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Heating intensity and radiative effects on turbulent buoyancy-driven airflow in open square cavities with a heated immersed body

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ABSTRACT

The influence of the radiative heat transfer and the effects of air variable properties on the natural convection flows within a vented square cavity with a heated inner body are numerically investigated. Two-dimensional, unsteady, laminar, transitional and turbulent simulations are obtained, for both uniform wall temperature and uniform heat flux heating conditions. The average Nusselt number and the dimensionless mass-flow rate are obtained for a wide range of the Rayleigh number varying from 10^4 to 10^{12}. The results obtained for different heating intensities are analyzed and compared. The influence of considering surface radiative effects on the differences reached for the Nusselt number and the mass-flow rate obtained with several heating intensities is studied for the isothermal heating condition. For isoflux heating, the obtained results show that the effects of thermal radiation on the appearance of the *burnout* phenomenon are particularly relevant under given circumstances. The conditions under which the flow becomes unstable, giving rise to a transient, mainly oscillating solution, are determined. The relevant changes produced in the flow patterns into the cavity, are also explained.

1. Introduction

1.1. Natural convection in cavities. Some topics

In the last four decades, the fluid flow induced by buoyancy forces in cavities and enclosures has received a considerable attention from researchers (Ostrach [1], Bejan [2]), for both laminar conditions (Turan et al. [3], for instance), as well as for turbulent situations (Ben Yedder and Bilgen [4], Henkes and Hoogendorn [5], among others). Different geometries have been studied, including several heating conditions. Regarding the sample configuration consisting of a square cavity in which the horizontal walls are insulated, whereas a vertical wall is heated (at T_h temperature) and the other is cooled (at T_c), the numerical benchmark solution of De Vahl Davies [6] has constituted a reference work for comparison and validation purposes. The case is commonly known as *cavity heated from the side* (a different, complementary case, is that called *cavity heated from below*). Ridouane et al. [7] compared their numerical results with those obtained by De Vahl Davies [6], as well as with those conducted by Ampofo and Karayiannis [8], who established experimental bechmark data for turbulent natural convection of air also within a square cavity. Markatos and Pericleous [9] presented numerical laminar and turbulent results, including in the study correlations for the Nusselt number as a function of the Rayleigh number. Their results were used as reference validating data by Khanafer et al. [10], although these authors focused their investigations on the nanofluids behavior.

Other examples of numerical studies focused on square cavities with different morphologies, are the works conducted by Bilgen and Oztop [11], Bilgen and Balkaya [12], and Muftuoglu and Bilgen [13], among others. The assessment of adequate boundary conditions for numerical simulation in cavities and enclosures was studied for laminar flow by Khanafer and Vafai [14], and Anil Lal and Reji [15]. An important motivation for studying the problem is its application to practical situations, such as passive cooling systems of buildings (la Pica et al. [16], Warrington and Ameel [17] or Radhakrishnan et al. [18], among others). Some particular applications of cavities including an immerse body will be explained later.

1.2. Variable thermophysical properties

The force impelling the fluid motion can be modeled through the *Boussinesq approximation*, which assumes constant the properties of the fluid (except the density variations produced by temperature differences in the buoyancy term of the momentum equation). It is well known that this model should be applied only when temperature variations are low enough. However, moderate and intense heating conditions can be found under some circumstances in applications such as passive heat dissipation in electronic systems or emergency cooling devices. This fact can severely modify the properties of the fluid (typically air), and therefore to vary the initial predictions of the heat

