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Plume separation from an adiabatic horizontal thin fin placed at different heights on the sidewall of a differentially heated cavity☆

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ABSTRACT

The separation of plumes from an adiabatic horizontal thin fin attached to a sidewall of a differentially heated cavity at quasi-steady stage is experimentally and numerically studied at three Rayleigh numbers (0.92×10^9, 1.84×10^9 and 3.68×10^9) and over a range of fin positions. Regular plume separation is observed over the present range of parameters during the quasi-steady stage. Both experimental and numerical results reveal that the plume separation frequency increases with the Rayleigh number and decreases with the fin height measured from the leading edge. A higher Rayleigh number leads to a more unstable flow above the horizontal thin fin which in turn leads to a higher plume separation frequency. The decrease of the plume separation frequency with the increasing fin height is mainly due to the reduction of the adverse temperature gradient in the unstable layer above the thin fin as a result of the cavity-wide temperature stratification. It is further revealed that the heat transfer through the sidewall is improved by the presence of the thin fin. An optimum fin height for maximum heat transfer enhancement has been identified for the case with a Rayleigh number of 0.92×10^9. For the other two higher Rayleigh number cases considered in this study, the heat transfer through the sidewall monotonically decreases with the fin height.

1. Introduction

Natural convection in a differentially heated cavity is a classical heat transfer problem which was first studied in the 1950s [1]. It is a simplified model for many industrial applications such as solar collectors and electronic cooling devices. This problem has drawn much attention over the past decades due to its significance for both fundamental fluid mechanics and industrial applications such as the works of [2,3].

The transient flow development in the differentially heated cavity following sudden start-up includes multiple stages [4]. Initially an unsteady one-dimensional thermal boundary layer forms on the vertical sidewalls at the early stage [5]. Following the arrival of a leading edge effect marked by an overshoot of the local temperature and the subsequent presence of travelling waves, the thermal boundary layer transits into a steady two-dimensional flow. Due to the presence of the ceiling, the vertical thermal boundary layer adjacent to the heated sidewall discharges horizontally and a hot intrusion is formed underneath the ceiling. In the meantime, a cold intrusion is also formed along the cavity bottom due to the discharge of the cold boundary layer adjacent to the cooled sidewall. A second group of travelling waves is triggered in the thermal boundary layer due to the arrival of the cold intrusion from the opposing sidewall. Subsequently, the core flow in the cavity undergoes a slow transition towards a steady or quasi-steady stage, during which process a cavity-wide temperature stratification establishes gradually. Flow features at the various stages have been extensively discussed and documented, such as the ones reported in [2,6–8]. Apart from numerical modelling, different experimental methods were also employed to visualise and measure the natural convection flow in the differentially heated cavity, such as the streak line technique [5], the shadowgraph method [7,8] and the smoke and interferometer approach [9].

In addition to understanding the fluid flow in the differentially heated cavity, the heat transfer property across the cavity is also an everlasting focus due to its significance for engineering applications. In recent years the transient flow and the consequent heat transfer associated with a horizontal adiabatic thin fin attached to the cavity sidewall have been intensively investigated (see for example [10–13]). This is a passive approach for heat transfer enhancement. With the presence of the adiabatic thin fin on the sidewall, the vertical thermal boundary layer is separated into two parts. For the thermal boundary layer flow upstream of the thin fin, no distinct temperature oscillations were observed as reported in [10]. An intrusion flow is formed under the fin and it wraps around the fin at the quasi-steady stage. It is demonstrated that the flow above the fin is unstable and plumes separate from the upper surface of the thin fin. The interaction of the separated plumes

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and the downstream thermal boundary layer results in some chaotic characteristics in the fin downstream thermal boundary layer [14], where heat transfer is enhanced at the quasi-steady stage. Shadowgraph flow visualisation experiments, see e.g. [8,13], have confirmed the numerically observed plume separation phenomenon at the quasi-steady stage. Apart from the above studies with one adiabatic fin on the sidewall, the convective flow in the differentially heated cavity with two adiabatic thin fins attached to the sidewall has also been investigated [15]. It is found that the heat transfer through the sidewall is further improved by the presence of the second shorter fin attached to the sidewall.

It is clear from the literature that the presence of the thin fin may lead to heat transfer improvement. In this study, several fin heights are experimentally and numerically tested at three different Rayleigh numbers to examine their effects on heat transfer enhancement through the sidewall. The problem under investigation and the experimental setup are described in Section 2. Section 3 presents the details of the numerical methods and the results are presented and discussed in Section 4.

