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Transition in Hypersonic Wall-Bounded Flows

Yiding Zhu · Cunbiao Lee

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Abstract The hypersonic boundary-layer transition is a strategic focus in the fluid mechanics community. This article reviews recent developments in the study of the hypersonic boundary-layer transition, especially at Peking University. The hypersonic quiet wind tunnel is introduced as a necessary device to obtain real flight data in near space. The most important issues in the recent development of the transition in the hypersonic boundary layer are addressed. The instability, its contribution to the aerodynamic heating and artificial control are discussed.

Keywords Hypersonic Boundary Layer Transition · Quiet Wind Tunnel · Aerodynamic Heating

1 Introduction

Development of hypersonic vehicles has become a hot topic today because of its great potential both in military and commercial application. One of the most important issues is the process of the hypersonic boundary-layer transition which is crucial to the design of thermal protection and flight maneuverability. The problem has been studied for about half a century, which has been systematically reviewed by Stetson and Kimmel [1], Schneider [2,3], Fedorov [4] and Zhong [5].

Yiding Zhu
State Key Laboratory for Turbulence and Complex System, Peking University, Beijing, China

Cunbiao Lee
State Key Laboratory for Turbulence and Complex System, Peking University, Beijing, China
Corresponding Author:
E-mail: cblee@mech.pku.edu.cn

Experimental investigation has played a crucial role in hypersonic transition investigation. The free stream disturbance level is a key parameter for the hypersonic wind tunnel which greatly affects the transition process. As known to all, the real flight is several tens of kilometers above the ground where the disturbance is at a very low level. However, most of the ground-test experiments are conducted in conventional wind tunnels with much higher disturbance levels so that their transitional process is commonly far from the real flight situation. To this end, constructions of hypersonic quiet wind tunnels are necessary to obtain the quasi-flight transition data [6–11]. From 2010 to 2014, Peking University (PKU) has built up two quiet wind tunnels [12,13], which not only provided basic transition but also explored the underlying physical mechanism that helps to promote new theories.

Besides the first mode that is the counterpart of TS wave in the incompressible flow, a unique feature of a high Mach number boundary layer stability is the appearance of a new family of neutral curves, i. e., the second- and higher-modes. Although the second mode has a much larger growth ratio than the first one has, previous experiments [14,15], numerical [19] and theoretical results have manifested that it is the first mode that obtains energy from the second one and finally triggers the turbulence. As soon as the hypersonic wind tunnel has been established, substantial experiments are conducted on the hypersonic transition mechanism. An entire measurement of the streamwise disturbance evolution has further validated the viewpoints above, which shows that the second mode only plays a catalytic role in the transition process [16,17]. Nonlinear interactions between the low frequency and second mode have been then theoretically discussed by the PKU's group [20].

As early as in 2013, with the help of near-wall PIV techniques, the PKU's group has discovered that the second mode is accompanied with a strong dilatation process [21]. Soon in 2014, the PKU's group realized that such process inevitably creates a strong dilatational viscous dissipation involving bulk viscosity which leads to the rapid annihilation of the second mode. Only until 2016 these results are published in [17]. The correlation between the second mode and the aerodynamic heating are also systematically investigated during from 2015 to 2016. Intense aerodynamic heating is found to be created by the second-mode-induced dilatational process. The results are summarized in [18] but can be published in 2018 [22–24]. The underlying mechanisms are then investigated based on both experiments and direct numerical simulations (DNS), which shows that the pressure dilatation has played a dominant role [25].

2 Hypersonic Quiet Wind Tunnel

From the late 1960s to middle 1990s, funded by the National Aerospace Plane (NASP) program, the NASA Langley laboratory have made substantial progress in developing quiet wind tunnel, covering the Mach number 3.5, 6, 8 and 18 [7]. Especially, the Mach 6 nozzle produces very uniform flow at a quiet-flow unit Reynolds number 10^7 m^{-1}. After the termination of the NASP program, NASAs interest in quiet tunnels and hypersonic transition went into a long decline. The Mach 6 quiet nozzle and associated hardware were shipped to Texas A&M University, where they are being reinstalled with support from the Air Force Office of Scientific Research (AFOSR) in 2010 . On the other hand, Schneider has partly attended the NASA Langley's work in 1990. As he joined Purdue University, he started to reconstruct the hypersonic quiet-flow facility. A Mach 6 quiet Ludwieg tube has been completed in Purdue University in 2001 and quiet flow has been achieved at Reynolds number as high as 13.0×10^6 m^{-1} in 2006 [8].

