



# Experimental Study of Turbulent Separated Flowfield Induced by a Perpendicular Blunt Fin

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**Abstract.** An experimental study of interaction flow induced by a perpendicular blunt fin was presented. The tests were carried out in a hypersonic gun tunnel with freestream Mach number of 6. Fluctuating heat-transfer rate was measured along model centerline and high speed schlieren photos were also taken to show complex interaction flow characteristics. Steady and unsteady features of turbulent interactive flowfield are presented. The results show that the fin induced separated flow is very complex. The distributions of the heat transfer rate are changed obviously due to the fin interaction. In the streamwise direction on the plate centerline two peaks are observed. Unsteady characteristics is very obvious. In the incipient separation region ahead of the fin the instantaneous heat transfer is highly intermittent. In the separation region, amplitude of the fluctuations of the heat transfer rate becomes extensive.

**Keywords:** Hypersonic flow · Heat transfer measurement · Turbulent separated flow

## 1 Introduction

Shock wave/boundary layer interaction, which often accompanied by separation, is a commonly feature of high speed flow over flight vehicles. Extensive work has been done over the past 50 years [1–5]. Most of the work has been done in fully-developed turbulent flows as the most applications in the past were at transonic and supersonic speeds, where the Reynolds numbers are large and the flow status is turbulent.

Previous research results [6–10] show that flow separation is highly unsteady and large fluctuating pressure loads up to 185 db or more occur in the interaction region. The unsteadiness observed in the interactions spans a wide range of frequencies and scales. It has been observed that the dominant frequency range that characterizing the motion of the separated shock is at least an order of magnitude lower than the nominal boundary layer frequency based on the free stream velocity and boundary layer thickness. The low frequency of the shock foot seems to be related to the low-frequency motion of the separated flow.

The oscillating characteristic frequencies are very close to the resonant frequencies of vehicle structural components. Additionally, high heating rate can further threaten the structural integrity of the vehicle. These flow features are corresponding some new problems for the design of vehicle structure, thermal protection system and noise reduction.

In spite of the increasing interest in the unsteady flow, we are despairing to say that our current understanding of unsteady flow induced by shock wave boundary layer interaction is plain. The experimental data from past study is very limited.

This study aims to investigate the steady and dynamic characteristics of the hypersonic separated flowfield induced by a perpendicular blunt fin. The primary diagnostics used are heat transfer rate measurement. The objective of the current work is to study the steady and unsteady characteristic of turbulent separated flowfield and show the dominant frequency of the flow.

## 2 Experimental Techniques and Conditions

### 2.1 Wind Tunnel

The experiments have been performed in FD-20 hypersonic gun tunnel of China Academy of Aerospace Aerodynamics (CAAA), in which the nozzle exit is  $\Phi 480$  mm &  $\Phi 400$  mm. Freestream Mach number is set with different Laval contour nozzles from 5 to 15. The typical stable flow period is about 20 ms. In present study Mach number is set to 6.0 for turbulent flow (Fig. 1).



Fig. 1. FD-20 hypersonic wind tunnel

### 2.2 Test Model

The model consists of two parts: (a) the flat plate with sharp leading edge; (b) the fin, with the sweep angle  $\Lambda = 0^\circ$ , as shown in Fig. 2(a). The dimensions for the flat plate are  $680 \text{ mm} \times 380 \text{ mm}$  and the sharp leading edge angle is  $10^\circ$ . The fin has the leading edge diameter  $D = 25 \text{ mm}$  and the sweep angle of  $\Lambda = 0^\circ$ . The distance between leading edge of the flat plate and the fin is  $432.5 \text{ mm}$ . The origin of the coordinate system is located in the intersection point of the leading edge of the fin and the centerline of the flat plate, as shown in Fig. 2(b). OX axis points to downstream along the centerline of the flat plate. OS axis points to the top of the fin along the leading edge of the fin. The model was supported by a sting in the test section.

