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Effect of surface radiation on RBC in cavities heated from below ☆

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ABSTRACT

Numerical investigations of combined free convection and surface radiation in enclosures for Rayleigh–Benard configuration of air are carried out using FLUENT 6.3, with a view to determine the onset of convection and to propose correlations for convection and radiation Nusselt numbers based on a detailed parametric study. The onset of Rayleigh–Benard convection is delayed with an increase in the emissivity of the sidewalls. The effect of surface radiation on the onset of convection however diminishes with aspect ratio (AR) and for AR = 8, the effect of surface radiation ceases. Post-onset, the effect of surface radiation on the convection heat transfer becomes insignificant beyond an aspect ratio of 5.

1. Introduction

Rayleigh–Benard convection occurs in a fluid layer which is confined between two thermally conducting plates, and is heated from below to produce a fixed temperature difference. Rayleigh–Benard convection (RBC) was first studied analytically by Lord Rayleigh in 1916 in relation to the experiments made by Benard in 1900. Though Rayleigh–Benard convection has been widely studied in the literature, studies on convection in a cavity heated from below that simultaneously take into account effect of surface radiation are scarce. The study of bottom heated cavities is important for a variety of engineering applications such as solar collector design, passive energy storage and micro-manufacturing techniques such as lithography.

2. Review of literature

Gille and Goody [5] conducted experimental studies on the effect of radiative transfer on the onset of Rayleigh–Benard convection by comparing data for dry air and NH_3 between parallel aluminum plates maintained at different temperatures. Their experiments indicated that the critical Rayleigh number in NH_3 is greatly increased compared to that for air. Lan et al. [6], experimentally, determined the onset of Rayleigh–Benard convection in horizontal layers of varying mixtures of air and CO_2. They found out a maximum increase of 20% in the critical Rayleigh number. Lan et al. [7] used linear stability analysis and weakly non-linear analysis to determine the critical Rayleigh number for the onset of convection in the presence of radiation in three-dimensional enclosure using spectral methods. Chunmei and Jayathi [3] carried out a numerical investigation of flow transitions in deep three-dimensional cavities heated from below to obtain the critical Rayleigh number for the onset of convection and the transition to turbulence in tall cavities with aspect ratio varying from 1 to 5. To determine the onset of convection, steady simulations were done starting with a Rayleigh number range across which the transition occurs. Tong et al. [12] carried out numerical simulations to determine the onset of natural convection in tall and shallow rectangular enclosures for both bottom heated and differentially heated configurations. The critical Rayleigh number was insensitive to the aspect ratio for flat, wide enclosures but, on the contrary, the critical value increased markedly with increasing aspect ratio for tall, narrow enclosures.

Though the literature on free convection in enclosures is vast, investigations which explore the effect of radiation on convection are scarce. Balaji and Venkateshan [1,2] carried out numerical investigations of free convection coupled with surface radiation in a differentially heated square cavity. They showed that surface radiation leads to a drop in the convective component but this reduction tends to be compensated by the radiative transfer between active walls. Ridouane et al. [10] discussed the effects of surface radiation on convection in an air filled square cavity heated from below cooled from above using a numerical model based on finite differences. Ridouane and Hasnaoui [11], numerically, investigated the influence of surface radiation on the flow and temperature patterns. The oscillatory behavior, characterizing the unsteady-state solutions during the transitions from bicellular flows to the unicellular flow were observed and discussed. Laboratory experiments exploring the effects of radiation on convection are scarce. Among the few studies are the one by Ramesh and Venkateshan [8] who conducted interferometric studies on the problem undertaken numerically by Balaji and Venkateshan. Later, Ramesh et al. [9] analyzed the effect of boundary conditions on natural convection in a square enclosure with surface radiation.

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Nomenclature

English symbols

AR	aspect ratio of cavity, L/H
C_p	specific heat of fluid, kJ/kg K
g	gravitational acceleration, 9.81 m/s^2
Gr	Grashof number, $g\beta\Delta TH^3/\nu^2$
H	characteristic height of the domain, m
L	characteristic length of the domain, m
N_{RC}	radiation conduction interaction parameter, $\sigma T_H{}^4 d/k(T_H-T_c)$
Nu	Nusselt number
Nu_C	convection Nusselt number, $q''_C L/k_f \Delta T$
Nu_R	radiation Nusselt number, $q''_R L/k_f \Delta T$
Pr	Prandtl number
Ra	Rayleigh number, $g\beta\Delta TH^3/\alpha\nu$
T	temperature of fluid, K
T_∞	ambient temperature, K
T_C	temperature of cold plate, K
T_H	temperature of hot plate, K
T_o	reference temperature, K
T_R	temperature ratio, T_C/T_H
U	velocity in x direction, m/s
V	velocity in y direction, m/s
x, y	coordinate directions

