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Effects of heating intensity on the transient natural convection flows in open cavities

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ABSTRACT

The effects of the air variable properties (density, viscosity and thermal conductivity) on the transient buoyancy-driven flows established in open square cavities are investigated. Two-dimensional, laminar, transitional and turbulent simulations are obtained, mainly considering uniform heat flux heating conditions. For the fully understanding of the transient flow, different configurations are considered, including those chosen for comparison purposes. 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 10^5 to 10^{12}. The changes produced along the time in the flow patterns inside the cavity when the effects of variation of properties are relevant, are also shown. The transient evolution of the flow is strongly affected when the heating parameter is high enough.

1. Introduction

A literature survey shows that several aspects of natural convection flows have been extensively investigated (Ostrach [1], Chan and Tien [2], Bejan [3], Kazansky et al. [4], Letan et al. [5], da Silva and Gosselin [6], Li et al. [7], Desrayaud and Lauriat [8], for instance). Convective flows in cavities and enclosures can be found in several engineering applications such as electronic cooling devices, thermal passive systems in buildings, or fire and smoke spread in rooms and atriums. Some examples of numerical studies dealing with square cavities with different morphologies are those conducted by Bilgen and Oztop [9], Bilgen and Balkaya [10], Bilgen and Muftuoglu [11], and Muftuoglu and Bilgen [12], among others. Most of the reported works were for steady conditions, being relatively small the number of studies related to the transient state. The fact remains that the transient study of the problem provides a substantial knowledge; indeed, the transient assumption is essential for the complete understanding of the natural convection flows. One can expect that some relevant effects could appear along the transient evolution of the flow, from the start towards the steady state. Present study mainly focuses on the influence of the variation of fluid thermophysical properties on the transient evolution of the convective flow, as will be explained later in a more detailed manner.

1.1. Some topics in transient natural convection flows

Regarding the transient analysis in *vertical channels systems*, some numerical studies can be cited, such as those of Joshi [13], Chang and Lin [14], Shyy and Rao [15] or Chang and Hung [16]. Joshi [13] presented simple correlations to calculate the minimum heat transfer and the maximum wall temperature along the transient evolution of the flow. The study carried out by Shyy and Rao [15] has a particular interest in electronics cooling. They determined the oscillatory transient flow into an enclosed vertical channel. Their calculations will be compared with those obtained in this work, for validation purposes. Later, Bhrowmik and Tou [17] presented an experimental study of transient natural convection heat transfer from simulated electronic chips. Langelloto et al. [18] carried out a numerical investigation of transient convective flows in a isoflux convergent vertical channel. They presented results for the stream function and dimensionless air temperature fields. Manca et al. [19] conducted a numerical study of transient natural convection in vertical divergent channels. Andreozzi et al. [20], and Buonomo and Manca [21], numerically studied the transient natural convection in vertical parallel-plate channels, and microchannels, respectively, with uniform heat flux at walls. They showed that the maximum wall temperature as a function of time, presented overshoots. The chimney effects were included by Andreozzi et al. [22] in their numerical investigations on transient natural convection in a vertical channel-chimney system. The channel was symmetrically heated with a uniform heat flux at walls, as above works. These authors found that the maximum wall

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Nomenclature

A, B, C, D	correlation factors, Eq. (26)
b	inter-plate spacing (Fig. 1a and b), m
b	width of the vent (Fig. 1c), m
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_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, $g\beta qH^4/\nu_\infty^2\kappa_\infty$
H	height of the channel (Fig. 1a) or the cavity (Fig. 1b and c), m
H_c	height of the enclosed channel, Fig. 1b, m
h_y	local heat transfer coefficient, $-\kappa(\partial T/\partial n)_w/(T_w - T_\infty)$, W m^{-2} K^{-1}
I	turbulence intensity, Eq. (22)
k	turbulent kinetic energy, Eq. (21), m^2 s^{-2}
L	length of the enclosure or the cavity (Fig. 1b and c), 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_y	local Nusselt number, $h_y H/\kappa$
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	wall heat flux, 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
t	time, s
t_0	typical time, s
$-\overline{T'u_j}$	average turbulent heat flux, K m s^{-1}
U_j (U_x, U_y)	average components of velocity, m s^{-1}
u_j (u_x, u_y)	turbulent components of velocity, m s^{-1}
$-\overline{u_i u_j}$	turbulent stress, m^2 s^{-2}
u^*	friction velocity, $u^* = (\tau_w/\rho)^{1/2}$, m s^{-1}
x, y	cartesian coordinates (Fig. 1), m
y_1	distance between the wall and the first grid point, m
y^+	$\rho y_1 u^*/\mu$

Greek symbols

α	thermal diffusivity, $\kappa/\rho c_p$, m^2 s^{-1}
β	coefficient of thermal expansion, $1/T_\infty$, K^{-1}
δ_{ij}	Krönecker delta
δ_T	thickness of the thermal boundary layer, m
ϕ	generalized dependent variable
κ	thermal conductivity, W m^{-1} K^{-1}
Λ	heating parameter, Eqs. (2) and (6)
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	dimensionless time, $\tau = \alpha_\infty t/H^2$
τ_w	wall shear stress, N m^{-2}
χ	exponent in Eq. (5)
ω	specific dissipation rate of k, s^{-1}

Subscripts

c	critical value
max	maximum value
ref	reference mesh
t	turbulent
w	wall
∞	ambient or reference conditions

Superscripts

–	averaged value

Abbreviations

UHF	uniform heat flux
UWT	uniform wall temperature

emperature at wall was never attained at the steady state time; in fact, they pointed out that this transient overheating, which is produced when a uniform wall heat flux is fixed at walls, is well documented in the literature.

More recently, the transient convective flow established in *enclosures or cavities* have deserved more attention. Banri [23], and Banri et al. [24] presented numerical and experimental results for parallelogramic enclosures, considering several values of the Rayleigh number. Oriented to air movements in ventilated rooms and thermal passive systems in buildings, it can be cited the works of Serrano-Orellano et al. [25] or Banri [26], for instance. Hinojosa et al. [27] studied numerically the transient and the steady-state natural convection coupled with surface thermal radiation in a square open cavity.

With respect to *three-dimensional morphologies*, a literature study shows that this topic deserved minor attention. Hinojosa and Cervantes-de Gortari [28] conducted a numerical simulation of the transient convective flow in an isothermal open cubic cavity. They found transient oscillations in the average Nusselt number due to the onset and displacement of thermal plumes. Similarly, the effects of the variable thermophysical properties of the fluid in transient studies have been included in a few number of works (see, for instance, Leal et al. [29]).

1.2. Influence of the variable thermophysical properties of fluid

The fluid considered in natural convection flows is typically air. 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 government equations), can be applied when temperature variations are low enough. However, moderate and intense heating conditions can be found under some circumstances (applications such as passive heat dissipation in electronic systems). This can severely modify the properties of the fluid, and therefore produce deviations from the previous predictions of the heat transfer and the mass flow rate (see for instance Gray and Giorgini [30]). Chenoweth and Paolucci [31] explained that the Boussinesq approximation could produce relevant discrepancies for temperature increments about 20% of T_∞. Zhong et al. [32], and Emery and Lee [33], analyzed the influence of property variations on convective flows in a square enclosure. Hernández and Zamora [34]