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Surface radiation effect on convection in a closed enclosure driven by a discrete heater ☆

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ABSTRACT

This paper is aimed at presenting the changes experienced by a convective flow in a closed square enclosure when surface radiation is taken into account. The flow is driven by a centrally placed discrete heater in an air filled two dimensional square enclosure. Symmetrically cooled isothermal vertical walls and insulated horizontal walls are considered. The governing coupled partial differential equations were solved using a finite volume method on a uniformly staggered grid system. The resulting augmentation of fluid velocities and the factors causing them are discussed.

1. Introduction

Natural convection in rectangular enclosures is an area of study for many researchers working on heat transfer in the past few decades due to its wide range of applications. In several practical situations, the temperature of the enclosure walls is significantly high so that the contribution from surface radiation cannot be neglected in comparison with natural convection. Although many experimental and numerical studies have been carried in this area, more information is still needed on the temperature distribution when the geometry involves an adiabatic boundary. The influence of surface radiation is more significant when the medium is filled with the transparent fluids. Surface to surface radiation through a transparent medium modifies the temperature distribution of the adiabatic boundaries which in turn affects the temperature stratification in the enclosure and thereby the convective heat transfer. Considerable works have already been performed on the coupled natural convection and surface radiation in simple enclosures [1–3]. The results obtained by these authors show that surface radiation alters significantly the temperature distribution inside the enclosure and the flow patterns. It is also found that the overall heat transfer rate across the cavity is a strong function of emissivity of the enclosure walls.

The interest has now shifted to complex enclosures with obstructions in the form of solid bodies or fins or partial baffles as their location, length and thickness can significantly control the resulting flow characteristics. Only few studies have been reported on the coupled convection and radiation heat transfer in complex enclosures [4–7]. An overview of the above studies clearly shows that there are many other physical setups of industrial interest for which the information on the effect of radiation on convection is still lacking. The objective of the present study is to discuss the effect of surface radiation on natural convective flow induced by a discrete heater in a closed enclosure with cold vertical walls. This type of basic configuration is often encountered in electronics industry, nuclear and chemical energy production systems and solar energy collection systems.

2. Mathematical formulation

The physical model considered here is a two dimensional square enclosure of length L containing a square discrete heater of length $L/3$ at its center (see Fig. 1). The discrete heater is assumed to be isothermal at a higher temperature T_h. The vertical walls are cooled at a constant temperature T_c while the horizontal walls are insulated. Air acts as the working medium within the enclosure. Non-emitting and non-absorbing characters of air under moderate temperatures make it radiatively non-participating. All enclosure walls and heater surfaces are assumed to be opaque, gray and diffuse emitters and reflectors of radiation. The flow is assumed to be laminar and incompressible. Then the governing equations under the Boussinesq approximation are

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

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

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Nomenclature

F_{kj}	view factor from the kth element to the jth element
$\overline{g}$	gravitational acceleration, ms^{-2}
I_k	dimensionless irradiation of the kth element
k	thermal conductivity of fluid, $W\ m^{-1}\ K^{-1}$
L	length of the cavity, m
N	total number of radiative surfaces
N_{RC}	Radiation–conduction number ($\sigma T_h^4 L/k\Delta T$)
p	pressure, Pa
P	dimensionless pressure ($pL^2/\rho\alpha^2$)
Pr	Prandtl number (ν/α)
q	flux, $W\ m^{-2}$
Q	dimensionless flux
Ra	Rayleigh number ($g\beta\Delta T L^3/\alpha\nu$)
R_k	dimensionless radiosity of the kth element
t	time, s
T	temperature, K
T_0	average temperature ($(T_h + T_c)/2$), 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 fluid, $m^2\ s^{-1}$
β	thermal expansion coefficient of fluid, K^{-1}
ΔT	characteristic temperature difference, K
ε	emissivity of the radiative surface
Θ	dimensionless temperature ratio (T_k/T_h)
θ	dimensionless temperature ($(T - T_c)/\Delta T$)
ν	kinematic viscosity of fluid, $m^2\ s^{-1}$
ρ	density of fluid, $kg\ m^{-3}$
σ	Stefan–Boltzmann constant, $W\ K^{-4}\ m^{-2}$
τ	dimensionless time ($\alpha t/L^2$)
Ψ	dimensionless stream function (ψ/α)
ψ	stream function, $m^2\ s^{-1}$