In China, Zhou and Chang were the pioneer in China to study quiet flow wind tunnels [26, 27]. They conducted both theoretical and experimental research on hypersonic quiet wind tunnels in 1997. Funded by the National Defense Study-in-Advance program, a low noise level Ma 4 wind tunnel with a nozzle 120 mm in exit diameter was built in 2000. However, due to the limitation of funding and techniques, the prosperities of the wind tunnel were limited. The maximum free stream Reynolds number under quiet-flow conditions was about 1.0×10^6 m^{-1}. Nevertheless, the wind tunnel substantially accumulated valuable experience. Between 2010 and 2011, Peking University (PKU) improved the design and built a low-noise Ma 6.0 wind tunnel with a nozzle 120 mm in exit diameter (then replaced with a new one 160 mm in exit diameter) [12]. The wind tunnel operated in quiet conditions with a stagnation pressure less than 0.25 MPa. The total temperature was 430 K. The noise level rose rapidly when the stagnation was higher than 0.25 MPa (see Fig 1. The maximum free stream Reynolds number under quiet-flow conditions was about 2.5×10^6 m^{-1} . In recent years, in order to increase the maximum free stream Reynolds number under quiet-flow conditions so that the wind tunnel condition could be comparable to the flight environment, Lee and Zhou drew on the experience of Beckwith and Schneider [28–30]. With the innovations in design and manufacturing methods, the State Key Laboratory of Turbulence and Complex Systems at Peking University developed a series of nozzles 300 mm in exit diameter covering both supersonic and hypersonic Mach numbers (Ma 3.0, 4.0, 5.0, 5.5, 6.0, 6.5). These nozzles are by far the largest nozzles in operation in the world. The detailed introduction see the previous review article [13]

3 Hypersonic Transition Mechanism

Since the hypersonic laminar boundary layer has different modes of instability, each of their roles with the transition process is mostly concerned. Bountin *et al* [14] have studied the instability evolution over a straight cone using hot wire measurement in a Mach 5.92 flow. Although the second mode has enjoyed a larger growth ratio than the first one has, the transition location is dominated by the first mode. Shiplyuk *et al* [15] conducted bicoherence analysis on the hot wire results. They found that there existed nonlinear interactions

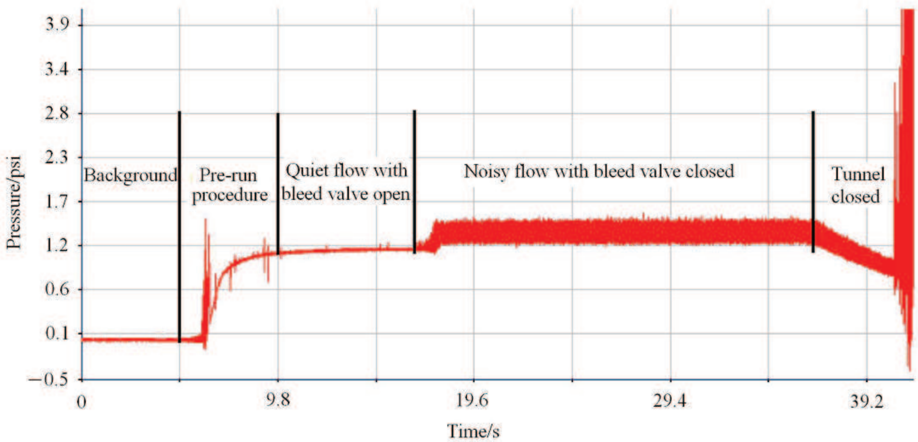


Fig. 1 Kulite pitot pressure trace of the PKU's hypersonic quiet wind tunnel (1 psi = 6 895 Pa). Reprinted from [12].