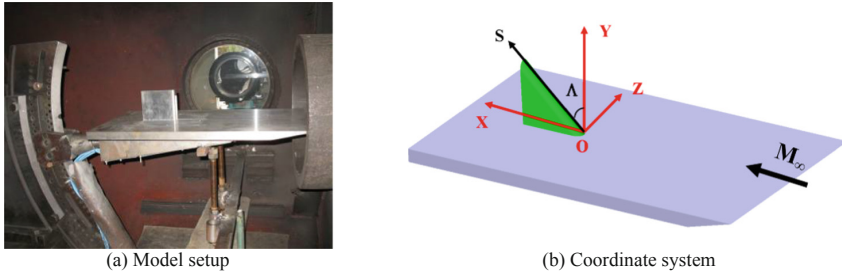


Fig. 2. The test model and coordinate system

### 2.3 Instrumentation and Data Acquisition

Heat transfer rate measurements were made along the flat plate centerline upstream of the blunt fin and the centerline of fin leading edge with high frequency responding and spatial resolution thin film transducers. The distance between the two transducers was 2.5 mm. 20 transducers or 39 transducers were integrated on a single element, as shown in Fig. 3. More detailed and credible data was obtained using those integrated elements compared with using isolated transducers before.

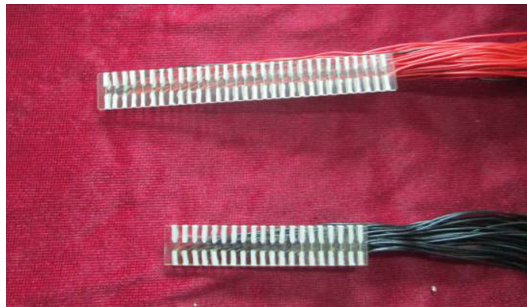


Fig. 3. The transducers

Output signals from the heating rate transducers were first amplified by DH3480V amplifiers and then low-pass filtered using three-order Butterworth analog filters. Filter cut-off frequencies were set at 10 kHz or 1 kHz. Filtered signals were then acquired with 25 kHz sampling rates and downloaded to a HC1210 work station.

### 2.4 Test Conditions

The experimental conditions are shown in Table 1. Under these conditions, it is known from the previous study [8] that at freestream Mach number 6.0, the status of boundary layer on the plate ahead of the fin is turbulent.

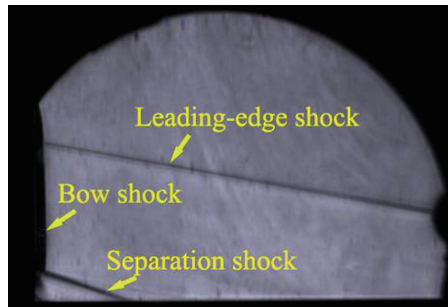
**Table 1.** Test conditions

Run.	Model	Ma	P <sub>0</sub> (MPa)	T <sub>0</sub> (K)	Re × 10 <sup>-7</sup> (m <sup>-1</sup> )
1215	Plate	6.0	11.98	900	3.99
1224	Plate	6.0	11.91	900	3.96
1234	Λ = 0°	6.0	12.19	900	4.06
1265	Λ = 0°	6.0	12.15	900	4.04
1267	Λ = 0°	6.0	12.15	900	4.04

### 3 Results and Discussion

#### 3.1 Typical Flow Characteristics

The typical flowfield of blunt fin induced separated flow is visualized by the schlieren photography as shown in Fig. 4. An upstream bow shock wave is formed induced by the blunt fin. It brings the converse pressure gradient. Disturbance transfers upstreamwise through the subsonic region of the boundary layer, which causes flow separated. The oblique separation shock eventually connects with the bow shock wave of the fin, and forms complex λ shock wave systems. An oscillating separation shock can be observed from the schlieren video.

**Fig. 4.** Typical flow structure

#### 3.2 Surface Heat Transfer Rate Distribution

The distributions of the mean heat transfer rate along the centerline of the flat plate are shown in Fig. 5. Solid symbols indicate the measuring results of the flat plate with the Λ = 0° blunt fin. Hollow symbols indicate the measuring results of plate boundary layer at the same conditions [8].

For the flat plate model, the heat transfer rate decreases slowly as the flow downstream. Under the same condition, the heat transfer rate distributions of the fin induced flow is very close to the plate heat transfer rate distribution until X/D = -2.7. From the location X/D = -2.7, the heat transfer rate is rapidly increased due to the separation. In the streamwise direction two peaks are observed. The higher peak of mean heat transfer are located at the attachment line. The peak value occurs at X/D = -0.2 and is about 750 kw/m<sup>2</sup>.