Subscripts

c	cold wall
h	hot wall
i	incoming radiation
o	outgoing radiation
rd	radiation

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + g\beta(T - T_c) \tag{3}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

with the boundary conditions

$$\begin{array}{llll} t=0: & u=v=0, & T=T_c, & \text{at } 0\le x\le L \text{ and } 0\le y\le L \\ t>0: & u=v=0, & T=T_c, & \text{at } x=0,\ L \text{ and } 0\le y\le L \\ & u=v=0, & \dfrac{\partial T}{\partial y}=\dfrac{q_{rd}}{k}, & \text{at } y=0 \text{ and } 0<x<L \\ & u=v=0, & \dfrac{\partial T}{\partial y}=\dfrac{-q_{rd}}{k}, & \text{at } y=L \text{ and } 0<x<L \\ & u=v=0, & T=T_h, & \text{on the heater} \end{array} \tag{5}$$

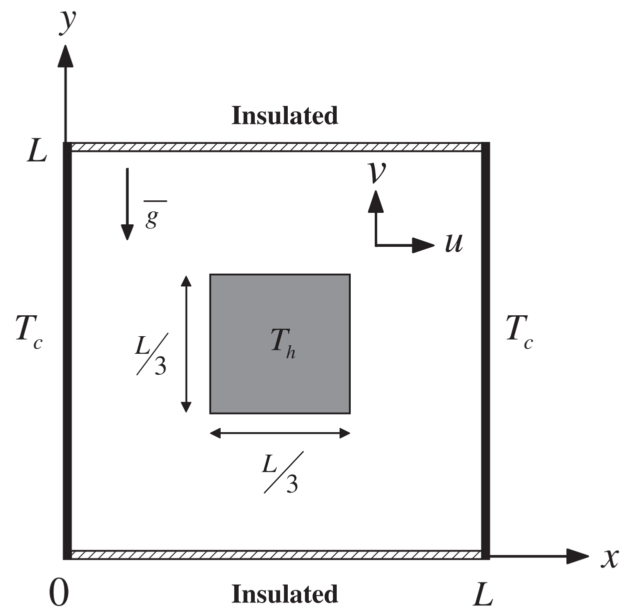

Fig. 1. Physical configuration.

Introducing the following dimensionless variables

$$X=\frac{x}{L},\quad Y=\frac{y}{L},\quad U=\frac{u}{\alpha/L},\quad V=\frac{v}{\alpha/L},\quad P=\frac{p}{\rho\alpha^2/L^2},\quad \tau=\frac{t}{L^2/\alpha}$$
$$Q_{rd}=\frac{q_{rd}}{\sigma T_h^4},\quad \theta=\frac{T-T_c}{\Delta T},\quad \text{where } \Delta T=T_h-T_c \tag{6}$$

the governing Eqs. (1)–(4) can be written in a dimensionless form as

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{7}$$

$$\frac{\partial U}{\partial \tau} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + Pr\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{8}$$

$$\frac{\partial V}{\partial \tau} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + Pr\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + RaPr\theta \tag{9}$$

$$\frac{\partial \theta}{\partial \tau} + U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \tag{10}$$

with the corresponding boundary conditions

$$\begin{array}{llll} \tau=0: & U=V=0, & \theta=0, & \text{at } 0\le X\le 1 \text{ and } 0\le Y\le 1 \\ \tau>0: & U=V=0, & \theta=0, & \text{at } X=0,1 \text{ and } 0\le Y\le 1 \\ & U=V=0, & \dfrac{\partial \theta}{\partial Y}=N_{RC}\,Q_{rd}, & \text{at } Y=0 \text{ and } 0<X<1 \\ & U=V=0, & \dfrac{\partial \theta}{\partial Y}=-N_{RC}\,Q_{rd}, & \text{at } Y=1 \text{ and } 0<X<1 \\ & U=V=0, & \theta=1, & \text{on the heater} \end{array} \tag{11}$$

The dimensionless parameters appearing in the Eqs. (7)–(11) are defined as

$$Pr=\frac{\nu}{\alpha}\quad Ra=\frac{g\beta\Delta T L^3}{\nu\alpha}\quad N_{RC}=\frac{\sigma T_h^4 L}{k}. \tag{12}$$