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3D effects in numerical simulations of convective flows in cubical open cavities

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ABSTRACT

Buoyancy-driven flows established in open cubical cavities are investigated. Three-dimensional, laminar, transitional and turbulent simulations are obtained, considering both uniform wall temperature and uniform heat flux heating. Aiming the study of 3D effects, results are compared with those previously obtained for 2D situations. To take into account the effects of the variable properties of air, it is assumed that both thermal conductivity and the viscosity depend on temperature, with the density estimated from the state equation. The low-Reynolds $k-\omega$ turbulence model is employed to simulate the transitional or fully turbulent flow. The average Nusselt number and the dimensionless mass flow rate have been obtained for Rayleigh numbers ranging $10^6 \le \mathrm{Ra}_H \le 10^{12}$. The results obtained taking into account variable properties effects are compared with those calculated assuming constant properties and the Boussinesq approximation. In addition, the influence of considering an internal wall (adiabatic or isothermal) is also studied, as well as the influence of the slope of external heated wall.

1. Introduction

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 (thermosyphons, solar chimneys, Trombe Walls) or fire and smoke spread in rooms and atriums. Several aspects of the problem were conducted by several authors (Ostrach [1], Bejan [2], Chan and Tien [3], Mohamad [4]). Recent examples of numerical studies focused on square cavities with different morphologies, fully or partially open, are works addressed by Bilgen and Oztop [5], Bilgen and Balkaya [6], Bilgen and Muftuoglu [7], and Muftuoglu and Bilgen [8], among others. It can be stated that there is a growing interest in square cavities. Although it is possible to find a considerable number of three-dimensional studies, the fact is that most of these studies are two-dimensional.

The assessment of appropriate boundary conditions for numerical simulation of flow in cavities and enclosures was studied for laminar flow by Khanafer and Vafai [9], and Anil Lal and Reji [10], 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 [11], Henkes and Hoogendorn [12], Xamán et al. [13]). A major motivation for studying the regarded problem is its application to passive cooling systems of buildings, as mentioned above (la Pica et al. [14], Warrington and Ameel [15] or Radhakrishnan et al. [16], among others). Because of the large scale of passive ventilation and heating systems, the convective flow may be laminar, transitional or even fully turbulent.

1.1. Influence of the variable thermophysical properties

The *Boussinesq approximation*, which assumes constant the thermophysical properties of the fluid (with the exception of the density differences due to temperature differences in the buoyancy term of governing equations), can be employed when temperature changes are low enough. However, moderate and intense heating conditions can be found under given circumstances in applications such as passive heat dissipation in electronic systems. This fact can severely modify the properties of air, and therefore to change initial predictions of the mass flow rate and the heat transfer (Gray and Giorgini [17]). Zhong et al. [18], and Emery and Lee [19] analyzed the influence of property variations on convective flows in a square enclosure. Chenoweth and Paolucci [20] showed that the Boussinesq approximation could produce important errors for temperature increases about 20% of T_∞. Hernández and Zamora [21] showed that for given conditions in cases with fixed heat flux at the walls, above a critical value of heat flow rate, the wall temperature increases dramatically. This finding, called *crisis phenomenon*, was previously described by Guo and Wu [22] (it is similar to the

