Yang *et al. Advances in Aerodynamics* (2022) 4:18
https://doi.org/10.1186/s42774-022-00105-1

Advances in Aerodynamics

REVIEW **Open Access**

Research Progress of hypersonic boundary layer transition control experiments

He-sen Yang, Hua Liang*, Shan-guang Guo*, Meng-xiao Tang, Chuan-biao Zhang, Yun Wu and Ying-hong Li

*Correspondence:
lianghua82702@163.com;
shanguang_guo@163.com
Science and Technology on Plasma Dynamics Laboratory, Air Force Engineering University, Xi'an, People's Republic of China

Abstract

Hypersonic boundary layer transition is a hot yet challenging problem restricting the development and breakthrough of hypersonic aerodynamics. In recent years, despite great progress made by wind tunnel experiment, transition mechanism and transition prediction, only partial knowledge has been gained so far. In this paper, firstly, the specific scenarios of hypersonic boundary layer transition control are clarified. Secondly, the experimental research progress and mechanism of passive control and active control methods under different hypersonic transition control demands are summarized, with their advantages and disadvantages being analyzed separately. Plasma actuation is easy to produce controllable broadband aerodynamic actuation, which has potential in the field of boundary layer transition control. Hence, the following part of the paper focuses on plasma flow control. The feasibility of plasma actuation to control the hypersonic boundary layer transition is demonstrated and the research ideas are presented. Finally, hypersonic boundary layer transition control methods are summarized and the direction of future research is prospected.

Keywords: Hypersonic boundary layer, Transition control, Active/passive control, Experimental research, Plasma actuation

1 Introduction

With great political, military and economic value, hypersonic vehicles can greatly expand the battlefield space, and it has gradually become the main development direction of the global aerospace industry in the twenty-first century [1]. Meanwhile, it goes without saying that the corresponding key science and technology is assuredly crucial.

In the last decade, many hypersonic topics have been continuously discussed, including the famous HIFiRE Project [2], in which 4 of 5 topics are closely related to the transition control of the hypersonic boundary layer, so the importance of transition control is obvious.

For half a century, through unremitting efforts, great progress has been made in the study of hypersonic boundary layer transition [3–9]. Especially, a certain research system has been formed in the research on hypersonic boundary layer transition development process, influencing factors, transition mechanism, transition prediction method and model, thus making a theoretical foundation with a certain degree of consensus. Moreover, many excellent reviews have also emerged.

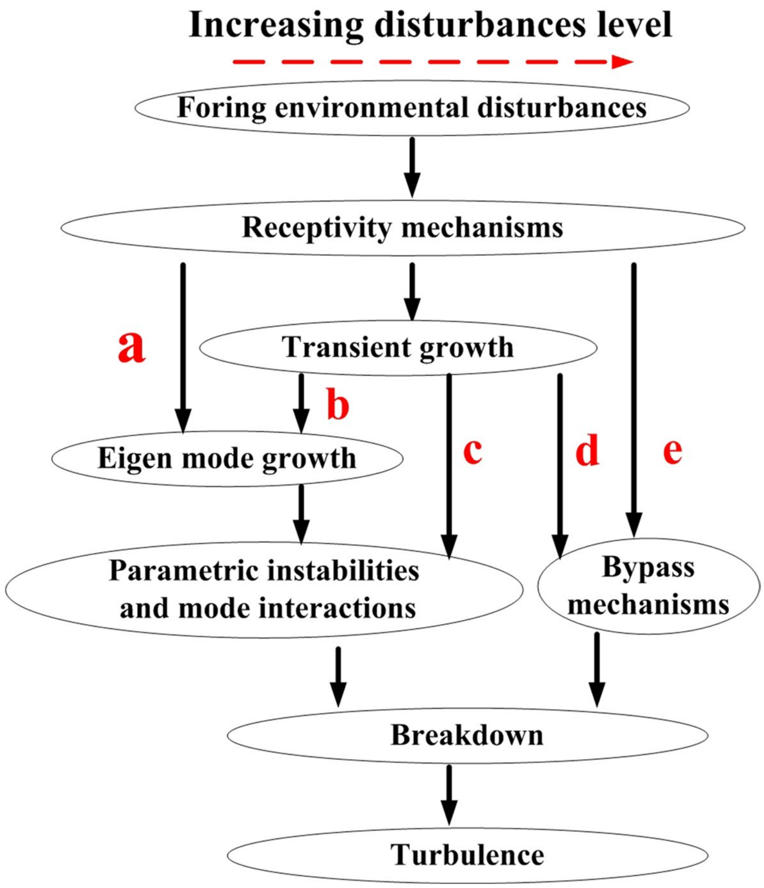


Fig. 1 Boundary layer transition process and path [16]

Fedorov [10] reviewed new mechanisms of receptivity and instability; Schneider [11] mainly summarized the experimental results obtained in quiet wind tunnels in recent years; Lee and Jiang [12] presented the principle of aerodynamic heating of hypersonic boundary layer, aiming to draw a simple and clear conclusion about the onset of turbulence.

Since 2017, Chen et al. [13] and other Chinese scholars [14, 15] introduced the latest detailed progress in process, mechanism and method from different aspects. According to the development process of the natural transition of the boundary layer (the boundary layer transition process and path recognized by academic circles are shown in Fig. 1 [16]), Lee and Chen [17] reviewed recent developments, research facilities and experimental techniques of hypersonic boundary layer transition as well. Moreover, Wu et al. [18] reviewed the current situation of wind tunnel experimental research on the susceptibility of the boundary layer and the linearization stage, respectively.