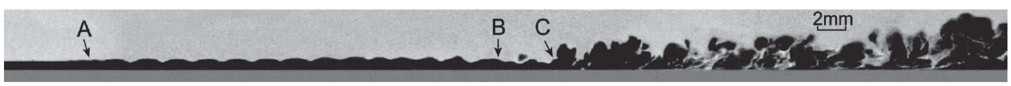


Fig. 2 Flow visualization of the hypersonic boundary layer transition. Reprinted from [16].

between the first and second mode and the former triggered the final transition to turbulence. Zhou's group in Tianjin University have substantially conducted both numerical and theoretical work on the stability and transition of hypersonic boundary layers. They found that the disturbance evolution distorted the mean velocity profile which benefited the first mode's growth but suppressed the second mode's. All the results are systematically published in their monograph [31].

The PKU's group has conducted experiments based on a combination of flow visualization, fast surface pressure measurement using PCB sensors and PIV [16,17]. Based on the rich experience in the optical measurement technique, they have succeeded to obtained the world's first clear view of the whole hypersonic transition process over a flared cone model covering from laminar to turbulent state (see Fig. 2). The picture clearly show that during the transition process, the second mode initially grows, reach its maximum value but finally decays to nearly zero before the transition is completed. PCB sensors have been later densely distributed along the streamwise direction, which can provide a simultaneous measurement of the disturbance evolution. The PCB results not only shows evolution of the second mode, which agrees well with the flow visualization, but also reveals that the low frequency disturbance continuously grows until the boundary layer is turbulent. A strong nonlinear interaction is further manifested by the bicoherence analysis of the PCB time series.

The PKU's group [20] further have performed a detailed stability analysis of the boundary layer of a flared cone for the same flow conditions as in the experiments. Using parabolized stability equations (PSE), they showed that

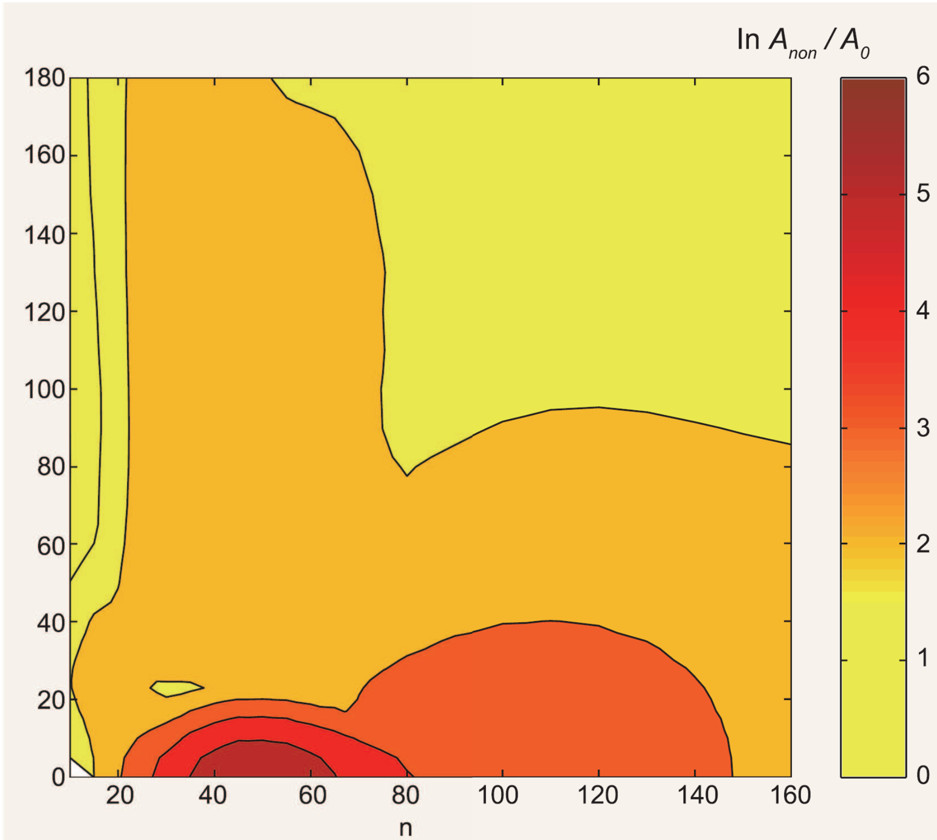
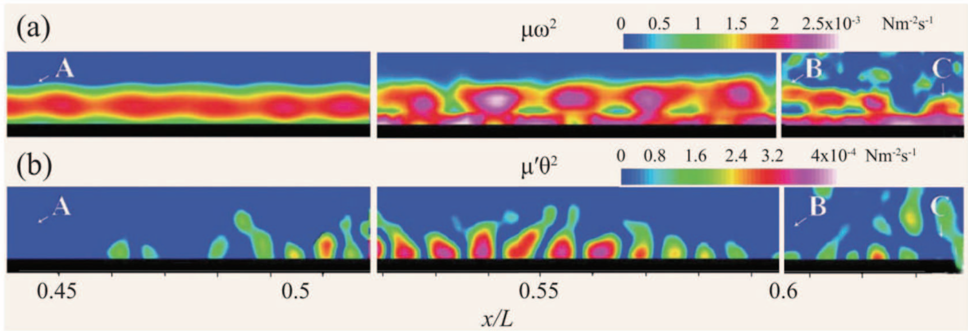


