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An Experimental Study of the Thermal Flow around a Thin Fin on the Sidewall of a Differentially Heated Cavity

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Abstract

The development of the thermal flow around a thin fin on the sidewall of a differentially heated cavity is investigated based on temperature measurements, and the impact of the thin fin on the transient flow is discussed. The experimental results demonstrate that a lower intrusion front may significantly disturb the thermal boundary layer flow at the downstream side of the fin in the early stage. In the quasi-steady stage, the temperature measurements indicate that the oscillations of the thermal flow around the fin are dominated by a single frequency for the present Rayleigh number.

Introduction

Heat transfer through a differentially heated cavity has been paid considerable attention due to its relevance to industrial applications such as solar collectors and nuclear reactors. Studies of heat transfer through the finned sidewall of the cavity have also been extensively reported, and the effect of the fin on natural convection in the cavity and heat transfer has been examined previously [1,2,4,6,7,8]. It has been demonstrated that the fin may depress the convective flow adjacent to the sidewall at low Rayleigh numbers. As a consequence, heat transfer through the finned sidewall is reduced. Most of the previous studies focus on steady laminar natural convection. However, the features of the transient natural convection flow induced by a thin fin on the sidewall have not been paid much attention.

The present authors have carried out a shadowgraph flow observation of the transient flows adjacent a finned sidewall [9]. It has been revealed in [9] that a lower intrusion front is formed underneath the fin in the initial stage. After the lower intrusion bypasses the fin, a starting plume arises. Subsequently, the plume is drawn to the downstream sidewall, and the thermal flow around the fin is formed. As indicated in [9], the thermal flow around the fin oscillates in the quasi-steady stage. However, these oscillatory features are difficult to characterize using the shadowgraph images. Therefore, further temperature measurements are performed using thermistors in this paper in order to examine the oscillations of the thermal flow around the fin. Time series of the temperatures at different positions along the finned sidewall are analysed, and the oscillatory features of the thermal flow around the fin are described in this paper.

Experimental procedures

The experiments are performed on the facility sketched in figure 1, which is the same as that described in [9]. The cavity is filled with water, and is 0.24-m high (H), 1-m long (L) and 0.5-m wide (W). A thin fin with a cross-section of 0.04-m × 0.002-m is attached at the mid height of the hot sidewall. The walls of the cavity and the fin are made of Perspex except for the heated and cooled sidewalls, which are made of 0.24-m × 0.5-m sheets of gold-coated copper plates of 0.001-m thickness. The reader may refer to [9] for further details of the apparatus.

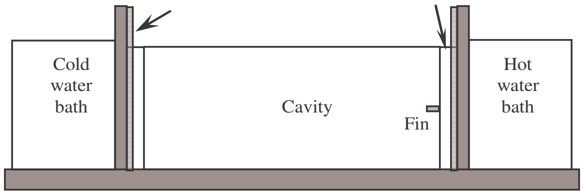

Figure 1 Schematic of the experimental setup

Figure 2 shows the thermistor locations for the temperature measurements. Since the thermal boundary layer flow is the focus of this paper, five thermistors are employed and placed in the vicinity of the thin fin and the hot sidewall. Three thermistors are placed at a distance of approximately 2 mm from the sidewall surface, but at different heights, and the other two are located around the fin. For comparison purpose, the temperatures at the locations of Thermistors 1, 4 and 5 are also measured for the case without a fin on the sidewall.

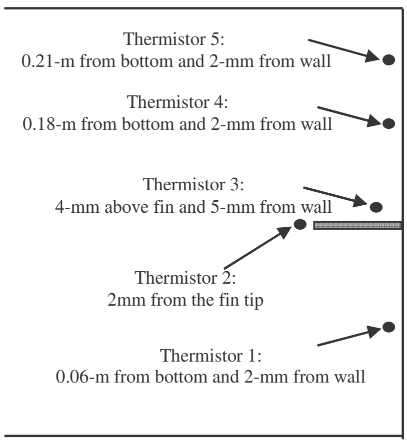

Figure 2 Thermistor locations

In order to achieve different Rayleigh numbers, the temperature difference between the heated and cooled sidewalls varies from 4 K to 32 K in this paper. The corresponding ranges of the experimental Rayleigh and Prandtl numbers are 9.5×10^8 to 7.7×10^9, and 6.6 to 6.8, respectively. Here the Rayleigh number (Ra), the Prandtl number (Pr) and the aspect ratio (A) are defined as follows,

$$Ra = \frac{g\beta\Delta T H^3}{\nu\kappa}, \quad (1)$$

$$Pr = \frac{\nu}{\kappa}, \quad (2)$$

$$A = \frac{H}{L}, \quad (3)$$

where ΔT is the temperature difference between the two sidewalls, g the acceleration due to gravity, β the coefficient of thermal expansion, κ the thermal diffusivity, and ν the kinematic viscosity.