The research on transition serves transition control, followed by wind tunnel experimental research and flight test verification [13], and transition control also belongs to the category of flow control. According to whether external energy injection is required, flow control methods can be divided into passive control and active control.

Passive flow control mainly achieves the control purpose through preset physical shapes or additional devices, usually including vortex generators, wing knives, and bionic leading edges [19, 20]. On the contrary, in off-design conditions, these control methods are difficult to achieve the expected control effect, and they may also become the source of noise and vibration [21]. Therefore, development is subject to many restrictions, which prompts researchers to explore active flow control.

Active control methods require energy input, which is achieved by controlling energy input. The main methods include boundary layer blowing/suction, synthetic jets, plasma actuation and other emerging methods [22–24]. In recent years, some active flow control methods have provided suitable control strategies based on the real-time changes of the controlled flow field, and gradually become the frontier and mainstream of some research fields [25], including plasma actuation in the control of high angle of attack flow separation [26], and blowing and suction in the control of rotor stalls [27, 28].

In fact, in the study on transition control, few experts conducted detailed collation and review on this point. Roger L. Kimmel [29] noted in his review entitled "Aspects of Hypersonic Boundary-Layer Transition Control" that the control of hypersonic boundary-layer transition was a potentially important topic for vehicle design, and a number of methods for hypersonic transition control have been developed at the basic research level. Passive porosity, blunt noses, and blunt 2D leading edges have the highest potential for integration onto vehicles. Finally, due to, perhaps, the lesser potential for practical application, he proposed that a number of other hypersonic transition control techniques have been developed. Further development of transition control for hypersonic vehicles awaits a system. Interactions among various control concepts and optimization would appear to be fruitful areas for study.

Lee and Chen [17] reviewed a series of progress made in transition delay control combined with mechanism exploration, especially the recent contributions at Peking University. Moreover, Chen et al. [13] only reviewed the research progress of passive control of hypersonic boundary layer transition.

There are insufficient reviews of hypersonic boundary layer transition control. They are all discussed from a certain angle or aspect, such as rough element [30, 31], and transition control means in inlet or air-breathing hypersonic vehicle application [32], mainly focusing on numerical simulation research. Recently, Liu et al. [33] reviewed the progress in hypersonic boundary layer transition delaying control. Similarly, this article did not involve much on active control methods.

On the whole, previous reviews of hypersonic boundary layer transition control mainly focused on passive control methods, and the experimental research was not comprehensive. Compared with the vigorous development of active control, passive control and their combined control in low-speed flow control, the research on hypersonic transition control is not rich and diversified.

In recent years, with the development of hypersonic field, traditional transitional measures and methods no longer meet the increasingly stringent transition control requirements. Therefore, the strategies and methods of hypersonic boundary layer transition control should be systematically combed. In particular, the development status of control methods in existing experimental research should be summarized and the common mechanism and experience should be refined to provide guidance for emerging control methods to achieve finer transition control requirements. Most importantly, whether active flow control can intervene the transition path and realize fine control under different flight conditions and different energy consumption requirements is a question that deserves to be pondered by researchers in this field.

2 Practical scenarios and control requirements for hypersonic boundary layer transition

At present, the understanding of some transition mechanisms is still developing [30]. Considering about the uncertainty of the transition pathway, the idea of refined research should be established in the process of transition control research, and control scenarios and control requirements should also be investigated in advance. The most effective way is to start from hypersonic vehicles, and clarify the aerodynamic components, types and reasons of transition that are prone to transition in different types of vehicles, so as to make the research on transition control more targeted, thus realizing more effective and cost-effective control.

First, the demand for transition control should be clarified. It is generally supported that, the ratio of payload to total weight of aircraft in full laminar flow state is usually about twice of that in full turbulent flow state, because the thermal conductivity of turbulent flow is much higher than that of laminar flow [34]. Transition can lead to a peak heat flow of up to 5 times than that in laminar flow state, which seriously affects the design of aerodynamic and thermal protection system [35], so transition should be suppressed. On the other hand, ensuring the turbulent state at the entrance of inlet can provide sufficient intake air flow for the propulsion system and promote the mixing of air and fuel in the combustion chamber, which requires the transition to occur as early as possible.

Consequently, promoting transition and delaying transition are the two dominant directions of transition control research [36, 37]. However, it's not specific enough. Hypersonic vehicles have wide flight speed range, wide airspace range, and complicated transition problems. Due to different design objectives, application scenarios, technical schemes, timing and environment of boundary layer transition, the impacts and the specific problems to be solved are also different [38]. In this paper, combined with the classification of hypersonic vehicles, both the detailed hypersonic boundary layer transition control scene and control requirement were described.

Hypersonic vehicles are divided into three categories in this paper, namely ballistic reentry vehicles [39], gliding vehicles [40] and air-breathing cruise vehicles [41]. The three types of vehicles have their own distinct characteristics in terms of design requirements, flight trajectories and combat styles, as shown in Fig. 2.

2.1 Ballistic reentry vehicles

The ballistic reentry category can be divided into small blunt cone ballistic reentry vehicles represented by inertial warheads and large blunt ballistic reentry vehicles marked by return capsules and Mars landing vehicles.