Fig. 3 Contours of amplitudes spectra in the azimuthal wave numberCfrequency plane at x = 180 mm. Reprinted from [20].

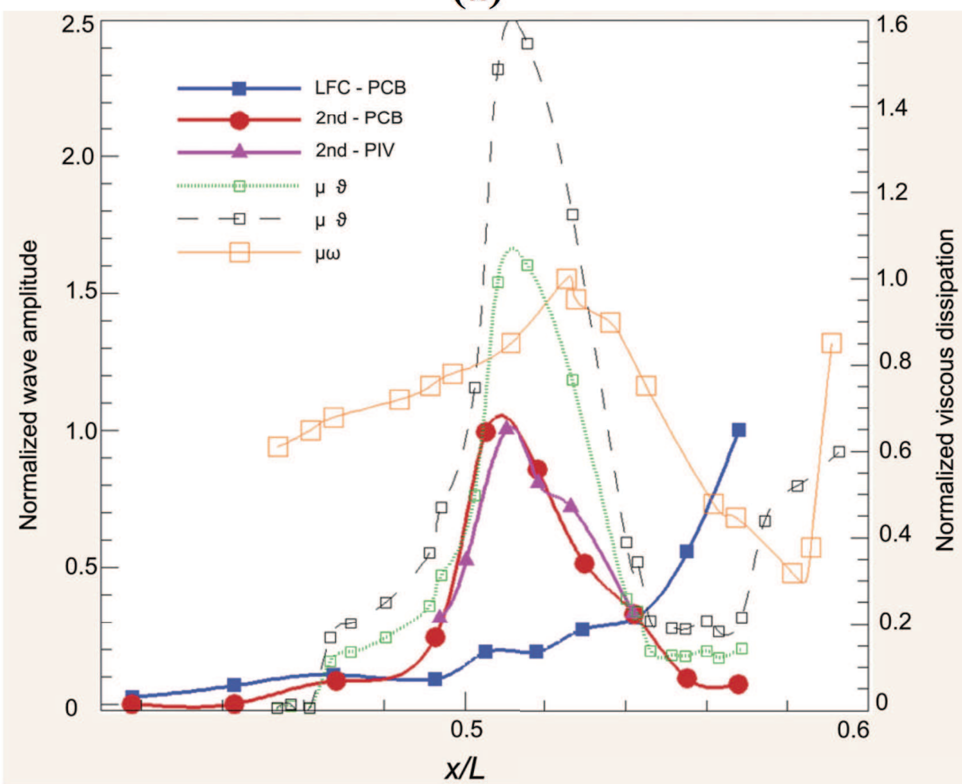
the low-frequency waves interacts with the second mode via the phase locked mechanism and the subsequent parametric resonance mechanism. The parametric study shows that very low-frequency modes are most heavily promoted, as shown in Fig. 3. The nonlinear interaction can be classified by the linear stage where the the phase-locked theory can be applied and the parametric-resonance stage where a sharp increase of the Reynolds stress works (see Fig. 3).

Recently, the PKU's group compared the instability evolution over a flared cone made with between the normal stainless steel and the porous steel. They found that latter has a larger growth of the second mode but a later transition to turbulence. The bicoherence analysis shows that nonlinear interactions has become weaker over the porous surface so that the low frequency mode is smaller. This is another proof that support the view point above. Such results are to be published in the near future.

