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Heat transfer modification induced by a localized thermal disturbance in a differentially-heated cavity

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ABSTRACT

Numerical investigation of a natural convection flow with a localized thermal disturbance is presented here. The configuration of a differentially heated cavity is considered with air as working fluid. In this study, the initial flow regime is steady and close to the transition to unsteadiness. Different cases of local wall temperature disturbances are tested in a thin area at the onset of the hot vertical boundary layer. These cases are distinguished by the time-averaged temperature of this area (higher or lower than the hot wall temperature) and by their temporal evolution (steady or periodic). In cases with a periodic disturbance, the imposed frequency corresponds to the first frequency emerging in the unsteady regime. The results show the spread of temperature fluctuations across the whole cavity with the periodic disturbance, in particular near the upper corner of the cavity. The hot steady disturbance trigs the onset of time-dependent flow. Moreover, the local modification of the hot wall temperature has an impact on global heat transfer: about 16% downstream the disturbance area and about 2% on the opposite cold wall.

1. Introduction

Natural convection flows occur in a wide range of practical applications in which heat transfer optimization is of great interest: a better insulation of the walls such as in buildings construction, enhancement of thermal flux for cooling electronic device or nuclear reactors, as for thermal storage tanks and solar energy collectors.

These practical applications can be modeled through the simpler representation of the differentially heated cavity (DHC) in order to have a better understanding of the associated physics. DHC have been deeply studied experimentally and numerically for decades since the pioneering works of Batchelor [1]. In 1983 de Vahl Davis and Jones [2] published a benchmark solution in an air-filled square DHC for a Rayleigh number varying in the range of 10^3 - 10^6. In the next years, several studies have been made to investigate the transition from a steady to a time-dependent flow [3–6]. Tric et al. [7] proposed 3D accurate solutions of air natural convection in a cubic DHC by mean of pseudo-spectral Chebyshev algorithm. Xin and Le Quéré [8–11] revisited the onset of time-dependent flows for aspect ratios between 1 and 8, for both adiabatic and perfectly conducting horizontal walls. They used several stability analysis algorithms to provide accurate critical Rayleigh numbers and associated frequencies of the most unstable modes.

Several authors have used multiple strategies to act on buoyancy-driven flows. For a heated vertical plate with a superimposed perturbation source, Zhao et al. [12] observed numerically a net heat transfer enhancement by a resonance-induced advancement of the laminar-turbulent transition. For the Rayleigh-Bénard convection, Howle [13,14] investigated the control of the flow using localized heat fluxes, whereas Abourida et al. [15] and Douamna et al. [16] chose to impose a time-dependent temperature at the isothermal walls. By varying amplitude, period and dephasing between walls, heat transfer was changed. Hossain and Floryan investigated the control of natural convection in a fluid layer heated from below [17] or from below and above [18] with a sine spatial distribution. They found a significant increase of heat transfer when a synchronized disturbance is applied over both walls. Focusing now on the DHC configuration, one of the first ways to act on the flow in DHC was by means of a thin fin on the hot wall, positioned horizontally [19–22] or tilted [23,24], and more recently by using a flexible fin [25]. As buoyancy-driven flows can be induced by means of appropriate temperature boundary conditions, several studies have been carried out on the thermal disturbance in DHC instead of a mechanical one. In 1996, Kwak et al. [26,27] imposed numerically a sine-varying temperature on the hot wall of a square cavity for a fixed Rayleigh number and varied the amplitude and the

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Nomenclature

A	Aspect ratio (A = H/L)
A_d	Disturbance amplitude
f	Dimensionless frequency (scaled by $f_0 = 1/t_0$)
g	Gravitational acceleration, m s^{-2}
H	Height of the cavity, m
L	Length of the cavity, m
Nu(Z,t)	Local Nusselt number based on height H, $Nu\,(Z,\,t) = -\,\partial\theta(X,\,Z,\,t)\,/\,\partial X$
$<\overline{Nu_{P\,i}}>$	Zonal Nusselt number (time and space-averaged Nusselt number on a part $P_{i,\ i=1,2,3}$)
p_m^*	Dimensionless motion pressure, $p_m^* = \frac{p_m}{Pr \times \rho_0 V_0^2}$
Pr	Prandtl number, Pr = ν/α
Ra_H	Rayleigh number based on height H, $Ra_H = (g\beta\Delta TH^3)\,/\,(\alpha\nu)$
t_0	Reference time, $t_0 = H/V_0$
t^*	Dimensionless time (scaled by t_0)
T	Temperature, °C
T_0	Mean temperature of the cavity, $T_0 = (T_h + T_c)\,/\,2$, °C
u, w	Horizontal and vertical velocity component in x and z direction
V_0	Reference velocity, $V_0 = \frac{\alpha}{H}\sqrt{Ra_H}$
x, z	Horizontal and vertical coordinates, m
X, Z	Dimensionless coordinates; $X = x/H$, $Z = z/H$
Z_1, Z_2	Limits of the disturbance area