The former theoretically flies near zero angle of attack, but the actual flying flow field is asymmetrical, thereby causing the asymmetrical transition of the missile body. There are great difficulties for the flight test of this kind of aircraft, dominantly because the

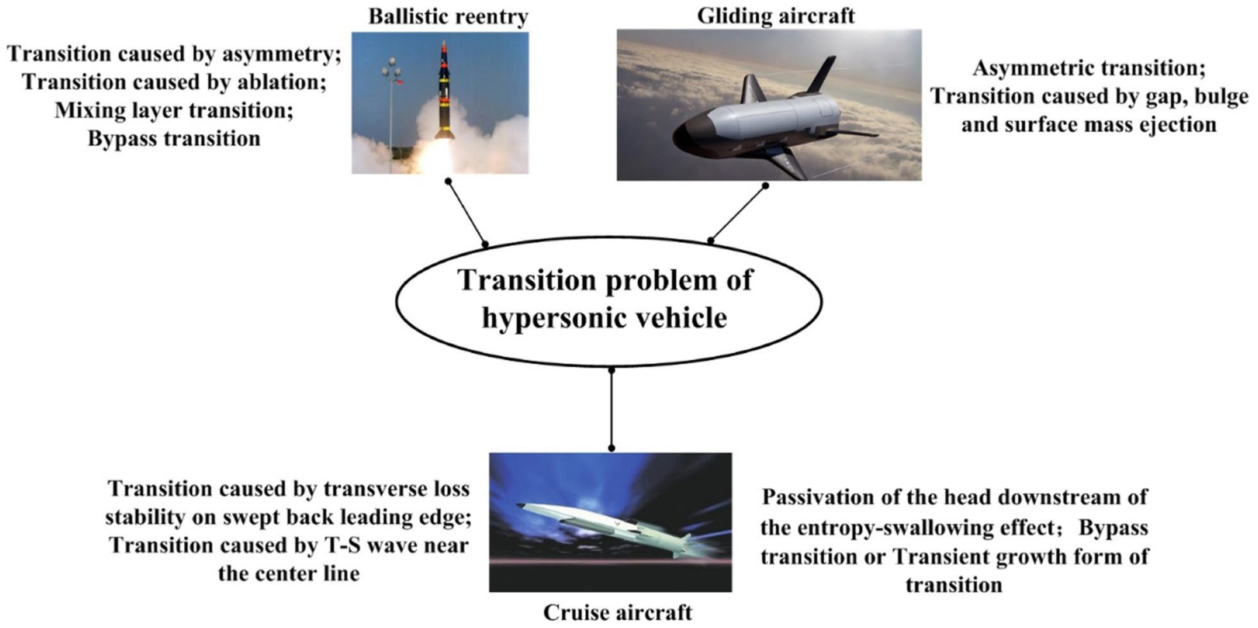


Fig. 2 Hypersonic vehicle transition problems and background combing

abnormal amplification and oscillation of the angle of attack appearing in the transition altitude interval will give rise to a large deviation in the landing point [42].

On the other hand, the latter must ensure that the overload caused by aerodynamic deceleration during the reentry flight is within the safe tolerance range of the astronauts, and it usually has a very large passivation half-cone angle in appearance. The main transition problems are as follows [43]: boundary layer transition caused by the ablation on the windward side of bluff body, mixed layer transition in the wake flow on the leeward side, and bypass transition phenomenon from the large disturbance of bluff body head.

This type of aircraft usually flies with an angle of attack, and transition control is more difficult. The heat protection design technology should be combined with a control method, which delays the transition to reduce the risk of the local burnout of this type of vehicle [44].

2.2 Gliding vehicles

Gliding vehicles can be divided into orbit return type denoted by X-37B orbital maneuver vehicle and long-range strike type represented by American HTV series vehicles [45]. Orbital return vehicles serve the space round-trip system, and generally adopt the design of large blunt head. This kind of aircraft generally adopts a gliding flight trajectory with a high angle of attack to maximize the flight altitude and reduce the thermal load as well.

During flight, transition caused by asymmetry mainly exists [46], and boundary layer transition caused by gaps, bulges, and surface mass ejection will occur.

The function of the long-range strike aircraft is to achieve ballistic and flexible maneuvering penetration and the evasion of anti-missile weapon interception. This type of aircraft generally adopts a small blunt slender body to obtain a larger lift-to-drag ratio. The main transition problems [47] are the transition caused by the horizontal loss on the front edge of the swept back, the transition caused by T-S waves near the centerline, and the entropic swallowing effects in the downstream of blunt head and during long flight. The surface material is ablated, thus causing bypass transition.

The boundary layer transition of this kind of aircraft will also bring stability and thermal protection risks. The leading edge boundary layer transition is the main reason for the aircraft to lose control. Similarly, the main transition control requirement of gliding vehicles is to suppress or delay transition.

2.3 Air-breathing cruise vehicles

The typical feature of air-breathing cruise vehicles is to maintain hypersonic cruise under the condition of high-performance ratio. The typical representatives are hypersonic vehicles, including X-43 and X-51. In order to maximize the working efficiency of the engine, the front body of the engine adopts wave-rider and leading-edge sharpening design. The existing transition-related problems are concentrated in the engine, including transition on the multi-stage compression or curved compression inlet. It is necessary to apply the occurrence of transition in the combustion chamber to achieve better fuel mixing and turbulence enhancement [48]. These problems seriously restrict the thrust and drag characteristics of the whole aircraft. If the transition problem existing in the engine can be effectively controlled in real time, it will save a lot of operating costs.

On the whole, from the perspective of engineering application and aircraft design, many problems caused by boundary layer transition cannot be completely solved from the design level and must be controlled [49]. Typical transition problems have been summarized in Fig. 2. Obviously, for air-breathing cruise aircraft, the control method to promote transition is the research focus, while for another two types of aircraft, effectively inhibiting the occurrence or development of transition is the main contradiction.