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Nomenclature

b	width of the vents, m (Fig. 1c)
C_1, C_2	constants in Eq. (16), K
C_{2w}	constant of the $k-\omega$ turbulence model
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
Fo	Fourier number, $\mathrm{Fo}=\alpha_\infty t_0/l^2$
g	gravitational acceleration, m s^{-2}
Gr_l	Grashof number for isothermal cases, $g\beta(T_w-T_\infty)l^3/\nu_\infty^2$
Gr_l	Grashof number for heat flux cases, $g\beta q l^4/\nu_\infty^2\kappa_\infty$
H	height of the cavity (Fig. 1), m
H_c	height (and length) of the heated inner body (Fig. 1b and c), m
h_x	local heat transfer coefficient, $-\kappa(\partial T/\partial n)_w/(T_w-T_\infty)$, W m^{-2} K^{-1}
I	turbulence intensity, Eq. (19)
J	radiosity (W m^{-2})
k	turbulent kinetic energy, Eq. (18), m^2 s^{-2}
L	length of the cavity (Fig. 1), m
l	typical length, m
M	dimensionless mass-flow rate, $m/\rho_\infty\alpha_\infty$
m	mass-flow rate, kg s^{-1} m^{-1} (two-dimensional)
n	coordinate perpendicular to wall, m
Nu_l	average Nusselt number based on l, isothermal cases, Eq. (5)
Nu_l	average Nusselt number based on l, heat flux cases, Eq. (6)
$\mathrm{Nu}_{l,r}$	radiative average Nusselt number based on l, Eq. (8)
Nu_x	local Nusselt number, $h_x l/\kappa$
P	average reduced pressure, N m^{-2}
p	pressure, N m^{-2}
Pr	Prandtl number, $\mu c_p/\kappa$
q	wall heat flux (convective), W m^{-2}
q_r	wall heat flux (radiative), W m^{-2}
R	constant of air, R = 287 J kg^{-1} K^{-1}
Ra_l	Rayleigh number based on l, $(\mathrm{Gr}_l)(\mathrm{Pr})$
$\widetilde{\mathrm{Ra}}_l$	Rayleigh number from which the flow becomes oscillating
S_{ij}	mean-strain tensor, s^{-1}
T, T'	average and turbulent temperatures, respectively, K
t	time, s
t_0	typical time, s
$-\overline{T'u_j}$	average turbulent heat flux, K m s^{-1}
U_j, u_j	average and turbulent components of velocity, respectively, m s^{-1}
$-\overline{u_iu_j}$	turbulent stress, m^2 s^{-2}
u_τ	friction velocity, $u_\tau=(\tau_w/\rho)^{1/2}$, m s^{-1}
V	absolute value of velocity, m s^{-1}
x, y	cartesian coordinates (Fig. 1), m
y_1	distance between the wall and the first grid point, m
y^+	$\rho y_1 u_\tau/\mu$

Greek symbols

α	thermal diffusivity, $\kappa/\rho c_p$, m^2 s^{-1}
β	coefficient of thermal expansion, $1/T_\infty$, K^{-1}
γ	exponent in Eqs. (33) and (34)
ε	coefficient of surface radiation emissivity
ϕ	dependent variable
κ	thermal conductivity, W m^{-1} K^{-1}
Λ	heating parameter, Eqs. (2) and (4)
μ	viscosity, kg m^{-1} s^{-1}
ν	kinematic viscosity, μ/ρ , m^2 s^{-1}
θ	dimensionless temperature difference, $\theta=(T-T_\infty)/(\Lambda T_\infty)$
ρ	density, kg m^{-3}
σ	Stefan-Boltzmann constant, $\sigma=5.6678\times10^{-8}$ W m^{-2} K^{-1}
τ	dimensionless time, $\tau=\alpha_\infty t/l^2$
τ_w	wall shear stress, N m^{-2}
ω	specific dissipation rate of k, s^{-1}

Subscripts

ave	averaged value
c	cooled
h	heated
max	maximum value
r	radiative
t	turbulent
w	wall
∞	ambient or reference conditions

Superscripts

–	averaged value

Abbreviations

UHF	Uniform Heat Flux
UWT	Uniform Wall Temperature

transfer and the mass-flow rate (Chenoweth and Paolucci [19]). Zhong et al. [20], and Emery and Lee [21], analyzed the influence of property variations on convective flows in a square enclosure. Hernández and Zamora [22] highlighted that for given conditions in cases with fixed heat flux at the walls, the wall temperature increases dramatically above a *critical* value of the heat flow rate. This finding, called *crisis phenomenon*, was previously described by Guo and Wu [23], being similar to the *burnout* in boiling two-phase flows.

1.3. Coupled natural convection and thermal radiation

In the field of interest, the radiative heat transfer should not be neglected in some cases. Focusing on cavity morphologies, the coupled natural convection and surface radiation in a differentially heated cavity was reported by Balaji and Venkateshan [24]; they numerically showed that thermal radiation produces a relevant contribution of the overall heat transfer as well as a decreasing of the convective part of heat transfer. Hinojosa et al. [25] studied the transient and steady-state natural convection coupled with surface thermal radiation in a square open cavity. Montiel et al. [26] carried out a numerical study on the heat transfer by thermal radiation and natural convection in an open cavity receiver; their results indicated that for large temperature differences, the thermal radiative exchange becomes more important than the convective one. Other works on several cavities geometries are those of Nouanégué et al. [27], Mezrhab et al. [28] for a cavity having a square body at its center, or Saravanan and Sivaraj [29], for a cavity with a heated immersed plate, for instance.

1.4. The inclusion of an immersed body

The flow established in cavities or enclosures in which a heated inner body can induce the buoyancy motion of the fluid deserves a particular attention mainly due to two reasons, which will be explained following.

The first reason is the fully understanding of the flow characteristics. In fact, the study of the structures of the resulting *buoyant plumes*, as well as their stability, or the presence of *bifurcation points* as the Rayleigh number increases, for different geometric configurations