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Radiative effects on turbulent buoyancy-driven airflow in open square cavities

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The effects of the radiative effects and the air variable properties (density, viscosity and thermal conductivity) on the buoyancy-driven flows established in open square cavities are investigated. Two-dimensional, laminar, transitional and turbulent simulations are obtained, considering both uniform wall temperature and uniform heat flux heating conditions. In transitional and turbulent cases, the low-Reynolds $k-\omega$ turbulence model is employed. The average Nusselt number and the dimensionless mass-flow rate have been obtained for a wide range of the Rayleigh number varying from 10^3 to 10^{16}. The results obtained taking into account the variable thermophysical properties of air are compared to those calculated assuming constant properties and the Boussinesq approximation. In addition, the influence of considering surface radiative effects on the differences reached for the Nusselt number and the mass flow rate obtained with several intensities of heating is studied; specifically, the effects of thermal radiation on the appearance of the *burnout phenomenon* is analyzed. The changes produced in the flow patterns into the cavity when the radiative heat transfer and the effects of variation of properties are relevant, are also shown.

1. Introduction

1.1. *Some topics in natural convection in cavities*

There is a growing interest in the heat transfer processes in cavities, mainly in square or rectangular ones. In fact, convective flows in enclosures and cavities can be found in different engineering applications such as electronic cooling devices, nuclear energy cooling systems, thermal passive systems in building (Trombe walls, thermosyphons, solar chimneys), drying of agricultural products, or fire and smoke spread in rooms and atriums. Different aspects of the problem were considered by several authors (Ostrach [1], Chan and Tien [2], Bejan [3]). Recent examples of numerical studies focused on square cavities with different morphologies, are the works conducted by Bilgen and Oztop [4], Bilgen and Balkaya [5], Bilgen and Muftuoglu [6], and Muftuoglu and Bilgen [7], among others.

The assessment of adequate boundary conditions for numerical simulation of flow in cavities and enclosures was studied for laminar flow by Khanafer and Vafai [8], and Anil Lal and Reji [9], among others. The simulation of turbulent flow has received more limited attention, although some relevant works can be found in literature (Ben Yedder and Bilgen [10], Henkes and Hoogendorn [11], Xamán et al. [12]). A clear motivation for studying the problem is its application to passive cooling systems of buildings, as mentioned above (la Pica et al. [13], Warrington and Ameel [14] or Radhakrishnan et al. [15], among others). Because of the large scale of passive ventilation and heating systems, the convective flow may be laminar, transitional or even fully turbulent; thus, depending on the main application, the studies should be consistent with this fact.

Most of the cited works deal with two-dimensional studies. Now then, although under given circumstances the obtained results can be extrapolated from two-dimensional (2D) to three-dimensional (3D) situations, it is clear that the morphology can force to carry out a 3D study (Fu et al. [16]). A relatively few number of works can be found on 3D turbulent natural convection in enclosures or cavities, although some of them are concerned with partitioned enclosures, large cavities or air-filled tall cavities (Khalifa and Khudheyer [17], Yang and Zhu [18], among others). In view of the above explanation, there are still several areas of study in the described problem. In this regard, for example, authors have

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Nomenclature

b	width of the vent, m (Fig. 1)
C,D	correlation factors
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
g	gravitational acceleration, m s^{-2}
Gr$_H$	Grashof number for isothermal cases, $g\beta(T_w - T_\infty)H^3/\nu_\infty^2$
Gr$_H$	Grashof number for heat flux cases, $g\beta q H^4/\nu_\infty^2\kappa_\infty$
H	height of the cavity (and the heated wall) (Fig. 1), 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}
k_s	coefficient of radiative scattering, m^{-1}
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$_H$	average Nusselt number based on H, isothermal cases, Eq. (8)
Nu$_H$	average Nusselt number based on H, heat flux cases, Eq. (9)
Nu$_r$	radiative average Nusselt number based on H, Eq. (11)
Nu$_x$	local Nusselt number, $h_x H/\kappa$
P	average reduced pressure, N m^{-2}
P_T	total-average reduced pressure, N m^{-2}
p	pressure, N m^{-2}
Pr	Prandtl number, $\mu c_p/\kappa$
Q_r	dimensionless boundary heat flux (radiative), Eq. (12)
q	wall heat flux (convective), W m^{-2}
q_r	boundary heat flux (radiative), W m^{-2}
R	constant of air, $R = 287$ J kg^{-1} K^{-1}
Ra$_H$	Rayleigh number based on H, (Gr$_H$) (Pr)
S_{ij}	mean-strain tensor, s^{-1}
T,T'	average and turbulent temperatures, respectively, K
$-\overline{T'u_j}$	average turbulent heat flux, K m s^{-1}
U_j,u_j	average and turbulent components of velocity, respectively, m s^{-1}
$-\overline{u_i u_j}$	turbulent stress, m^2 s^{-2}
u_τ	friction velocity, $u_\tau = (\tau_w/\rho)^{1/2}$, 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}
α_r	coefficient of radiative absorption, m^{-1}
β	coefficient of thermal expansion, $1/T_\infty$, K^{-1}
δ_{ij}	Krönecker delta
δ_T	thickness of the thermal boundary layer, m
ε	coefficient of surface radiation emissivity
ϕ	dependent variable
κ	thermal conductivity, W m^{-1} K^{-1}
Λ	heating parameter, Eqs. (2) and (6) for UWT and UHF heating, respectively
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, $\sigma = 5.6678 \times 10^{-8}$ W m^{-2} K^{-1}
τ_w	wall shear stress, N m^{-2}
ω	specific dissipation rate of k, s^{-1}

Subscripts

B	constant properties and Boussinesq approximation
max	maximum value
r	radiative
t	turbulent
w	wall
∞	ambient or reference conditions

Superscripts

–	averaged value

Abbreviations

RTE	Radiation Thermal Equation
UHF	Uniform Heat Flux
UWT	Uniform Wall Temperature

studied recently 3D effects on cavities (Zamora and Kaiser [19]). Now, present study focuses on two topics: the influence of the variation of fluid thermophysical properties, and the effects of the thermal radiation, as will be explained later.

1.2. Influence of the variable thermophysical properties

It is well known that the *Boussinesq approximation*, which assumes constant the thermophysical properties of the fluid (except the density variations produced by temperature differences in the buoyancy term of the momentum equation), can be applied 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. This fact can severely modify the properties of the fluid (typically air), and therefore to vary the previous predictions of the heat transfer and the mass flow rate (see for instance Gray and Giorgini [20]). Zhong et al. [21], and Emery and Lee [22], analyzed the influence of property variations on convective flows in a square enclosure. Chenoweth and Paolucci [23] explained that the Boussinesq approximation could produce important errors for temperature increases about 20% of T_∞. Hernández and Zamora [24] showed that for given conditions in cases with fixed heat flux at the walls, above a *critical* value of the heat flow rate, the wall temperature increases dramatically. This finding, called *crisis phenomenon*, was previously described by Guo and Wu [25] (it is similar to the *burnout* that appears in boiling two-phase flows). It can be considered that there is a gap of publications in recent years for studies focusing directly on the variation of air properties in convective flows, thus authors have studied the problem applied to open square cavities (Zamora and Kaiser [26]).

1.3. Coupled natural convection and thermal radiation

In the field of interest, the radiative heat transfer effects were not included in most of cases because they were negligible