Results and discussion

The results of the temperature measurements are presented based on the development of the thermal flow around the fin in this section. Unless specified, the results presented in this paper are for the case with $Ra = 3.8 \times 10^9$ and $Pr = 6.7$.

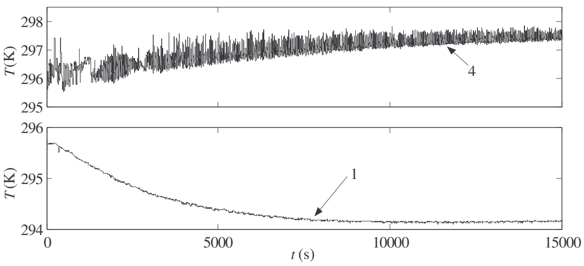

Figure 3 Time series of the temperatures from Thermistors 1 and 4

Figure 3 shows the time series of the temperatures from thermistors 1 and 4. The temperature fluctuations in the thermal boundary layer on the downstream side of the fin (see the temperature from Thermistor 4) are distinct. It is also clear that the two time series of the temperatures from different thermistors eventually approach a quasi-steady state, which is consistent with the flow visualization described in [9]. It is found in this figure that the temperature measured by Thermistors 4 in the upper part of the cavity increases with time, whereas the temperature measured by Thermistor 1 in the lower part of the cavity decreases with time. Accordingly, the temperature difference between the two locations increases with time. This implies that a thermal stratification of the fluid in the cavity is continuously reinforced; that is, in the stably stratified ambient, the higher the position, the higher the temperature.

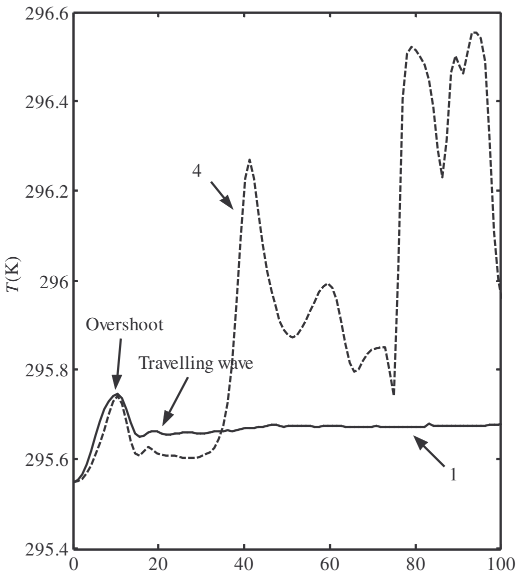

Figure 4 Time series of the temperatures in the early stage from Thermistors 1 and 4.

The LEE in the early stage

In order to illustrate details of the transient thermal flow around the fin, the time series of the temperatures are replotted based on the transient flow features and discussed below. Figure 4 shows the temperature time series from Thermistors 1 and 4 at early times (up to 100s). The LEE is clear, which is described by an overshoot followed by travelling waves (also see [5]). Subsequently, the temperature from Thermistor 1 remains approximately at a constant value, whereas the temperature from Thermistors 4 stays approximately constant for a short while until it is perturbed by the thermal front bypassing the fin, as indicated by [9]. Figure 4 indicates that there are distinct variations of the initial temperature growths recorded by Thermistors 1 and 4. This may be attributed to the experimental errors in placing the thermistors. Although the distance from the thermistor tips to the sidewall is approximately 2 mm, a small error of the thermistor position in the direction normal to the sidewall could result in a significant variation of the measured temperature, as indicated in [5].

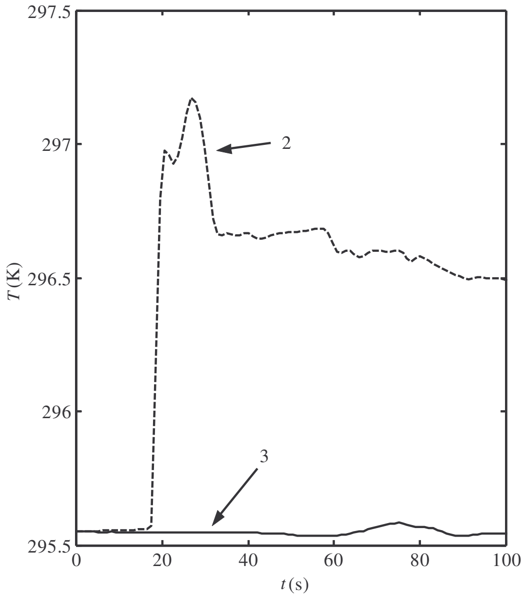

Figure 5 Time series of the temperatures in the early stage from Thermistors 2 and 3

Figure 5 presents the time series of the temperatures from Thermistors 2 and 3. Based on the temperature from Thermistor 2, it is seen that the lower intrusion front bypasses the fin after approximately 20 seconds. Subsequently, the perturbations from the lower intrusion front are felt by Thermistors 4 and 5 respectively (also see figure 4). Clearly, the perturbations recorded by Thermistor 2 are stronger than those recorded by Thermistors 4. This is because Thermistor 2 is on the direct path of the lower intrusion front.

