micropolar fluid in a right-angled wavy triangular cavity using the Boussinesq approximation. The effects of different parameters such as Prandtl number, vortex viscosity parameter, and undulation number were investigated on streamlines, isotherms, vorticity isolines, and average Nusselt number. Armengol et al. [39] studied a two-dimensional transient natural convection in a differentially heated square cavity in which the effects of variable properties, large temperature differences and different Rayleigh numbers have been investigated.

Due to its wide applications in industries such as cooling of the electronic devices, the conjugate natural convection heat transfer in enclosure has been of great significance for both scientists and engineers. An unsteady conjugate natural convection in a square cavity with finite thickness heat-conducting walls filled with a porous medium was studied by Aleshkova and Sheremet [40]. Effects of Darcy number, Rayleigh Number, transient factor, and heat conductivity ratio on the thermal behavior and flow characteristics inside the enclosure were investigated. The unsteady conjugate conduction-natural convection in an inclined cavity with finite thickness walls was studied by Zhang et al. [41] in which one of the vertical sidewalls was exposed to time-periodic temperature. Accurate numerical results revealed that the heat transfer rate decreases with the inclination angle and could be enhanced or weakened by selecting different temperature pulsating period. Martyushev and Sheremet [42,43] presented two- and three-dimensional numerical study of transient conjugate natural convection of an air filled closed square cavity with heat-conducting solid walls containing a heat source of constant temperature. The effects of different factors such as Rayleigh number, internal surface emissivity, thermal conductivity ratio, the ratio of solid wall thickness to cavity spacing, and the dimensionless time on the fluid flow and heat transfer were analyzed. Miroshnichenko et al. [44] presented a detailed numerical analysis of complex heat transfer in a rectangular enclosure including a heat source. Numerical results showed that convective Nusselt number is an increasing function of Rayleigh number and a decreasing function of the surface emissivity, and also the effect of thermal radiation leads to the heat transfer enhancement.

Despite the literature highlighting in importance of conjugate natural convection and radiation in an enclosure in engineering applications, more investigation is needed to clarify the effect of thermal radiative properties of participating media on transient behavior of the temperature and flow field in a double space cavity, which is the main motivation of this paper. Therefore, the present study focuses on simulation of cooling process in electronic equipment in which heat transfer occurs from the hot surface toward the cold one through a double space cavity with conducting walls. Two spaces are filled with different radiating gases and the effect of optical thicknesses of these gaps at different arrangements is studied on transient cooling of the system. The problem is a conjugate one, in which the heat-conduction equation inside the cavity walls is also solved simultaneously with the flow and energy equations for two separate convective flows. Also, for computation of radiative term in the gas energy equation, the RTE is solved numerically by the well-known DOM. The effect of radiative parameters of participating gases in each sub cavity and also their arrangements are investigated on the thermal behavior and transient cooling of the system.

2. Physical and mathematical model

A schematic representation of the enclosure configuration is shown in Fig. 1 in which two cavities occupied by radiating gases are surrounded by thick and conductive solid walls of the same material. The length of square enclosure is equal to L and the thicknesses of walls and gas gaps are considered to be $a = 0.1L$ and $b = 0.35L$, respectively. The top and bottom walls ($y = 0, y = L$) are adiabatic while the left and right boundary walls ($x = 0, x = L$) are the hot and cold isotherm surfaces, respectively. All the physical properties of the gas and solid phases are assumed to be constant and independent of temperature, except for the gas density in which its variation with temperature is governed by the Boussinesq approximation. The two cavities are filled with different gray gases which participate in thermal radiation by emitting, absorbing and scattering. Also, all internal boundary surfaces are assumed to be gray with constant emissivity. Numerical results are

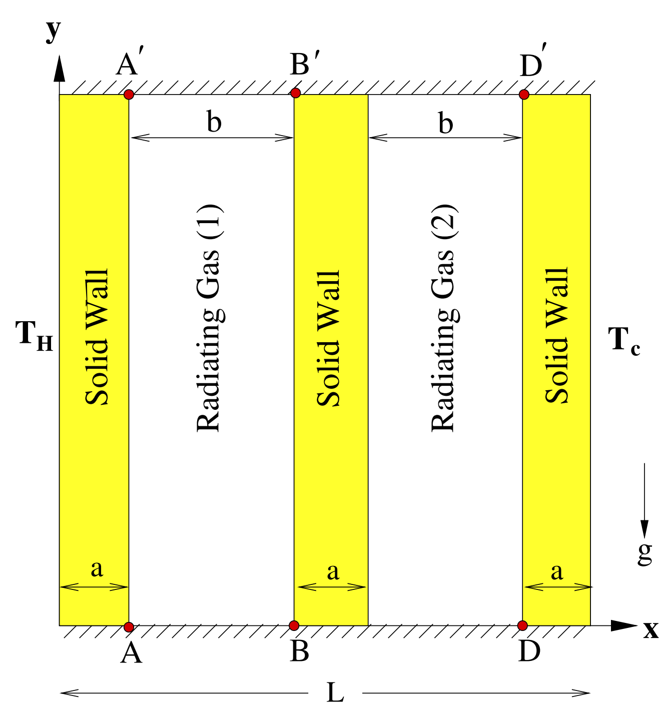

Fig. 1. Schematic of physical model and coordinate system.