Figure 6 shows the heat transfer rate distributions along the centerline of the fin leading edge. Heat transfer rate increases rapidly near the fin root and reaches maxima at  $S/D = 0.8$  and then decreases as  $S/D$  increases and finally it reaches a plateau mean value. The existence of the plateau is the characteristic of two dimensional bow shocks. The peak value of heat transfer rate, which was caused by shock impingement, is about  $2000 \text{ kw/m}^2$ .

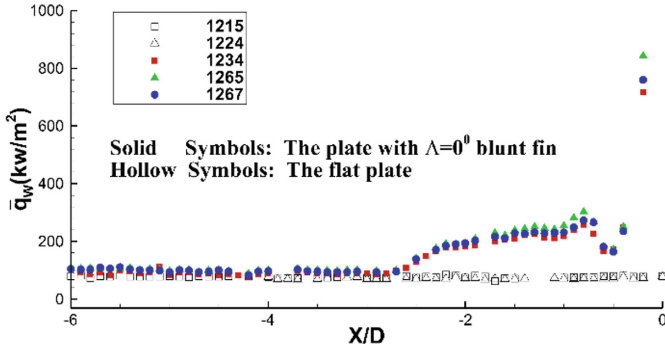


Fig. 5. The distributions of the heat transfer rate along the centerline of the flat plate

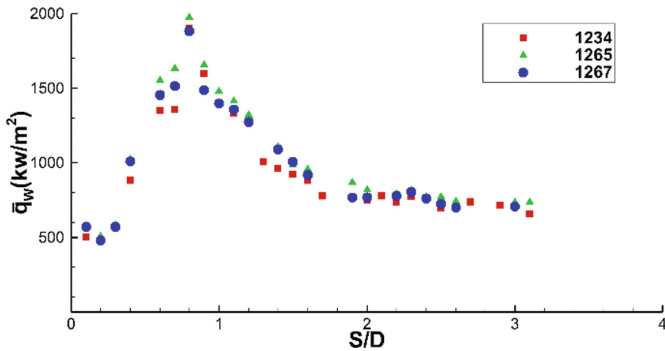
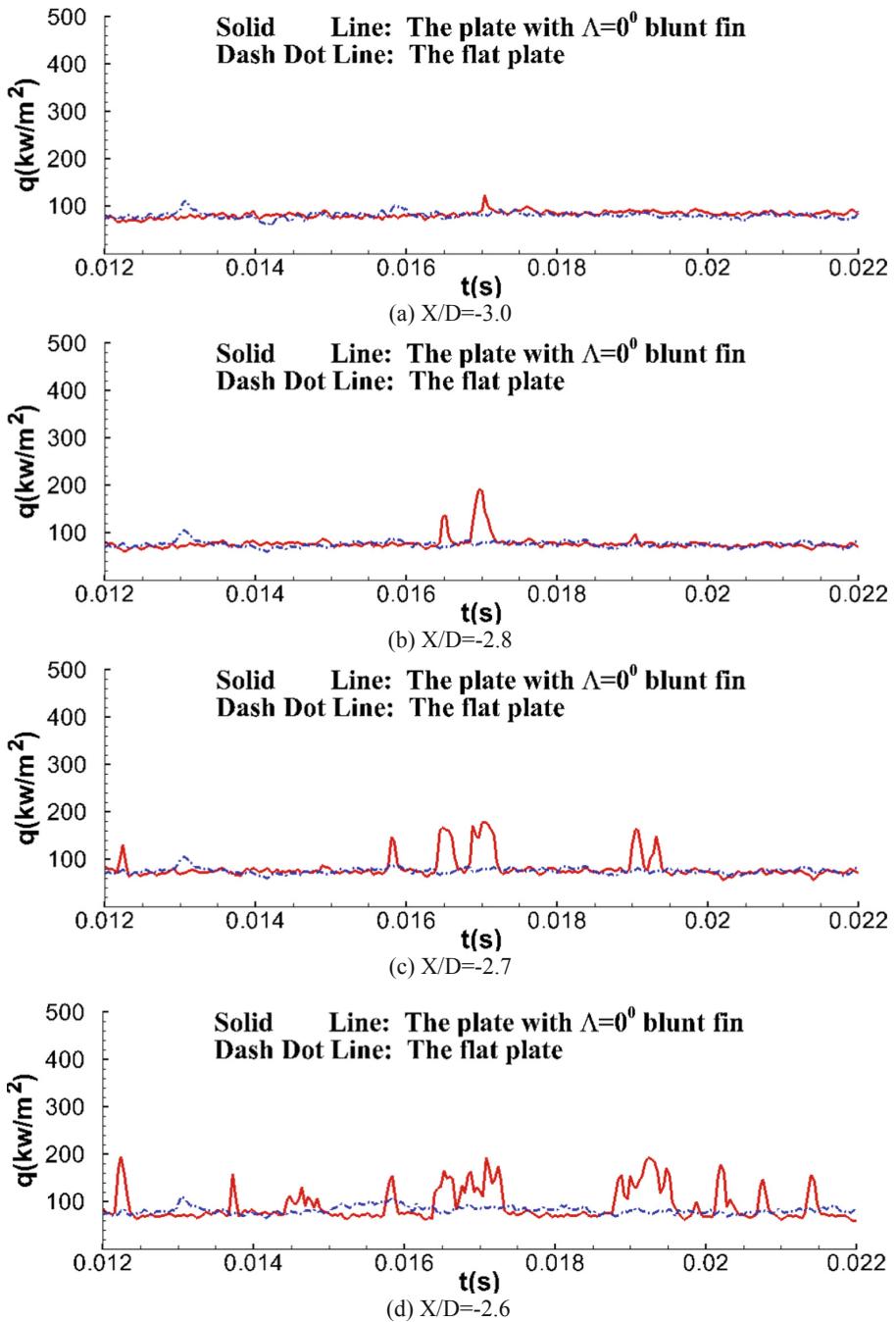