After determining whether the transition needs to be delayed or promoted, the choice of control methods and strategies should also be accurately analyzed for different aircraft. What's more, whether the application of control methods could result in other negative effects still needs specific analysis.

The three types of aircrafts cover the future development direction of hypersonic technology and the repeated occurrence of transition problems will undoubtedly give birth to the development of new control methods and strategies.

3 Experimental study Progress of hypersonic boundary layer transition

Hypersonic boundary layer transition control experiments should be sorted out from different perspectives. For example, from the perspective of measurement technology, it can be classified into qualitative measurement experimental research and quantitative experimental research. According to the path of transition development, it can be classified into natural transition experimental research and bypass transition experimental research. Based on the control intention, it can be divided into promoting transition experimental research and delaying transition experimental research [3, 50]. However, these methods are not conducive to explaining the advantages, energy consumption, cost and feasibility of control methods, and the selection of control methods for different transition problems.

As mentioned in Introduction, the transition control problem is a flow control problem. Since the 1990s, flow control has flourished and gradually developed into two branches, namely passive control and active control. By comparison, the research on the active flow control technology is more active and gradually becomes the forefront and mainstream in the past 10 years of the entire flow control field, especially plasma actuation, synthetic jet and other means [51–53].

On the contrary, due to the current development status of hypersonic vehicles and the technical complexity of active transition control, the research on hypersonic transition control mainly focuses on passive control methods [29]. Even since the twentieth century, the National Center for Hypersonic Laminar-Turbulent Transition Research in the United States has mainly investigated the passive transition control technology [5]. However, there are various active control methods emerging, while they are still in the embryonic stage.

This paper attempted to review the experimental studies on hypersonic boundary layer transition control, clarify the control mechanism of different transition control methods, guide the emerging methods and means with control advantages to optimize the layout of control devices (actuators), parameter selection, energy utilization and other issues, further develop hypersonic boundary layer transition control strategies, and provide technical support for aerodynamic optimal design.

3.1 Passive control

It is well known that there are lots of researches on passive control, and many experts and scholars have sorted out and analyzed them. Here, the typical results are just picked out to show the methods and the corresponding control mechanisms are pointed out.

Passive control methods mainly include rough element, cavity, corrugated wall, porous wall, micro channel, and so on [3]. In the following, four typical methods are introduced separately.

3.1.1 Rough element

Rough element has been investigated in depth and certain results were achieved in engineering application. There are many experiences that can be summarized.

The forced transition devices of X-43A, X-51A, Hyfly and other hypersonic vehicles were designed as rough element arrays, and corresponding experimental research has been carried out in the United States [54]. The forced transition devices of rough belt studied involve randomly distributed rough elements, discrete spheres, discrete diamond bodies and slope transition devices. The flight tests conducted by X-43A, X-51A and Hyfly are all ramp-type transition devices, mainly due to the high transition efficiency and low heat flow characteristics of the ramp-type transition devices. Figure 3(a) illustrates the rough belt installed on the X-43A. The slope rough belt successfully achieved a forced transition in the precursor during the flight test of the X-43A. Figure 3(b) demonstrates the forced transition device installed on the X-51A [54].

However, flight tests need the support of a lot of ground wind tunnel experimental research. In the wind tunnel experiments, Schneider et al. [30] took the lead in carrying out a large number of experimental studies and summarized three modes of rough element affecting transition, which provided an important reference for the development and analysis of the subsequent research on the influence law of parameters.

A great deal of subsequent research works [55–59] display that, among many parameters of rough element, the height of the rough element plays the most important role in the transition effects [60, 61], and evaluating whether the height can effectively promote transition (or lead to forced transition) by the local parameters of boundary layer has been recognized by academic circles. The corresponding empirical formula has also been summarized. The control effects of the rough element on the windward centerline can be quantified by Eq. (1), where k/δ represents the rough element height versus the local boundary layer thickness, and Re_θ/M_e refers to the boundary layer momentum thickness Reynolds number versus the outer edge Mach number. Later, a further research revealed that the empirical formula is also suitable for the rough elements in other positions on the windward side, and even suitable for cavities [62].

$$(Re_\theta/M_e)\cdot(k/\delta)=\mathrm{C} \tag{1}$$

For most hypersonic vehicles (the first two types of vehicles mentioned in the second section of this article), the transition control measures are mainly to prevent the transition caused by rough elements. According to the wind tunnel data of the space shuttle, McGinley et al. [63] obtained that when k is the height of the surface roughness element, $\mathrm{C}=27$ is taken; if k is the depth of the cavity, $\mathrm{C}=100$ is taken; if the length of the cavity is

