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Natural convection in a differentially heated cavity with two horizontal adiabatic fins on the sidewalls

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ABSTRACT

In this study the natural convection flow adjacent to a finned sidewall of a differentially heated cavity is experimentally investigated using the shadowgraph technique. Two Perspex fins of different lengths are placed horizontally at different heights along each of the cavity sidewalls. It is revealed from the shadowgraph observation of the heated sidewall that similar horizontal hot intrusions form underneath the fins and the cavity ceiling at the early stage. In the transitional stage, the thermal flows bypassing the fins are entrained towards the heated sidewall and a cavity-scale interior temperature stratification is gradually established. In the quasi-steady stage, regular oscillations are observed above the lower fin. The oscillation in the horizontal thermal flow above the lower fin results in strong mixing in the thermal boundary layer between the two fins and that downstream of the upper fin. As a consequence, heat transfer through the downstream thermal boundary layer is greatly enhanced. A corresponding numerical simulation is also conducted and a good agreement between the simulation and the experiment is achieved. It is further revealed numerically that the convective flow across the cavity is significantly enhanced due to the presence of the fins. The heat transfer is improved by up to 17.1% over the investigated Rayleigh number range. The dependency of the time averaged Nusselt number at the finned sidewall on the Rayleigh number has been quantified.

1. Introduction

Buoyancy driven natural convection in a differentially heated cavity is a classical problem of fundamental fluid mechanics and heat transfer. It is a simplified model of many industrial applications such as solar collectors, electronic cooling systems and nuclear reactors. Consequently numerous theoretical, experimental and numerical studies of various aspects of the natural convection flows have been performed in the past several decades. In particular, the idealised model with laminar flows in an enclosed rectangular cavity has been studied extensively (e.g. [1–3]).

Most of the early studies focused on steady natural convection flows in a differentially heated cavity. However, the natural convection flows in industrial systems are usually unsteady. Accordingly, considerable attention has been given over the last three decades to the transition of the natural convection flow in the cavity subject to sudden heating and cooling. In experimental aspects, different methods have been employed to study this flow. For instance, the shadowgraph visualisation technique was adopted by Bathelt et al. [4] and Sparrow and Husar [5]; and interferometry and PIV (Particle Image Velocimetry) techniques were adopted by Corvaro and Paroncini [6] to observe and measure the natural convection flows. In theoretical aspects, Patterson and Imberger [7] reported a scaling approach to describe the transient flow and to reveal the underlying flow mechanisms. Scales quantifying the flow at different stages of the transient flow development were developed in terms of governing parameters.

Further to understanding the fluid flow in the differentially heated cavity, the heat transfer property across the cavity is also of great interest due to its significance for engineering applications. Various techniques have been proposed in an attempt to enhance heat transfer. For instance, an active approach was proposed by Kwak et al. [8], in which a time dependent temperature is imposed at the cavity sidewall, and a passive approach was proposed by Khanafer et al. [9], in which nanofluids were utilised to improve the fluid thermal conductivity. In recent years the transient flow and the consequent heat transfer properties associated with one horizontal adiabatic thin fin attached to the cavity sidewall were intensively investigated by Xu et al. [10–12]. In the experimental work reported in Xu et al. [10], the flow development at different stages was visualised using the shadowgraph technique and the temperature variation around and downstream of the fin was measured by fast-response thermistors. The existence of intermittent flow above the fin was experimentally confirmed and a reasonable

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agreement was found between the experimentally and numerically obtained frequencies. It was further revealed numerically in Xu et al. [11] that the temperature structure above the fin was unstable and it in turn resulted in a Rayleigh–Benard type instability where regular oscillations were seen in the thermal layer above the fin at the quasi-steady stage. Accordingly, the heat transfer downstream of the fin was improved by the disturbance caused by the fin while the heat transfer rate upstream of the fin was barely changed compared to the same segment of a non-finned cavity. This confirmed the effect of the fin on heat transfer enhancement. The natural convection flow in a finned cavity with the fin placed at different positions was studied by Liu et al. [13] and the fin downstream flow was investigated through a direct stability analysis by Liu et al. [14]. The dominant frequency above the fin was found to be dependent on the position of the fin. It was further shown that the heat transfer rate through the sidewalls also depended on the fin position, and an optimal fin position was identified. The interaction of the unstable flow above the fin with the downstream boundary layer resulted in better heat transfer performance through the downstream section of the sidewall.