Greek symbols

A	Thermal diffusivity, $m^2\ s^{-1}$
B	Thermal expansion coefficient, K^{-1}
Δ	Temperature level of the disturbance, $\delta \in \{-1;\ 0;\ 1\}$
ΔT	Temperature difference between the hot and the cold walls, $\Delta T = T_h - T_c$, °C
E	Numerical parameter; ε = 0 steady disturbance, ε = 1 sine disturbance
Ψ (Z)	Spatial term of the disturbance function
θ	Dimensionless temperature, $\theta = (T - T_0)\,/\,\Delta T$
N	Kinematic viscosity, $m^2\ s^{-1}$

Subscripts and Superscripts

c	Cold wall
h	Hot wall
d	Disturbance
rms	Root mean square
crit	critical
0	Reference value
Φ'	Fluctuation of Φ, Φ' = Φ − < Φ>
$\overline{\Phi}$(t)	Spatial averaged value of h, $\overline{\Phi}(t) = \int_0^1 <\Phi\,(Z,\,t)>\,dZ$
<Φ(Z)>	Time average value of h, $<\Phi\,(Z)> = f_d \int_t^{t+1/f_d} \Phi\,(Z,\,t)dt$
*	Dimensionless quantity
–	Steady disturbance
~	Sine disturbance

Abbreviations

CS	Cold Spot
HS	Hot Spot
DHC	Differentially Heated Cavity

frequency. The wall temperature oscillation caused an increase in time-average heat transfer, which was maximal at the resonant frequency. More recently, Mahapatra et al. [28,29] used alternatively active heat sources on the bottom wall of an enclosure. Heat transfer was higher compared to the case with a single steady heater and increased with frequency. In an experimental study, Penot et al. [30] investigated the effect of a thin pipe localized close to the hot wall. The pipe temperature was varied periodically at the resonant frequency of the critical flow regime. The thermal disturbances increased velocity fluctuations, but the introduction of the pipe acted in the opposite manner due to an obstacle effect, and a decrease of the global Nusselt number is observed.

In this paper, a thermal disturbance localized on the hot wall is used as actuator to act on natural convection and to modify heat transfer. Wall temperature is modified on a thin area at the onset of the hot vertical boundary layer. An aspect-ratio of 4 is considered, being the first aspect-ratio for which unsteady flow displays traveling waves near the cavity walls [10]. Air is taken as working fluid. In such a case, the flow is steady laminar up to the critical Rayleigh number of 10^8 where unsteady regime appears in the outer edge of the boundary-layers. A 2D numerical study is performed in order to evaluate the feasibility and the pertinence of such an approach. The flow is idealized with a bi-dimensional aspect, since the first weak 3D flow does not alter the transition scenario to unsteadiness [11].

In the following sections, the model, the numerical methods and the validation are provided. Then an analysis of the results in terms of temperature fluctuations in the whole cavity and in terms of heat transfer through the active walls is carried out.

2. Model and validation

The DHC considered in this study is a parallelepiped-shaped cavity

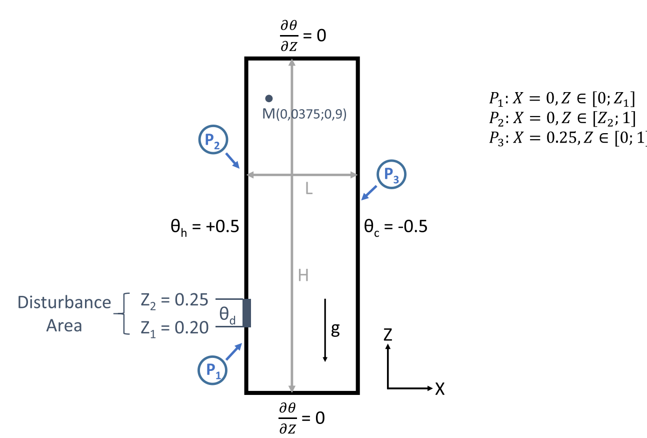

Fig. 1. Scheme of the rectangular cavity with disturbance area on the hot wall for Z between Z_1 and Z_2; the measuring point M is located at (X = 0.0375; Z = 0.9); the wall parts (P_1, P_2, P_3) are respectively upstream and downstream the disturbance area, and all along the cold wall.

of aspect ratio H/L = 4. It is composed of two vertical opposite isothermal walls, whereas the others walls are adiabatic (see Fig. 1). Two different temperatures (T_c and T_h) are imposed on these isothermal walls. Air thermophysical properties are evaluated at the mean temperature of the cavity $T_0 = \frac{T_c + T_h}{2} = 20\,°C$. Due to small temperature variation in the cavity (the temperature difference between active walls is at worse $\Delta T = T_h - T_c = 2.7$ °C), these properties are given constant in the computational domain, except for the density in the buoyant term where the Boussinesq approximation is used. The characteristic Rayleigh number is $Ra_H = 9.0 \times 10^7$, close to the critical value. In this