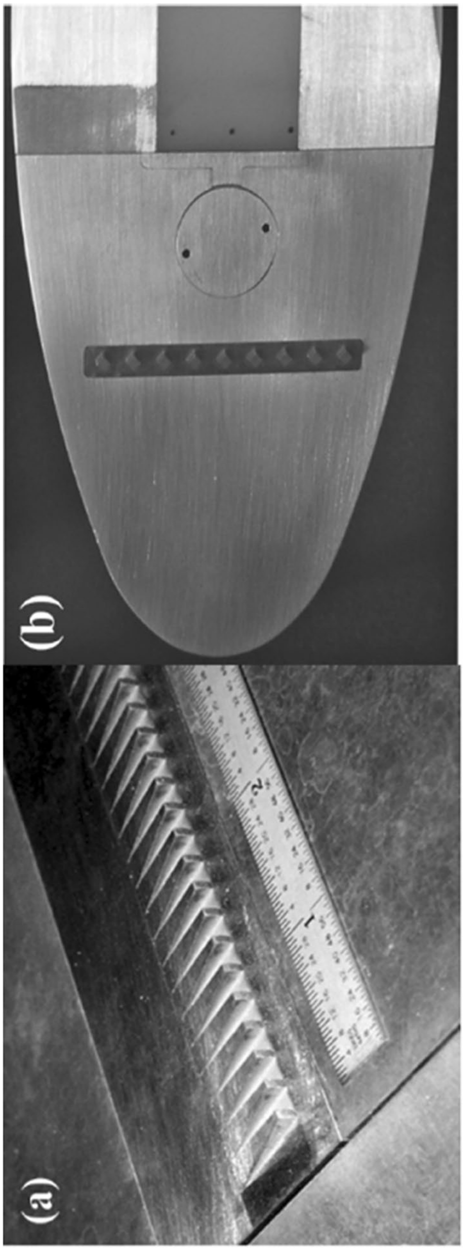


Fig. 3 Rough element array for forced transition on X-43A and X-51A [54]

taken, C = 900 is taken. These values indicate that the rough element cannot cause transition and does not affect the maximum size of the transition position. This provides a criterion for whether gaps, bulges and ablated walls can cause boundary layer transition.

From the demand of promoting transition, another problem that needs to be paid more attention to is the minimum size of transition caused by rough element and its influence on transition position.

In response, Van Driest [61] proposed the concepts of "critical" and "effective", which solves the measurement problem for the boundary of the control effects of promoting transition demand, and provides a reference for parameter selection for rough element transition control.

In recent years, the relational mechanism was explained by combining control effects. Wheaton et al. [64] systematically studied the influence of different heights of cylindrical rough element in Boeing/AFOSR Mach 6 quiet wind tunnel of Purdue University. It was obvious that the change of the height of the rough element will inevitably lead to the change of the instability mechanism, but the root cause and influence law are still unclear.

Interestingly, even the effects of delaying transition appear with further research. In the Mach 6 quiet wind tunnel of Peking University, Tang et al. [65] captured the instantaneous velocity field and flow structure of the second mode unstable wave passing through the rough element for the first time. The results revealed that rough elements can not only be used to promote transition, but also play a role in delaying transition when the parameters are appropriate through refined flow field display. Here, it should be noted that, as early as the 1950s, Sterrett et al. [66] have discovered the phenomenon of rough elements delaying transition at Mach 6. Fujii et al. [67] and Fong et al. [68] also confirmed this point in subsequent studies, which attached the importance of parameter optimization and adjustment, and also showed the advantages and necessity of active control in hypersonic transition control research.

3.1.2 Cavity

After the crash of the U.S. space shuttle Columbia in 2003, the wind tunnel tests were carried out by Everhart J et al. [69, 70] on the space shuttle model and the flat plate model to study the influence of the cavity on the transition at Mach 6 and Mach 10.

Firstly, the flow physics of different cavity types was reviewed by Everhart J et al. The length-to-depth ratio L/H is typically used to distinguish and classify different cavity flow regimes, as depicted in Fig. 4. He specifically pointed out that transitional cavities ($10 < L/H < 14$) are avoided where possible in the present tests due to the complexity of the required instrumentation and test time necessary to address flow steadiness, which provides guidance for the subsequent experimental research.

The research work of NASA's Langley Research Center revealed that the influence of the cavity on the transition depends on the length-depth ratio, the length-width ratio, and the ratio of depth to boundary layer thickness. The cavity with longer flow direction, wider span-wise and deeper depth is more likely to promote the downstream boundary layer transition.

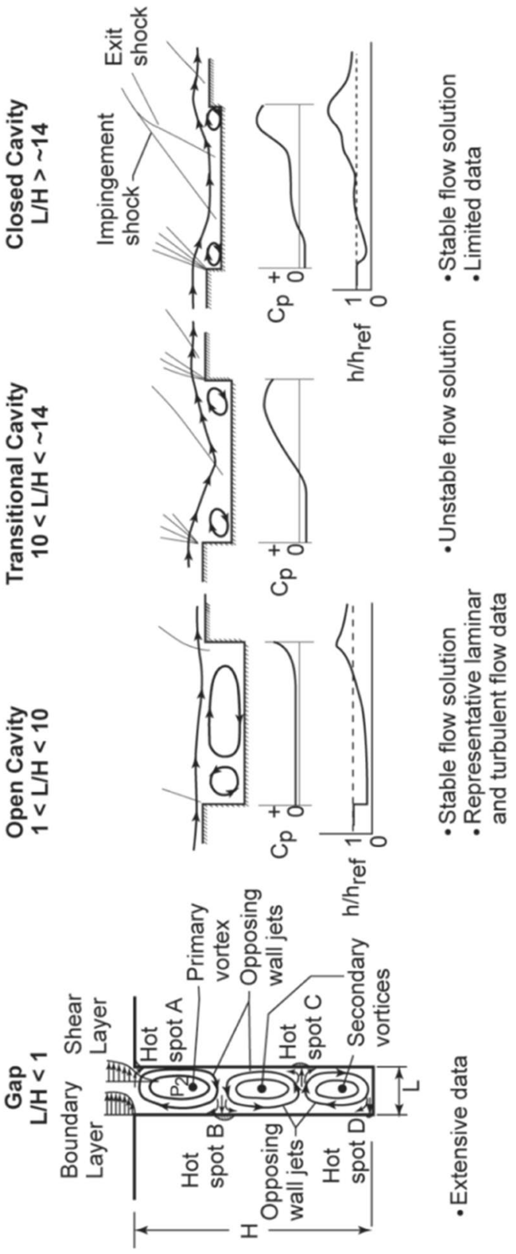


Fig. 4 Cavity flow regimes physics [69]