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Nomenclature

$A1$, $A2$	spacing between internal and external walls, m (Fig. 1c)
b	width of the vent, m (Fig. 1)
C, D	correlation factors
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
E	thickness of the internal wall, m (Fig. 1c)
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_y	local heat transfer coefficient, $-\kappa(\partial T/\partial n)_w/(T_w - T_\infty)$, W m^{-2} K^{-1}
I	turbulence intensity, Eq. (18)
k	turbulent kinetic energy, Eq. (17), m^2 s^{-2}
H	height of the cavity (and the external heated wall) (Fig. 1a and b), m
L	length of the cavity (Fig. 1), m
L_c	typical length, m
M	dimensionless mass flow rate, $m/\rho_\infty\alpha_\infty W$
m	mass flow rate, kg s^{-1}
n	coordinate perpendicular to wall, m
$\mathrm{Nu}_H(z)$	average Nusselt number based on H, at a given z-plane
Nu_H	global Nusselt number based on H, isothermal cases, Eq. (8)
Nu_H	global Nusselt number based on H, heat flux cases, Eq. (10)
Nu_y	local Nusselt number, h_yH/κ
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 the gas, J kg^{-1} K^{-1}
Ra_H	Rayleigh number based on H, $(\mathrm{Gr}_H)(\mathrm{Pr})$
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}
$-\overline{u_iu_j}$	turbulent stress, m^2 s^{-2}
u_τ	friction velocity, $u_\tau = (\tau_w/\rho)^{1/2}$, m s^{-1}
W	width of the cavity (Fig. 1a and b), m
x,y,z	Cartesian coordinates (Fig. 1), m
y^+	$\rho y_1u_\tau/\mu$, with y_1 the distance between the wall and the first grid point

Greek symbols

α	thermal diffusivity, $\kappa/\rho c_p$, m^2 s^{-1}
β	coefficient of thermal expansion, $1/T_\infty$, K^{-1}
γ	slope of the external heated wall (Fig. 1c)
δ_{ij}	Krönecker delta
δ_T	thickness of the thermal boundary layer, m
ϕ	dependent variable
κ	thermal conductivity, W m^{-1} K^{-1}
Λ	heating parameter, Eqs. (3) and (5) 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, $\theta = (T - T_\infty)/(T_w - T_\infty)$
ρ	density, kg m^{-3}
τ_w	wall shear stress, N m^{-2}
Ψ	heating wall ratio, $(T_{w,\mathrm{int}} - T_\infty)/(T_{w,\mathrm{ext}} - T_\infty)$
ω	specific dissipation rate of k, s^{-1}

Subscripts

1,2	outer/inner sides of the internal wall (Fig. 1c)
ave	average value of the Nusselt number at a given y-plane
B	constant properties and Boussinesq approximation
ext	external (heated) wall of the cavity
int	internal (adiabatic or isothermal) wall of the cavity
max	maximum value
ref	reference grid
t	turbulent
w	wall
∞	ambient or reference conditions

Superscripts

$-$	averaged value

Abbreviations

2D,3D	two-dimensional and three-dimensional simulations, respectively
UHF	uniform heat flux
UWT	uniform wall temperature

burnout that appears in boiling two-phase flows). More recently, Morrone and Campo [23] have revealed that there is a gap of publications in recent years for studies focusing directly on the variation of air properties in convective flows.

1.2. Three-dimensional aspects of the problem

So far, most of the cited works deals with two-dimensional studies. Now then, although under given circumstances the obtained results can be extrapolated from 2D to 3D situations, it is clear that the morphology can force to carry out a three-dimensional study (Fu et al. [24]). In the field of interest, Bohn et al. [25] addressed experimental 3D studies on natural convection in enclosures with differentially heated vertical walls at high Rayleigh numbers; they verified the existence of a relatively inactive core surrounded by boundary layers on each of the four vertical walls. Yang and Tao [26] included an internal isolated vertical plate in their investigations. Several numerical studies can be found in literature, although many of them deal with laminar flow (Yu and Joshi [27]). da Silva and Gosselin [28] and Frederick and Moraga [29], among others, studied the performance of the natural convection flow established in finned cubical enclosures. More recently, several aspects of the problem have deserved the attention of researchers, such as the influence of including a sphere at different vertical locations in a cubical enclosure (Yoon et al. [30]), or the effects of considering pin arrays attached to heated wall in 3D rectangular enclosures (Bocu and Altac [31], for instance). A relatively few number of works can be found on 3D turbulent natural convection on enclosures or cavities, although some of them deal with partitioned enclosures, large cavities or air-filled tall cavities (Khalifa and Khudheyer [32], Yang and Zhu [33], among others).

1.3. The aim of this work

To our knowledge, there is a clear lack of systematic studies of convective flow established in 3D cavities, considering on one hand