The rapid annihilation of the second mode instability has been related to the strong dilatation process and related bulk-viscosity-induced viscous dissipation [17]. The dilatation has been calculated from the velocity field captured by the near-wall PIV techniques (see Fig 4). Because the second-mode instabilities are acoustic, and the instabilities may be accompanied with both vortical



(a)



(b)

Fig. 4 (a): The vorticity and dilatation of the hypersonic boundary layer velocity field from PIV. (b): Comparison of the instability evolution with different viscous dissipation. Reprinted from [17].

and dilatational waves, viscous dissipation cannot be neglected. The viscous dissipation function per unit volume can be written as

$$\Phi = \mu\omega^2 + (\lambda + 2\mu)\theta^2 \tag{1}$$

where λ is the second coefficient of viscosity by Stokes. The second term s-tands for the dissipation caused by dilatation, which has been considered as a stabilizing effect on the second mode. Let the longitudinal viscosity be μ' $= \lambda + 2\mu$. If Stokes hypothesis holds, i.e. $\mu_b = 0$ and $\lambda = 2\mu/3$, then $\mu' =$

$4\mu/3$. In our study, the wall temperature is about 300 K, so μ' was chosen to be 2.06 μ its value in low-pressure N_2 at T =293 K [81]. Figure 14 shows the viscous dissipation induced by vorticity and dilatation. It displays clearly the peak values of $\mu\omega^2$ and $\mu'\theta^2$, as well as their correlation with the spatial evolutions of low-frequency and second-mode wave amplitude. Recently, the effect of high-bulk-viscosity gas, *e.g.* the CO_2 on the hypersonic transition has been concerned due to the flight in the atomosphere of the Mars. Elliot *et al*. [32] have found that increasing the concentration of CO_2 will significantly delay the transition.

4 New Principle for Aerodynamic Heating and Its Control

Using temperature sensitive paint, Schneiders group [34] observed hot streaks on a Ma 6 flared cone under quiet flow conditions. The spanwise-averaged temperature exhibited a second rapid growth (HT), which was not quite as strong as that in the midst of the transitional region (HS). PCB piezoelectric pressure sensors were also applied within that region and indicated the appearance of second mode instability. However, the spatial resolution of the experiments was insufficient to elucidate the relation between the evolution of second-mode instability and the temperature distribution. Schneiders group attributed HS to the nonlinear development of second-mode instability, but no further investigation has been performed on its mechanism. Sivasubramanian and Fasel [35] used DNS to investigate the laminar-to-turbulent transition in a sharpcone boundary layer at Ma = 6. They focused on the fundamental resonance mechanism. Streamwise hot streaks were observed before the boundary layer became turbulent. Either spanwise-averaged heat transfer or that along a single streak exhibited both HS and HT in the streamwise direction. The Stanton number at HS was twice that at HT, but the skin friction of the former was only half that of the latter. Based on direct numerical simulations (DNS), Franko and Lele [36] investigated the transition mechanisms of a Ma = 6 planar hypersonic boundary layer. Three types of such mechanisms were identified: first-mode oblique interaction, second-mode fundamental resonance, and second-mode oblique interaction. For the first-mode oblique interaction mechanism, a distinct overshoot of heat transfer was observed near the end of the transitional region, HT, which was attributed to the generation of streamwise vortices and correspondingly increased wall shear stress. However, for the fundamental resonance dominated by the 2D second mode, an additional peak of heat transfer, HS, appeared where the second mode reached its maximum. The temperature values at HS are slightly higher than those at HT, while the associated skin friction of the former is no more than half of the latter. The appearance of HS was commonly attributed to the second-mode evolution, but no physical explanation was given in terms of fundamental thermo-aerodynamics.