Fig. 6. The distributions of the heat transfer rate along fin leading edge

### 3.3 Fluctuations of the Heat Transfer Signals

Figure 7 shows the heat transfer signals of seven typical measuring points along the centerline of the plate. Positions at which the signals are recorded are located in undistributed region ( $X/D = -3.0$ ), incipient separated region ( $X/D = -2.8 \sim -2.4$ ), separated region ( $X/D = -0.2$ ) respectively. Signals of the flat plate without fin are also plotted in the figures for comparison. As shown in Fig. 7(a), in the undistributed region signals of the plate with  $\Lambda = 0^\circ$  fin are similar with signals of the plate model without fin. In the incipient separated region compared with the undistributed case, it can be seen from the record of signals that both the instantaneous heat transfer is highly



**Fig. 7.** The heat transfer signals of seven typical measuring points along the centerline of the plate

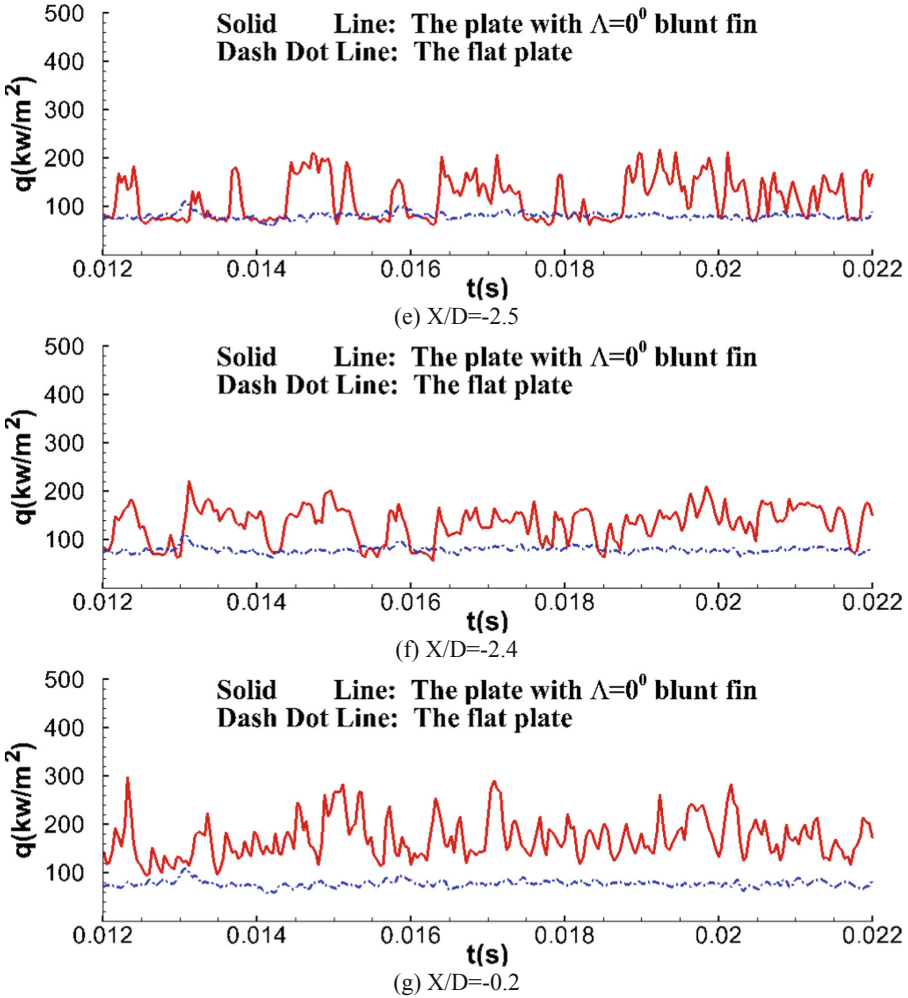
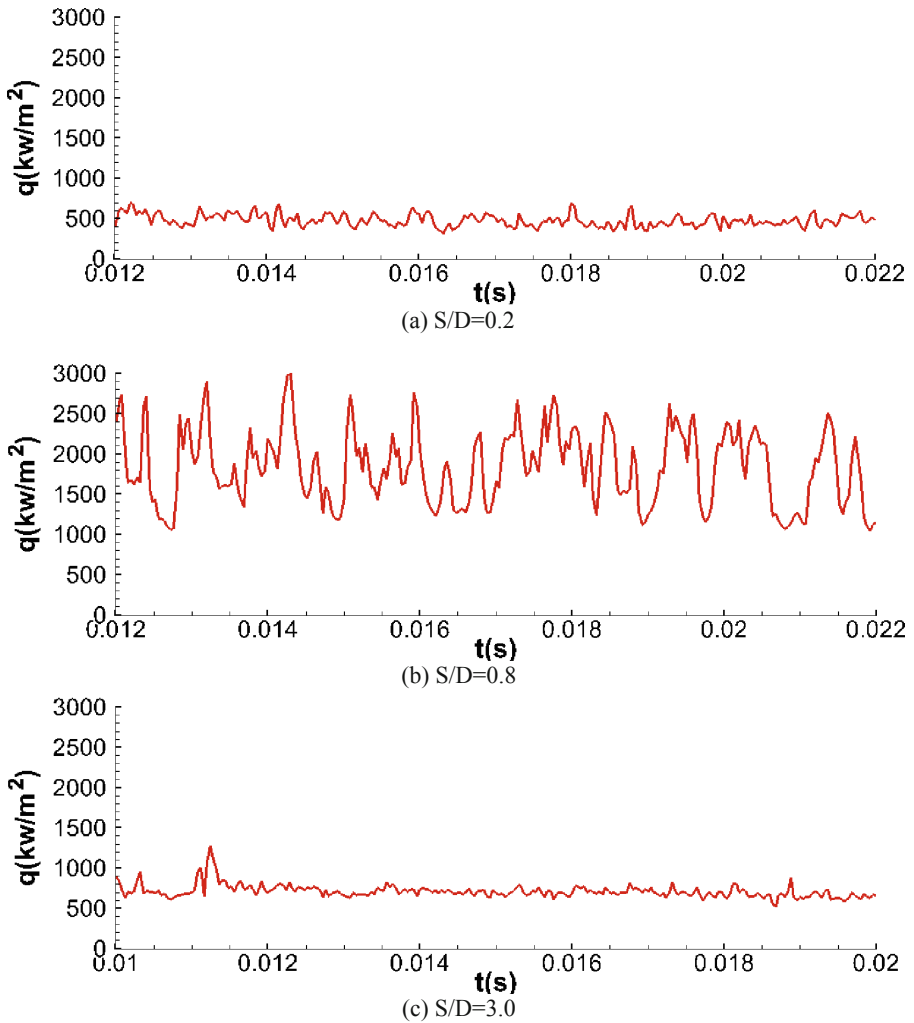


Fig. 7. (continued)

intermittent. In the separated region the amplitude of the fluctuations of the heat transfer rate becomes extensive and unsteady characteristic is very obvious.