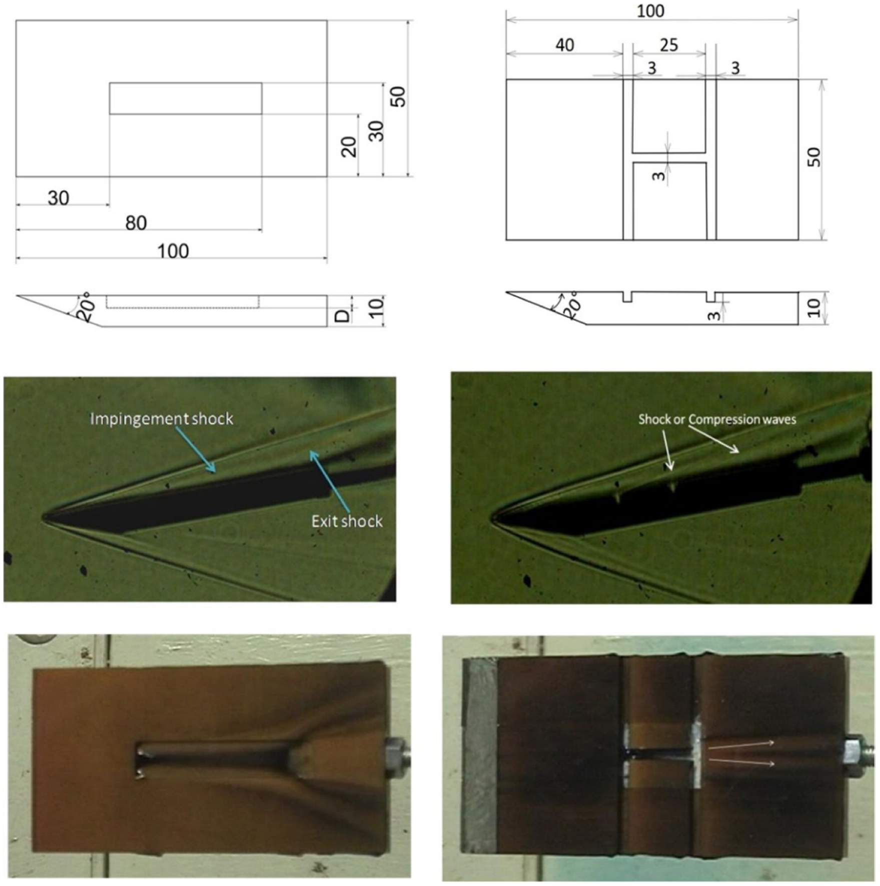


Fig. 5 Experimental configuration and results by Ohmichi and Suzuki [72]

Lawson and Barakos [31] also come to a similar conclusion with that of NASA's Langley Research Center: In three-dimensional cavity flow, the flow characteristics depend not only on the length-depth ratio, but also the width-depth ratio of the cavity.

Ref. [71] pointed out that it is the downstream shear layer flow caused by the cavity that leads to boundary layer transition. Ohmichi and Suzuki [72] carried out wind tunnel experiments on the flow of a flat plate with a three-dimensional rectangular cavity under the condition of $Ma = 7$. It was discovered that the cavity induces flow vortex structure inside and outside the cavity, thus enhancing the heating rate of the inner wall and downstream region of the cavity and promoting the transition process. The conclusion is consistent with that of Ref. [71], and the internal physical mechanism is preliminarily revealed. The control mechanism can be described as that a shallow cavity generates longitudinal vortices inside and outside of the cavity and these vortices augment heating rates on the cavity floor, rear and side walls and the downstream region of the cavity. Figure 5 displays the experimental configuration and experimental results by Ohmichi and Suzuki. This figure first shows the schlieren results, and then the oil flow results of two configurations.

With the continuous development of flow field testing methods, the mechanism of using the cavity to control the transition of the hypersonic boundary layer has been further revealed. During the last 2 years, several hypersonic quiet wind tunnel tests were conducted on the flat-plate model with independent cavity on the surface under the condition of $Ma = 6.5$ by Shuo Chen [73]. Figure 6 illustrates the boundary layer structure in the presence or absence of a cavity.

In Fig. 6(a), when the airflow passes through the cavity, the flow begins to become unstable. It is determined to be the first mode wave by the wavelength of the disturbance wave. While, in Fig. 6(c), when the flow passes through 200 mm, the boundary layer still maintains a stable laminar flow state. The first mode wave structure begins to appear at a further downstream position.

Through PCB pressure measurement, Shuo Chen also found that when a cavity was present, the second mode wave did not appear, then the secondary mode appeared, and gradually the amplitude remained at the same level as the flat-plate model. This indicated that the cavity itself does not stimulate the secondary mode, which is consistent with Ref. [65]. Therefore, the cavity promotes the transition by increasing the growth of the first mode wave rather than the growth of the second mode wave [73].