From 2015 to 2017, the PKU's group have conducted a series experiments, involving the surface temperature measurement by temperature sensitive paint, the PIV and PCB sensor measurements. Combined with numerical

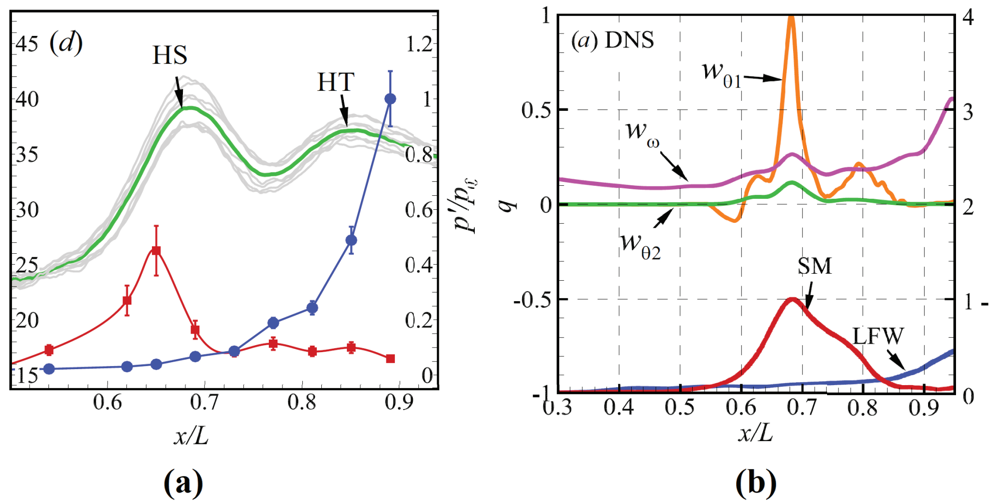


Fig. 5 Comparison of the instability modes (red: second mode; blue: first mode) with (a) surface temperature (green: spanwise-averaged value) and (b): different heat generation ratios (orange: pressure work; magenta: shear-induced dissipation; green: dilatation-induced dissipation). Reprinted from [25].

and theoretical study, they have firstly determined the direct relation between the local heating peak and the evolution of the second mode. Fig. 5a compares the evolution of second-mode instability with the spanwise-average surface-temperature rise. The second-mode amplitudes are normalized to their maximum value. For the highest Reynolds number, the second-mode peak appears at $x/L = 0.65$, corresponding to a local peak of temperature at $x/L = 0.68$. Such correlations between the second mode and the surface temperature are also observed both in PSE analysis and DNS. Both the physical and numerical experiments shows that the evolution of the second mode has brought about a local peak of surface-temperature HS that shifts slightly downstream. Increasing unit Reynolds number has promoted the strength of HS, leading to a stronger dissipation of the second mode.

The new discoveries has been submitted to several journals but rejected to be published for more than one year. Only until 2018, the new discoveries have been published in January 2018[22]. The new discovery is considered as a new principle for aerodynamic heating [23,24] and paid attention by [37]. The underlying physical mechanism has been further investigated [25]. It is found that the pressure dilatation $-p\ \nabla \cdot \mathbf{U}$ has played a dominant role in the creation of HS (see Fig. 5b), where $\mathbf{U} = (u, v, w)$ is the velocity vector. Meanwhile, Kuehl has given a thermal-acoustic interpretation of the second mode which has been published in [38] in April 2018 and introduced by [39]. Kuehl discussed the linear inviscid solution of the second mode and simplified it as a 1-D standing wave model in the normal direction.

The PKU's group then applied a wavy wall to control the hypersonic boundary layer transition and the related aerodynamic heating on a flared cone at a range of unit Reynolds numbers. Experiments are conducted in a