It is seen in figure 4 that the perturbations from the lower intrusion front have a negligible impact on the temperatures recorded by Thermistor 1 since Thermistor 1 is located on the upstream side of the fin. Furthermore, the temperature signal recorded by Thermistor 3 (see figure 5) does not show the LEE and large perturbations from the plume front, and is almost a straight line in the earlier stage (e.g. < 60 s). This is because Thermistor 3 is located at the leeward corner of the fin, and thus is sheltered by the fin. It is also further away from the sidewall, and thus the LEE is not detected. The above-mentioned wave features of the temperature time series are consistent with the previously visualized flow features in the same stage [9].

Figure 6 compares the early-stage temperatures recorded at the same location (x = 0.498 m, y = 0.06 m, corresponding to the location of Thermistor 4) at the same Rayleigh and Prandtl numbers in the cases with and without a fin. It is seen in this figure that the initial growths (< 10 s) of the temperatures in the two cases are very similar since the initial thermal boundary layer is approximately one-dimensional, and its temperature growth is independent of the vertical position before the arrival of the LEE (also see [3,5]). In the case with a fin, the temperature reaches a maximum value earlier, and an overshoot and travelling wave features follow. However, in the case without a fin, the temperature grows for a relatively longer period until an overshoot appears. This variation between the two cases with and without a fin is because the fin separates the thermal boundary layer into an upper and a lower section in the early stage. For the early thermal boundary layer in the case with a fin, there are indeed two independent leading edges: one is at the corner between the fin and the sidewall (for the upper section of the thermal boundary layer); and the other is at the bottom corner between the bottom boundary and the sidewall (for the lower section of the thermal boundary layer). Since the distance from the location of Thermistor 4 to the fin is only 1/3 of that to the bottom, it takes less time for the LEE to reach the point in the case with the fin compared with that without a fin, as seen in figure 6. Later on, a strong perturbation from the starting plume is recorded in the case with the fin, in contrast to the travelling waves observed in the case without a fin.

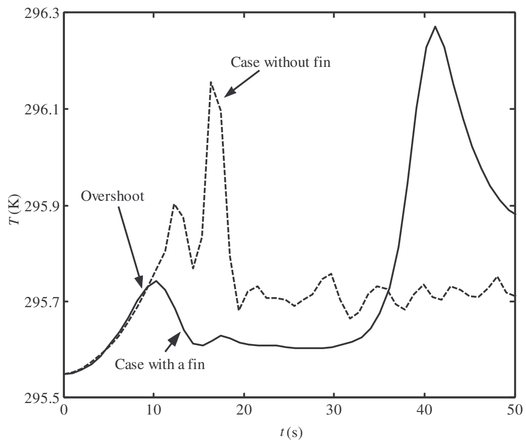

Figure 6 Temperature time series at the position of Thermister 4 in the cases with and without a thin fin

Oscillations in the quasi-steady stage

As seen in figure 3, the amplitude of perturbations recorded by Thermistors 4 approaches approximately a constant value with the passage of time. In order to display these wave features of the thermal boundary layer flow at the downstream side of the fin in the quasi-steady stage, figure 7 presents the temperature time series from Thermistors 3, 4 and 5. It may be seen in this figure that the amplitude of the temperature waves is strongly dependent on the spatial location but less dependent on the time in the quasi-steady stage. According to the thermistor locations, it is expected that the temperature time series from Thermistor 3 (at the leeward side of the fin) displays the oscillations of the thermal flow around the fin, that from Thermistor 4 shows the travelling waves in the downstream thermal boundary layer, and that from Thermistor 5 shows the travelling waves in the further downstream thermal boundary layer and the corner (also see figure 2).