2. Problem description and experimental setup

The physical problem considered here is a differentially heated cavity (1-m long, 0.24-m high and 0.5-m wide) with a horizontal adiabatic thin fin of a fixed length attached to each sidewall, as sketched in Fig. 1a. The ceiling and bottom of the cavity are insulated. The initial fluid temperature in the cavity is T_0 and the initial velocity is zero everywhere (i.e. isothermal and stationary). The temperatures of the sidewalls are maintained at $T_h = T_0 + \Delta T/2$ and $T_c = T_0 - \Delta T/2$, respectively. The natural convection flow in the finned cavity can be characterised by the fin position h measured from the leading edge and the following three dimensionless governing parameters: the Rayleigh number (Ra), the Prandtl number (Pr) and the cavity aspect ratio (A). They are defined as follows:

$$Ra = \frac{g\beta\Delta T H^3}{\nu\kappa} \tag{1}$$

$$Pr = \frac{\nu}{\kappa} \tag{2}$$

$$A = \frac{H}{L} \tag{3}$$

where g, β, v, k, H and L are the gravitational acceleration, the thermal expansion coefficient, kinematic viscosity and thermal diffusivity of the working fluid and the height and length of the cavity respectively. In this study, the aspect ratio of the cavity is fixed at 0.24 and the fin length is fixed at 1/6 of the cavity height H, i.e. 40-mm. The geometric configurations are adopted based on the experimental model reported in [10]. The cavity is filled with water with a fixed Prandtl number of 6.64. In the present work, three different Rayleigh numbers ($Ra = 0.92 \times 10^9$, 1.84×10^9 and 3.68×10^9 respectively) and seven different fin heights (h = 60-mm, 80-mm, 100-mm, 120-mm, 140-mm, 160-mm and 180-mm respectively) are studied to investigate the dependence of the plume separation frequency on the Rayleigh number and the fin position, as well as their effects on the heat transfer through the sidewall.

Fig. 1b illustrates a schematic of the experimental setup for the shadowgraph flow visualisation employed in this work, which is briefly described here. A point light source is placed at the focal point of a concave spherical mirror of a 30-cm diameter to generate a horizontal parallel light beam. When the parallel light beam passes through the cavity filled with water with non-uniform temperatures, it is deflected by the water at different rates due to variations of the refractive index

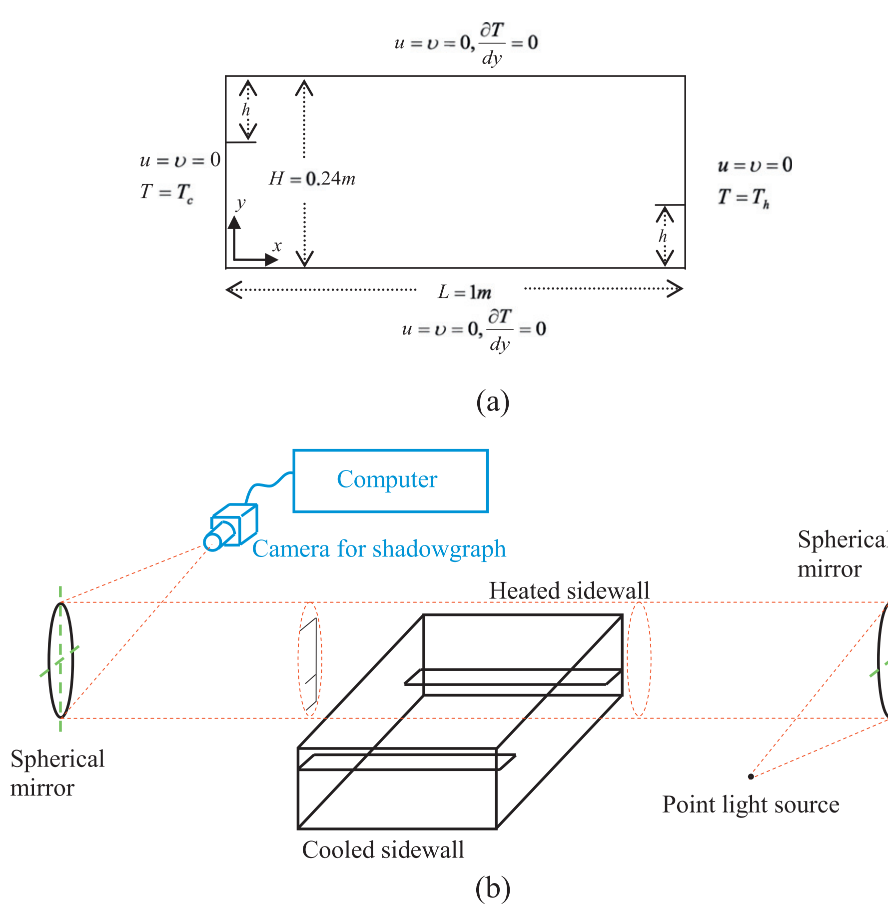

Fig. 1. (a) Schematic of the physical and numerical models. (b) Experimental rig and the flow visualisation setup.