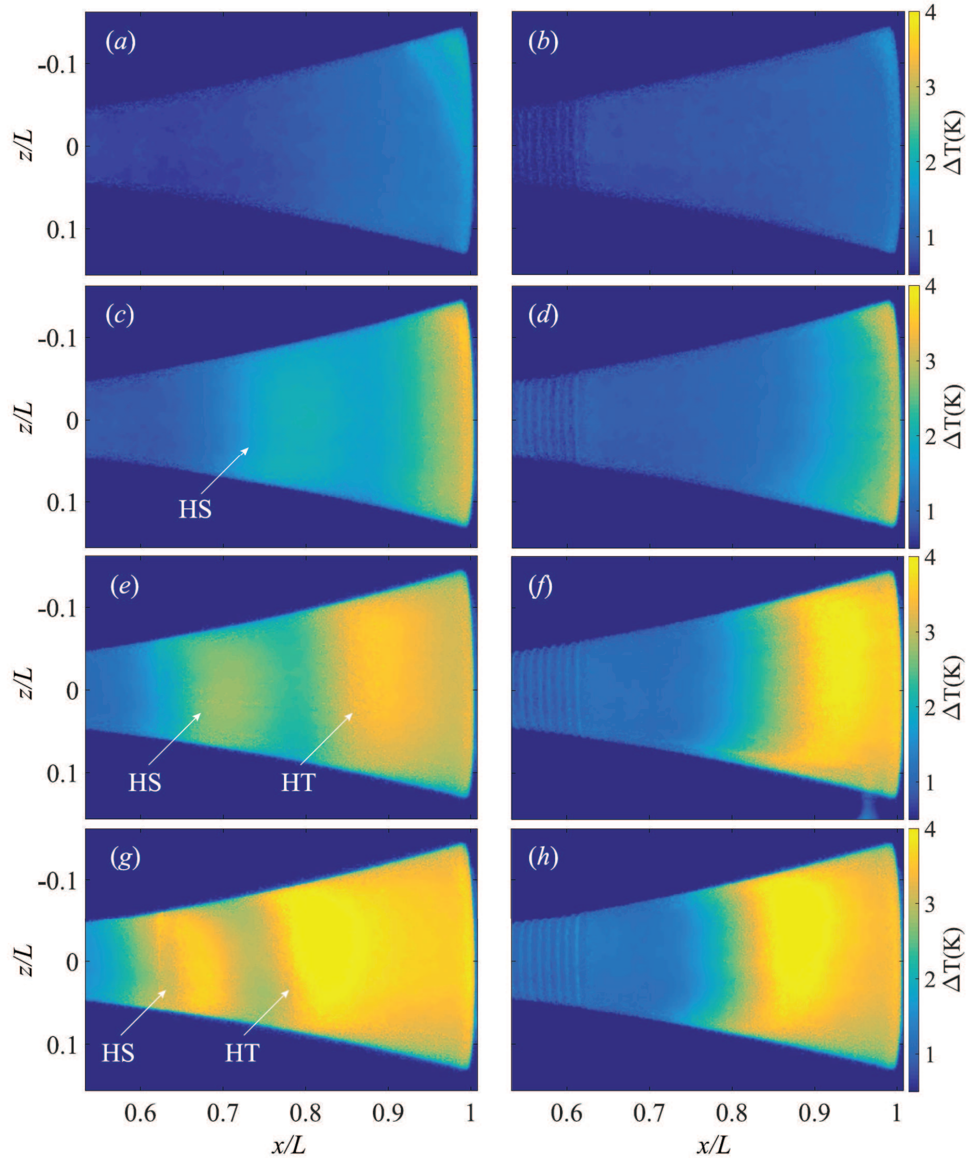


Fig. 6 Comparison of surface temperature between (left) without and (right) with wavy wall. Reprinted from [40].

Mach 6 wind tunnel using Rayleigh-scattering flow visualization, fast-response pressure sensors, and infrared thermography. The results show that compared to the smooth-wall cone, the wavy-wall one can suppress the second-mode instability to a certain degree and eliminate the local heating spot before transition is completed (see Fig 6). These verify our recent work on aerodynamic heating that HS is caused by the second-mode instability.

5 Conclusion

Hypersonic flow transition is at present one of the focuses of fluid mechanics, due to the importance of both fundamental research and real application. Experimental investigation has played a crucial role in hypersonic transition investigation and constructions of hypersonic quiet wind tunnels are necessary to obtain the quasi-flight transition data. The two quiet wind tunnels built up in Peking University help to not only provide basic transition data but also explore the underlying physical mechanism that helps to promote new theories.

Although the second mode has a much larger growth ratio than the first one has, experiments, numerical simulations and theoretical results have manifested that it is the first mode that obtains energy from the second one and finally triggers the turbulence. Nonlinear interactions between the low frequency and second mode has also been identified by using experimental and theoretical method.

The second mode is accompanied with a strong dilatation process which inevitably creates a strong dilatational viscous dissipation involving bulk viscosity and leads to the rapid annihilation of the second mode. Intense aerodynamic heating is also found to be created by the second-mode-induced dilatational process. The pressure dilatation has played a dominant role. Application of the wavy wall can significantly decrease the second mode and the related aerodynamic heating.

6 Acknowledgement

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