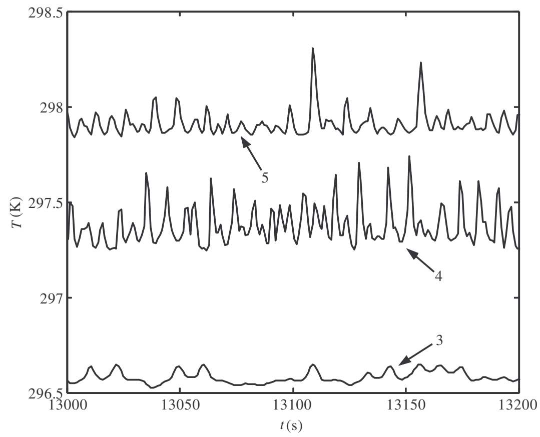

Figure 7 Temperatures from Thermistors 3, 4 and 5 in the quasi-stage stage

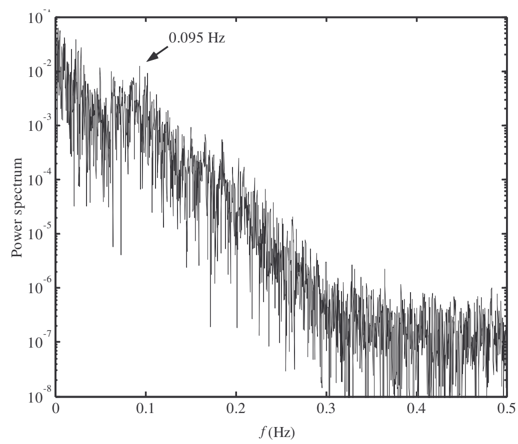

Figure 8 Spectrum of the temperatures from Thermistors 3 in the quasi-stage stage

Figure 8 plots the results of the spectral analysis of the temperature time series from Thermistor 3. It is clear that the oscillations of the thermal flow around the fin have a very low frequency peak with a noticeable hump around 0.1 Hz describing the oscillations of the thermal flow around the fin.

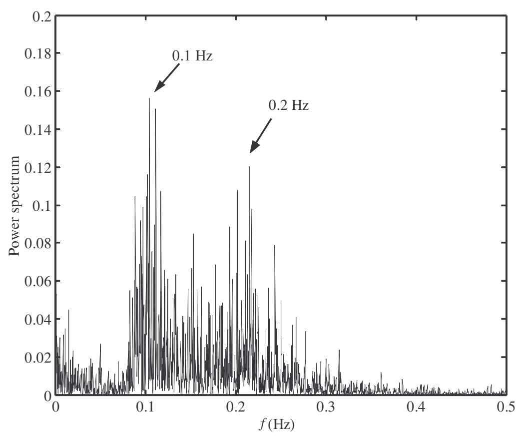

Figure 9 Spectrum of the temperatures from Thermistors 4 in the quasi-stage stage

For the purpose of illustrating clearly the peaks around the dominant frequency, the spectrum from Thermistor 4 is plotted with a linear scale in figure 9. It is clear that the temperature waves in the downstream thermal boundary layer are dominated by two major frequencies, one around 0.1 Hz, which may originate from the oscillations of the thermal flow around the fin, and the other around 0.2 Hz, which may be triggered by the impact of the entrainment of the thermal flow around the fin into the thermal boundary layer.

Figure 10 shows the spectrum from Thermistor 5. The frequency around 0.1 Hz is still significant but the higher frequency of 0.2 Hz has decayed as travelling waves in the thermal boundary layer propagate downstream. In summary, apart from the spatial growth of the amplitude of the temperature waves, the variations of the frequency peak of the temperature time series from Thermistors 3 to 5 are clear; that is, temperature time series at different locations have different frequency modes. However, the thermal flow downstream of the fin has a dominant frequency around 0.1 Hz for the present Rayleigh number.

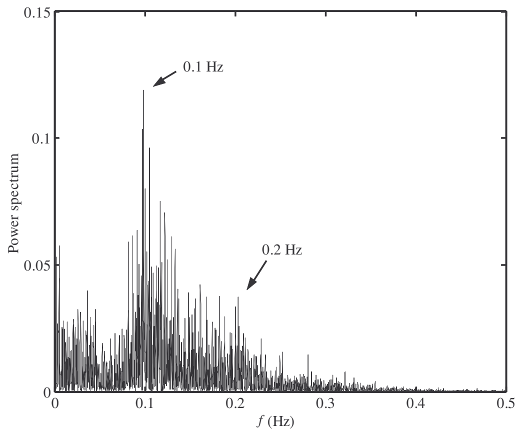

Figure 10 Spectrum of the temperatures from Thermistors 5 in the quasi-stage stage

Conclusions

In this paper, the temperature time series from thermistors at different locations clearly describe the oscillatory features of the thermal flow adjacent to the finned sidewall, including the LEE and other transient features in the transition from sudden heating to a quasi-steady state. A spectral analysis of the temperature time series has demonstrated that oscillations of the thermal flow around the fin have a dominant frequency around 0.1.Hz for the present Rayleigh number ($Ra = 3.8 \times 10^9$). Furthermore, the present temperature measurements are consistent with the previous visualizations of the transient thermal flow around the fin in [9].

Acknowledgment

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