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Combined natural convection and thermal radiation in a square cavity with a nonuniformly heated plate

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ABSTRACT

The present investigation deals with the combined effect of natural convection and surface radiation in an air filled square cavity with a nonuniformly heated thin plate placed horizontally or vertically at its center. The non-uniform heating is due to the non-linearly varying temperature of the plate. The vertical walls of the two dimensional cavity are cooled while the horizontal ones are insulated. The resulting coupled equations were solved using the finite volume method on a uniformly staggered grid system. Numerical simulations were carried out for a wide range of values of non-uniform heating, plate length and surface emissivity at a Rayleigh number of $Ra = 10^7$. It is found that the surface radiation makes the entire cavity thermally active with a good homogenization of the temperature field for both uniform and nonuniform heating of the plate. The heat transfer rate for a vertically placed plate is always higher than that of a horizontally oriented one. The increase of emissivity always enhances the heat transfer within the cavity, while the plate length can have both augmenting and dampening effects. The non-uniform heating results in a dual effect depending on the plate length and emissivity. The effect of uniform and non-uniform heating of the plate on the total and convective heat transfer rates is presented and discussed.

1. Introduction

Natural convection cooling in rectangular cavities using air has been the subject of many studies due to its cheapest and efficient cooling mode of heat transfer. Numerous theoretical and experimental studies on natural convection in cavities have been carried out over the past several decades because of the wide range of science and engineering applications. In most cases, wherein air or other radiatively transparent fluid is under consideration the interaction of surface radiation on natural convection in cavities is omitted due to low emissivities of surfaces. In many practical situations, the emissivities of the surfaces are generally very high. Therefore, we cannot neglect surface radiation in comparison with natural convection even at room temperature. Understanding the dynamical behavior of heat and fluid flow due to surface radiation coupled with natural convection in a cavity without obstructions has received significant attention from many researchers [1–13]. In recent years the current interest has switched to complex cavities with obstructions in the form of solid bodies or fins or partial baffles. Considerable attention has been focused in recent years on the coupled natural convection and surface radiation in partitioned cavities [14–23]. However still a better insight in heat transfer analysis is required to improve their thermal performances in scientific and industrial applications. This includes thermal design of buildings, solar collectors, nuclear reactors, furnaces and aeronautics and particularly the electronic equipment cooling.

Chang et al. [14] studied numerically natural convection and thermal radiation interactions in a square cavity with equal vertical finite thickness partitions located at the centers of the ceiling and floor. They analyzed the effects of partition heights at two levels of Grashof numbers for radiatively participating and nonparticipating gases. It was found that the radiation effects are much more sensitive to the presence of the partitions than the pure 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 a partitioned and differentially heated square cavity was presented by Mezrhab and Bchir [15]. 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. [16] numerically studied the combined natural convection and surface radiation in a

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Nomenclature

D	dimensionless plate length (h/L)
F_{kj}	view factor from the kth element to the jth element
$\bar{g}$	gravitational acceleration, ms^{-2}
h	length of the plate, m
k	thermal conductivity of the fluid, W m^{-1} K^{-1}
L	length of the cavity, m
N	total number of radiative surfaces
$\overline{Nu}$	average Nusselt number
$\overline{Nu}_{cv}$	average convective Nusselt number
$\overline{Nu}_{rd}$	average radiative Nusselt number
N_{RC}	radiation–conduction number $\left(\sigma T_A^4 L/k\Delta T\right)$
p	pressure, Pa
P	dimensionless pressure $\left(pL^2/\rho\alpha^2\right)$
Pr	Prandtl number (ν/α)
q	heat flux, W m^{-2}
Q_{rd}	dimensionless net radiative flux $\left(q_{rd}/\sigma T_A^4\right)$
Ra	Rayleigh number $\left(g\beta\Delta T L^3/\alpha\nu\right)$
R_k	dimensionless radiosity of the kth element $\left(q_{o,k}/\sigma T_A^4\right)$
t	time, s
T	temperature, K
u, v	velocity components, m s^{-1}
U, V	dimensionless velocity components (uL/α, vL/α)
x, y	Cartesian coordinates, m
X, Y	dimensionless coordinates ($x/L, y/L$)

Greek symbols

α	thermal diffusivity of the fluid, m^2 s^{-1}
β	thermal expansion coefficient, K^{-1}
ΔT	temperature difference ((($T_{h1}+T_{h2})/2) - T_c$), K
δ	thickness of the plate
ε	emissivity of the radiative surface
Θ	dimensionless temperature ratio (T_k/T_A)
θ	dimensionless temperature ($(T-T_c)/\Delta T$)
λ	source nonuniformity parameter ($(T_{h1}-T_{h2})/2\Delta T$)
ν	kinematic viscosity, m^2 s^{-1}
ρ	density of the fluid, kg m^{-3}
σ	Stefan–Boltzmann constant, W K^{-4} m^{-2}
τ	dimensionless time $\left(\alpha t/L^2\right)$
Ψ	dimensionless stream function (ψ/α)
ψ	stream function, m^2 s^{-1}

Subscripts

c	cold surfaces
cd	conduction
cv	convection
h	hot surfaces
l	left wall
r	right wall
max	maximum
o	outgoing radiation
rd	radiation

differentially heated 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. Very recently, Saravanan and Sivaraj [17] numerically studied the interaction between surface radiation and natural convection in an air filled cavity with a heated plate placed at its center. The results indicated a better homogenization of temperature field within the cavity by radiation. It was also found that the contribution of the convective mechanism to the overall heat transfer increases with emissivity when the plate is horizontally placed whereas decreases when it is vertically placed.

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 [18] numerically studied the conjugate conduction, convection and radiation problem for a heated block in a vertical differentially heated square cavity. They concluded that radiation has a strong influence on temperature and velocity distributions and the emissivity has a significant influence on the global flow when more heat is generated in the block. Mezhrab et al. [19] 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 increased 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 were studied numerically by Bouali et al. [20]. The vertical walls of the cavity were maintained at different 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 radiation heat transfer is considered. Sun et al. [21] have investigated the effect of surface radiation on the stability properties of natural convective flows in an air filled square cavity cooled from below and above, with a hot isothermal square body located at the cavity center. They predicted that the transition Rayleigh number representing the initiation of unsteady flows increases considerably under the influence of radiation. The combined influence of surface radiation and natural convection on the fluid flow inside a square enclosure containing a discrete heater at its center has been investigated by Saravanan and Sivaraj [22]. 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 [23]. 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.

Most of the previous studies investigated the combined natural convection and surface radiation in cavities with inner components dissipating heat at a constant rate. These components were modeled as uniformly heat generating discrete heat sources or