Recently Zhao et al. [15] revealed that resonance of the natural convection boundary layer adjacent to a vertical heated surface can be triggered by an external perturbation at the characteristic frequency of the thermal boundary layer under which condition a maximum heat transfer rate can be achieved. Since travelling waves have been observed downstream of a horizontal fin placed at the mid-height of a differentially heated cavity, as reported in Xu et al. [12], the present study is motivated by the interest in determining whether a similar resonance condition and consequently improved heat transfer performance can be triggered by multi-fins placed on the sidewall with spacing between neighbouring fins matching the wavelength of the travelling waves. As a preliminary study reported here, two fins are employed on both the heated and cooled sidewalls respectively, with the aim of studying the transient flow features and the heat transfer property of this new configuration. The shadowgraph technique is adopted for the flow visualisation. Corresponding numerical simulations are also carried out to investigate the heat transfer performance through the sidewall, and the numerical results are compared with the experiments. It is found that the numerical model employed in this study is capable of giving accurate predictions of the physical flows. It has been further demonstrated numerically that the heat transfer through the cavity sidewall is improved by up to 17.1% over the investigated Rayleigh number range by the current two-fin configuration compared to a differentially heated cavity without any fin. For the particular case with a moderate Rayleigh number of $Ra = 1.84 \times 10^9$ considered in this study, the heat transfer at the quasi-steady stage is improved by 13%, compared to an improvement of approximately 5% for the same Rayleigh number but with only one 40-mm wide adiabatic thin fin placed at the middle of the sidewall, as reported in Xu et al. [11]. This demonstrates that the current two-fin configuration is superior to the one-fin configuration in term of heat transfer enhancement. In addition, the present investigation has also demonstrated that the average Nusselt number at the sidewall under different configurations, including the present one with two adiabatic thin fins on each sidewall, increases with the Rayleigh number according to a scaling law of $Nu \sim Ra^{1/4}$.

The rest of this paper is organised as follows: Section 2 states the physical problem under investigation. The experimental rig and methods are described in Section 3, followed by a brief introduction of the numerical approach in Section 4. In Section 5, the experimental results are presented along with the corresponding numerical data. Finally, Section 6 presents a summary of the major results of this investigation.

2. Description of the experimental model

The problem under investigation is a 1-m long, 0.24-m high and 0.5-m deep (in the page direction) differentially heated cavity (see Fig. 1). The ceiling, bottom, front and rear surfaces are all made of transparent Perspex to facilitate shadowgraph visualisation, and the thickness of the Perspex walls is 19-mm. The two cavity sidewalls are made of copper plates of approximately 1.1-mm thickness. Two horizontal non-conductive thin fins (also made of Perspex) are attached to each sidewall, one 40-mm wide fin attached at 0.06-m from the leading edge and the other 10-mm wide fin attached at 0.12-m from the leading edge. The geometric configuration of the fins is symmetric about the centre of the cavity. The thickness of all the fins is 2-mm, and all the fins extend to the full depth of the sidewalls (in the page direction). The working fluid in the cavity is water. Before the experiment starts, the water in the cavity is stationary and isothermal with an initial temperature of T_0. The water temperatures in the two water baths are maintained constant by two circulators (JULABO FP45) with a temperature stability of 0.01-K. The water bath is separated from the respective cavity sidewall before the experiment starts by a pneumatically operated gate and an air gap between the gate and sidewall. The cavity is a slightly modified version of an earlier experimental rig [11].

When the experiment starts, the two pneumatically operated gates are lifted up rapidly and the hot and cold water in the water baths flushes to the cavity sidewalls respectively, resulting in a virtually instantaneous heating and cooling through the sidewalls (refer to e.g. [11]). The temperatures of the heated and cooled sidewalls are maintained at $T_0 + (\Delta T/2)$ and $T_0 - (\Delta T/2)$ respectively by the water baths. The water in the water baths is stirred continuously during the experiment in order to avoid the formation of thermal boundary layers on the water bath sides of the sidewalls and to maintain uniform temperatures in the water baths.

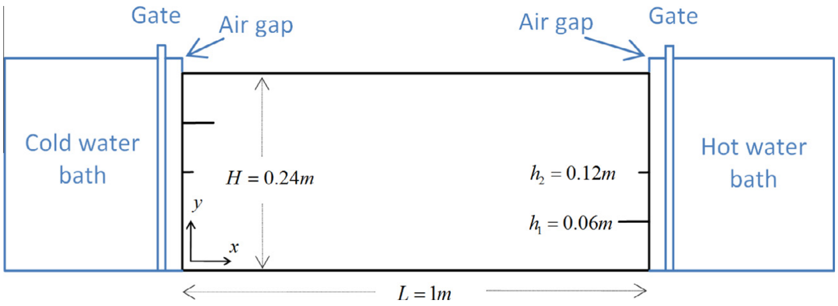

Fig. 1. Schematic of the experimental cavity with thin fins.