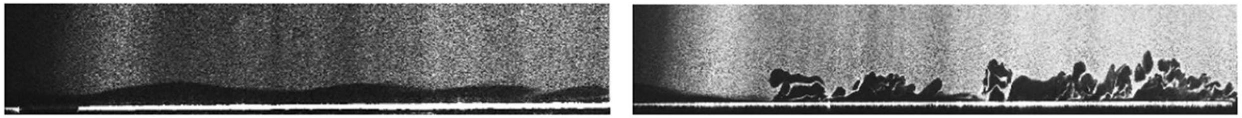
3.1.3 Porous Wall

Porous wall is considered as a passive method with high practical prospect, and its main function is to delay transition, which is of great significance to drag reduction and thermal protection of hypersonic vehicles. The instability of the second mode disturbance wave is one of the main reasons and leads to the transition in hypersonic boundary layer. The second mode has acoustic mode characteristics, so the control mode capable of absorbing sound waves generally has the potential to inhibit the growth of the second mode. In 1998, Malmuth et al. [74] was the first to discover that a porous coating capable of absorbing high-frequency sound waves can effectively inhibit the growth of the second mode. Subsequently, as a potential passive control method to delay hypersonic boundary layer transition, this porous surface has attracted the attention of a large number of scholars.

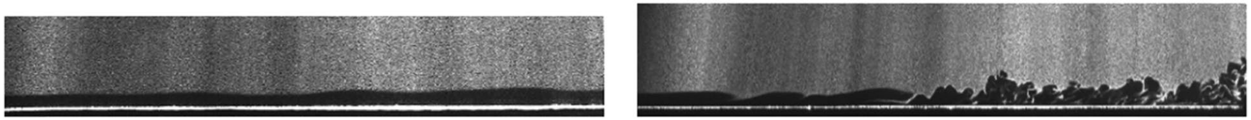
Maslov [75] confirmed the attenuation effects of the porous wall on the disturbances with more in-depth analysis. In fact, the porous wall used by Maslov is an ultrasonically absorptive coating (UAC) with conventional porosity, and “UAC” reflects the nature of the acoustic disturbance generated by the porous wall. This method can delay the transition and has a certain relationship with the acoustic mode of the hypersonic boundary layer [10]. As shown in Fig. 7, the boundary layer can be regarded as an acoustic waveguide, and acoustic disturbances such as the second mode and its higher-order harmonics propagate forward between the wall and the sonic line.

Fedorov et al. [76–80] found that the use of ultrasonic absorbing materials can inhibit the development of unstable waves of the second mode and higher frequency, and the porous wall can inhibit the transition of hypersonic boundary layer, thus increasing the Reynolds number of boundary layer transition by 50%.

Chokani et al. [81] used bispectral analysis to compare the nonlinear interaction (subharmonic resonance) of the second mode in the boundary layer of conventional wall and porous surface, in which the harmonic resonance of the boundary layer of porous surface was almost completely eliminated.



(a) Re = 6.41×10^6/m, Shooting range :195-395mm (b) Re = 6.39×10^6/m, Shooting range :395-595mm



(c) Re = 6.47×10^6/m, Shooting range :195-395mm (d) Re = 6.35×10^6/m, Shooting range :395-595mm

Fig. 6 The boundary layer structure in the presence or absence of a cavity [73]

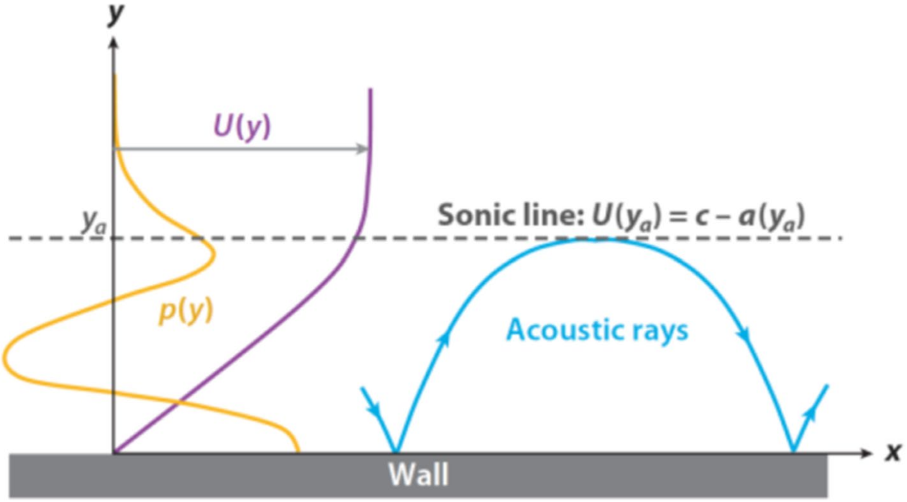


Fig. 7 Schematic diagram of acoustic modes in the hypersonic boundary layer [10]

Maslov et al. [82] also carried out comparative experiments by adding braided materials to the part of a sharp cone at Mach 6. The magnified sixty-fold image and distribution of porous materials on the model are shown in Fig. 8. The experimental results proved that this measure prolongs the laminar flow area by 15% – 66% or even longer. Based on their analysis, the porous surfaces absorb part of the energy increased by the second mode disturbance, thus weakening the development of the second mode disturbance. Therefore, the flow can still remain stable and the transition is delayed.

With the gradual deepening of the research on the influence of porous wall on boundary layer instability, the mechanism of delayed transition of porous wall also develops.

During the last 2 years, combining wind tunnel experiments and theoretical analysis, Zhu et al. [83–85] found that the permeable wall can suppress the near-wall disturbances by changing the spatial distribution of perturbations in the fundamental resonance, which disrupted the phase-locked relationship and prevented the growth of fundamental oblique waves. Meanwhile, the research also indicated that the permeable surface greatly reduced the aerodynamic heating and delayed the transition. According to the effects of permeable wall on aerodynamic heating, he inferred that the behavior of the two-dimensional structure on the permeable wall was correlated with the suppression of the growth of three-dimensional waves. The distribution and surface microstructure of the permeable material are displayed in Fig. 9, and Fig. 10 shows the effects of the permeable wall on aerodynamic heating.

