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Transition to an unsteady flow induced by a fin on the sidewall of a differentially heated air-filled square cavity and heat transfer

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ABSTRACT

The transition from a steady to an unsteady flow induced by an adiabatic fin on the sidewall of a differentially heated air-filled cavity is numerically investigated. Numerical simulations have been performed over the range of Rayleigh numbers from Ra = 10^5–10^9. The temporal development and spatial structures of natural convection flows in the cavity with a fin are described. It has been demonstrated that the fin may induce the transition to an unsteady flow and the critical Rayleigh number for the occurrence of the transition is between 3.72×10^6 and 3.73×10^6. Furthermore, the peak frequencies of the oscillations triggered by different mechanisms are obtained through spectral analysis. It has been found that the flow rate through the cavity with a fin is larger than that without a fin under the unsteady flow, indicating that the fin may improve the unsteady flow in the cavity.

1. Introduction

The thermally driven air flow is present in various industrial applications such as electronic cooling systems and heat exchangers, and thus the studies of the flow in a differentially heated cavity have been extensively reported in the literature over the past decades.

One of the earliest studies by Batchelor [1] has shown that heat transfer through the cavity is dominated by conduction for sufficiently small Rayleigh numbers. Most subsequent investigations (e.g. De Vahl Davis [2]) have focused on the steady natural convection flow in the cavity. However, natural convection flows in industrial systems are usually unsteady. Accordingly, the development of natural convection flows in the cavity following sudden heating and cooling has been given considerable attention over the last three decades. The study by Patterson and Imberger [3] has shown that transient natural convection flows in the cavity (where the Prandtl number is however larger than unity) mainly involve a vertical boundary layer flow, a horizontal intrusion flow, and the flow in the core. It has been demonstrated that if the Rayleigh number is sufficiently large (e.g. larger than the critical value), natural convection flows in an air-filled cavity could become unsteady [4–6] and even fully turbulent [7–14].

The study of heat transfer through a cavity is of practical significance in many industrial applications such as heat exchangers, and thus the effort to manipulate the flow regimes and in turn determine heat mass transfer in the cavity has been performed. One simple way to enhance or depress heat transfer through the cavity is to place a horizontal fin on the heated or cooled sidewall, which has also been considerably reported in the literature (refer to e.g. [15–17]). The focus of the early studies (e.g. [15]) is on steady laminar natural convection flows induced by a fin at low Rayleigh numbers. It has been demonstrated that if the length of a fin is sufficiently large, secondary circulations arise at both the upper and lower corners of the fin [18], and the heat transfer through the finned sidewall is reduced as the fin length increases due to the depression of the flows adjacent to the finned sidewall [19,20]. However, the study by Ooshuizen and Paul [21] has revealed that the secondary circulations resulting from the presence of a large fin on one wall of the cavity enhance the flows adjacent to the opposite sidewall and thus enhance the heat transfer through the opposite sidewall.

Transient natural convection flows in a cavity with a fin have also been recently investigated [22–24]. The experiment by Xu et al. [22] shows that the development of natural convection flows induced by a fin following sudden heating includes three stages: an initial stage, a transitional stage, and a fully developed stage. At the initial stage, the fin blocks the upstream vertical boundary layer flow and forces it to detach from the finned sidewall, and thus a lower intrusion front is formed. The lower intrusion reattaches to the downstream sidewall after it bypasses the fin. A double-layer structure of the vertical boundary layer appears and develops at the transitional stage, and is ultimately formed with a stratification of fluid in the cavity at the fully developed stage.

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Nomenclature

A	aspect ratio
f	frequency
f_p	peak frequency
g	acceleration due to gravity
H, L	height and length of the cavity
l	length of the fin
k	thermal conductivity
Nu	Nusselt number of the finned sidewall
p	pressure
Pr	Prandtl number, ν/κ
Ra	Rayleigh number, $g\beta\Delta TH^3/\nu\kappa$
Ra_c	critical Rayleigh number of the transition to an unsteady flow
Ra_{loc}	local Rayleigh number, $g\beta\,(T_{max} - T_{min})\Delta y^3/\nu\kappa$
t	time
Δt	time step
T	temperature
T_0	initial temperature
T_c, T_h	temperatures of the cold and hot sidewalls
T_{max}, T_{min}	maximum and minimum temperatures of the fluid layer above the fin
u, v	velocity components in the x and y directions
x, y	horizontal and vertical coordinates
Δy	thickness of the fluid layer (with an adverse temperature gradient) above the fin
β	coefficient of thermal expansion
κ	thermal diffusivity
ν	kinematic viscosity
ρ	density
Superscripts	
f	peak frequency of the oscillations induced by the fin
t	peak frequency of instability of the thermal boundary layer adjacent to the cold wall
i	peak frequency of internal waves