Figure 8 shows heat transfer rate signals of three typical measuring points along the centerline of the fin leading edge. Positions at which the signals are recorded are located in fin root region ( $S/D = 0.2$ ), peak value region ( $S/D = 0.8$ ), plateau region ( $S/D = 3.0$ ) respectively. The amplitude of the heat transfer rate fluctuations and the mean value of the heat transfer rate become large as  $S/D$  increases near the fin root. The mean value of the heat transfer rate and the amplitude of the heat transfer rate fluctuations reach maxima at the same location ( $S/D = 0.8$ ). In the plateau region, the amplitude of the heat transfer rate fluctuations is very weak. The low-level heat transfer rate fluctuations are corresponding to the wind tunnel background noise.



**Fig. 8.** The heat transfer signals of three typical measuring points along the centerline of the fin leading edge

### 3.4 Discrete Fourier Transform (DFT) Analysis

Discrete Fourier Transform (DFT) has been used to transfer heat-transfer rate signals from the time domain into the frequency domain. Only signals obtained under 10 kHz cut-off filter frequency are considered here.

Figure 9 gives typical power spectral at three different points along the plate centerline which locate in undistributed region, incipient separated region, separated region respectively. We can see that amplitude of heating rate signals increases as flow goes downstream in separated region. At  $X/D = -3.0$  and  $X/D = -0.2$ , the frequency distributions are broadband. At  $X/D = -2.6$ , the dominate low frequency is under 1 kHz.



Figure 10 gives typical power spectral at three different points along the fin leading edge centerline. We can see that amplitude of heating rate signals increases as flow goes from  $S/D = 0.2$  to  $S/D = 0.8$ . At  $S/D = 0.8$  the amplitude of heating rate signals is largest. At  $S/D = 3.0$ , the amplitude of heating rate signals in plateau region is very small.

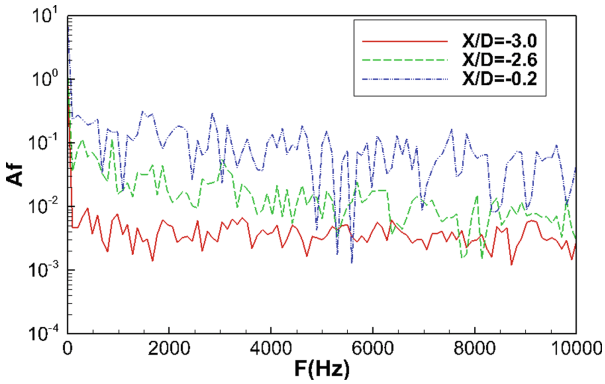


Fig. 9. Typical power spectral at three different points along the plate centerline

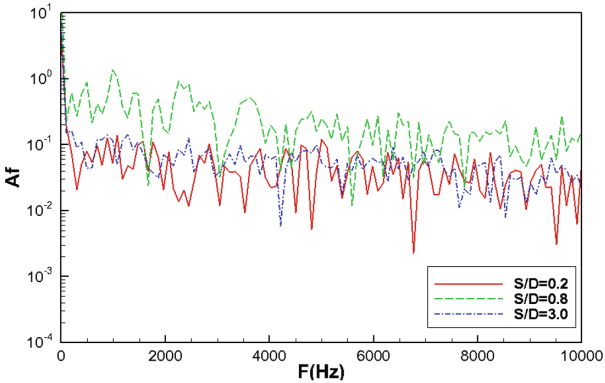


Fig. 10. Typical power spectral at three different points along the fin leading edge centerline

### 4 Conclusion

Experimental studies of the hypersonic separated flow characteristics induced by a perpendicular blunt fin on the flat plate were carried out. Steady and unsteady flow characteristics are studied by heating transfer rate measurements. The main results in present paper are shown as following:

- (a) The existence of the fin changes flowfield significantly. There is a highly complex disturbance region upstream of the fin.
- (b) The distribution of heat transfer rate is changed in separated flow compared with the attached flow. In the streamwise direction two peaks are observed.
- (c) Remarkable fluctuations of the heat transfer rate exist in the interaction region. Unsteady flow characteristics are very clear. The low oscillating frequencies obtained from heat transfer rate signals are lower than 1 kHz. The identical conclusions are obtained by fluctuating pressure measurements under the same model and freestream conditions [9].

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