Greek symbols

α	thermal diffusivity, $\frac{k}{\rho C_p}$, m^2/s
β	coefficient of thermal expansion, K^{-1}
ΔT	(T_H-T_C), K
ε	emissivity
ε_H	emissivity of the hot wall
ε_C	emissivity of the cold wall
ε_B	emissivity of the bottom wall
ε_T	emissivity of the top wall
ε_R	emissivity of the right wall
ε_L	emissivity of the left wall
ρ	density of fluid, kg/m^3
ρ_o	density of fluid at reference temperature, kg/m^3
μ	dynamic viscosity of the fluid, Ns/m^2
ν	kinematic viscosity of fluid, m^2/s

Though the preceding literature review shows that convection in a cavity has received considerable attention, the problem of convection in a cavity heated from below where surface radiation influences the heat transfer has not received much attention. In consideration of this, the objectives of the present study are to determine the effect of surface radiation on the onset of Rayleigh–Benard convection for various aspect ratios and to study the effect of surface radiation on the fluid flow and heat transfer characteristics for bottom heated cavities.

3. Methodology

3.1. Governing equations

All the problems considered for the present study involve two-dimensional, laminar steady convection with surface radiation. The medium under consideration is air which is considered to be of constant thermo-physical properties except for density. The density changes are modeled via the Boussinesq approximation. Viscous heat dissipation and compressibility effects are considered to be negligible. Based on the above assumptions, the governing equations for mass, momentum and energy for a steady two-dimensional flow in the fluid domain are given below in terms of primitive variables.

Continuity equation

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{1}$$

X momentum equation

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{1}{\rho}\frac{\partial P}{\partial X}+\nu\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \tag{2}$$

Y momentum equation

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{1}{\rho}\frac{\partial P}{\partial Y}+\nu\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+g\beta(T-T_\infty) \tag{3}$$

Energy equation

$$U\frac{\partial T}{\partial X}+V\frac{\partial T}{\partial Y}=\alpha\left(\frac{\partial^2 T}{\partial X^2}+\frac{\partial^2 T}{\partial Y^2}\right) \tag{4}$$

For the problem under consideration, the performance of discrete ordinates (DO) radiation heat transfer model in FLUENT was found to be better than the surface-to-surface (S2S) radiation heat transfer model for the range of emissivity under consideration. In the present study, the optical thickness is set to 0, signifying a transparent medium.

3.2. Physical model and boundary conditions

The geometry under consideration is shown in Fig. 1. The fluid zone is initialized as being at rest. The bottom and top plates are isothermal, with the bottom plate at a higher temperature and the horizontal sidewalls are adiabatic. The emissivity of the top and bottom walls is kept 0.85 throughout the study. The emissivity of the horizontal sidewalls is a variable ($\varepsilon_L=\varepsilon_R$). These boundary conditions are expressed mathematically in Eqs. (5)–(9) and are shown in Fig. 1.

The important non-dimensional numbers for the problem are: aspect ratio—AR, temperature ratio—T_R, Grashof number—Gr and the radiation conduction interaction parameter, N_{RC}.

For the horizontal sidewalls,

$$\sum q=0 \tag{5}$$

$$\varepsilon_R=\varepsilon_L=\varepsilon \tag{6}$$

For the bottom wall,

$$T=T_H, \varepsilon_H=0.85 \tag{7}$$

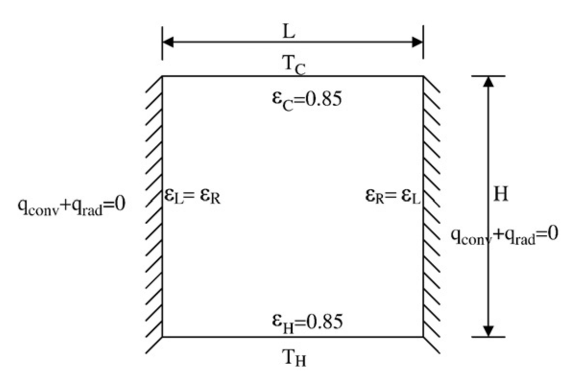

Fig. 1. Geometry and boundary conditions.