The fin influences on laminar natural convection flows in the cavity [19–21] and even may trigger the transition to unsteady natural convection flows in the cavity [23,24]. The study by Xu et al. [24] has demonstrated that the transition to a periodic flow around the fin in a water-filled cavity may happen if the Rayleigh number is large and the fin length is sufficiently long (the fin thickness is often considered to be negligibly small in comparison with its length, i.e. so-called thin fin, refer to [15–17] for details). The studies [23–25] show flow separation and oscillations of the thermal flow above the fin in the water-filled cavity. These oscillations in turn trigger traveling waves in the thermal boundary layer downstream of the fin. As a consequence, heat transfer through the water-filled cavity is significantly enhanced by up to 23%.

The previous study by Le Quére and Behnia [6] shows that natural convection in an air-filled cavity without a fin is unsteady if $Ra > 1.82 \times 10^8$. However, the study of unsteady natural convection flows in the air-filled cavity with a fin has not been investigated previously. Due to the distinct variations between natural convection flows in the air-filled and the water-filled cavity with a fin (see e.g. [17,24]), it is of practical significance to confirm whether the fin is able to induce the transition to an unsteady flow in the air-filled cavity and investigate the dependence on the Rayleigh number of the frequency of the mechanism-different oscillations and heat mass transfer in the air-filled cavity with a fin. These motivate the present numerical study.

In the rest of this paper, the numerical procedures are given in Section 2; the development of natural convection flows in the air-filled cavity following sudden heating and cooling is described and the oscillations induced by the fin are characterized in Section 3; heat transfer through the air-filled cavity is quantified in Section 4; and finally, the conclusions are presented in Section 5.

2. Numerical procedures

The previous studies [23,24] show that two dimensional (2D) numerical simulations may describe well the transient features of natural convection flows in a water-filled cavity. Accordingly, the 2D numerical procedure, similar to that in [24–26], was used to describe natural convection flows induced by a fin on the sidewall of a differentially-heated air-filled cavity. The 2D governing equations may be non-dimensionalized using the following scales: $x, y \sim H$; $t \sim H^2/(\kappa Ra^{1/2})$; $(T - T_0) \sim (T_h - T_c)$; $u, \boldsymbol{v} \sim \kappa Ra^{1/2}/H$; and $\rho^{-1}\partial p/\partial x$, $\rho^{-1}\partial p/\partial y \sim \kappa^2 Ra/H^3$, and written in the following non-dimensional forms,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{Pr}{Ra^{1/2}}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right), \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \frac{Pr}{Ra^{1/2}}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + PrT, \tag{3}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{1}{Ra^{1/2}}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right). \tag{4}$$

Natural convection flows in the cavity are determined by three governing parameters: the Rayleigh number (Ra), the Prandtl number (Pr) and the aspect ratio (A) (also refer to [1]). They are defined as follows,

$$Ra = \frac{g\beta(T_h - T_c)H^3}{\nu\kappa}, \quad Pr = \frac{\nu}{\kappa}, \quad A = \frac{H}{L}. \tag{5}$$

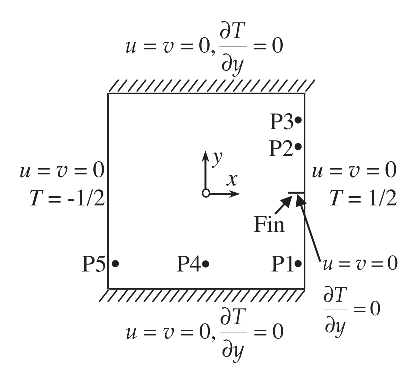

Fig. 1. Schematic of the computation domain and boundary conditions. P1 ($x = 0.492$, $y = -0.375$), P2 ($x = 0.492$, $y = 0.25$), P3 ($x = 0.492$, $y = 0.375$), P4 ($x = 0$, $y = -0.375$) and P5 ($x = -0.492$, $y = -0.375$) are recording the points used in the subsequent figures.