The inherent control mechanism of delaying the transition can be summarized in this way. Acoustic disturbances in the hypersonic boundary layer cause violent movement of the internal air after entering the porous material. Under the action of viscous dissipation, part of the mechanical energy of the acoustic disturbance is converted into heat energy. In addition, when the acoustic disturbance in the flow passes, it will produce changes in compression and expansion. The temperature gradient between the adjacent compression zone and expansion zone could cause heat transfer from the high temperature part to the low temperature part. What's more, part of the mechanical energy of

Fig. 8 The model and the magnified sixty-fold image of the porous surface with 0.5 × 0.5 mm grid used by Maslov et al. [82]

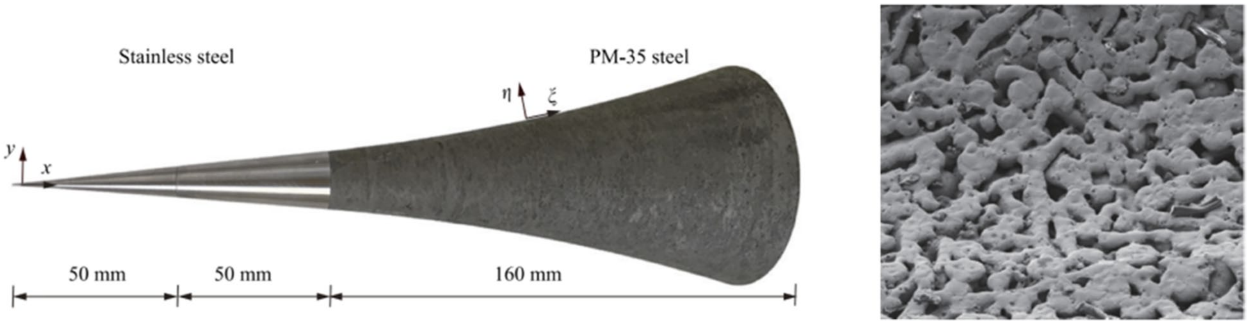


Fig. 9 The permeable wall used by Zhu et al. [85]

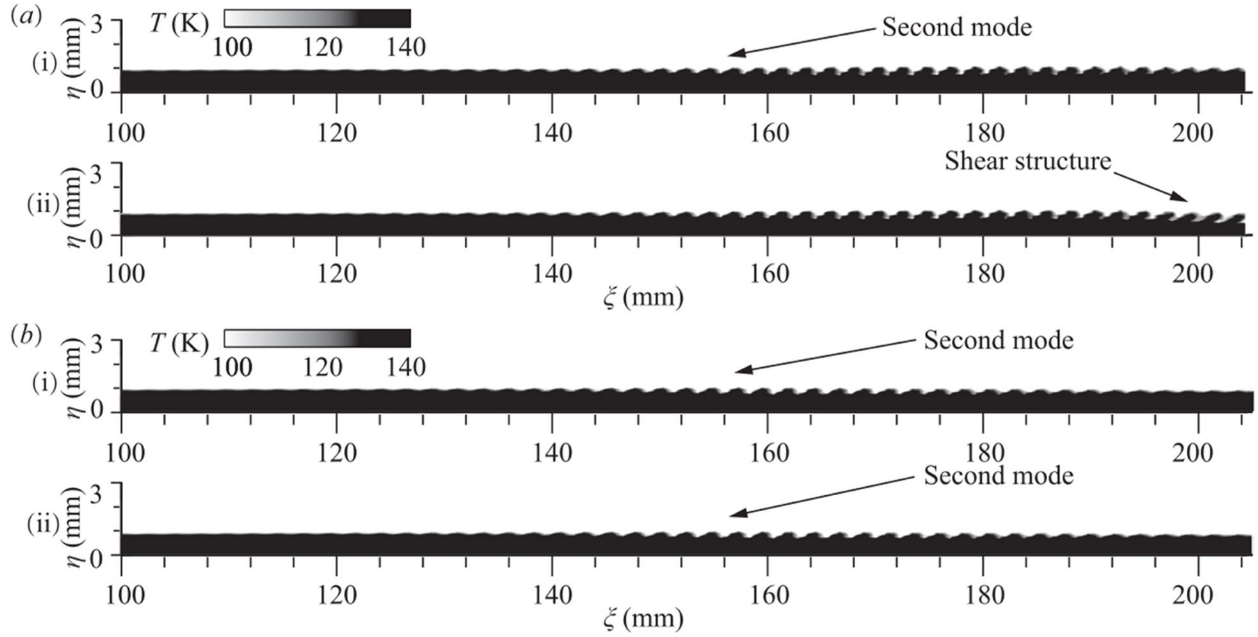


Fig. 10 Snapshot of temperature contours at various ξ–η planes: **a** smooth wall and **b** permeable wall; (i) center line of low-speed streak and (ii) center line of high-speed streak. A darker region represents a higher temperature

the acoustic disturbance will also be converted into thermal energy. Therefore, under the combined action of viscous dissipation and heat conduction, the mechanical energy of the second mode wave is converted into heat energy, and the second mode unstable wave is suppressed, thereby delaying the transition of the boundary layer [33].

However, Fedorov A also discovered that, although the porous surface could suppress the instability of the second mode, it also brings the phenomenon of low-frequency disturbances [10], which may be a problem we expect to solve in active control.

3.1.4 Wavy wall

Recently, with the emergence of various new measurement techniques, the experimental research on the stability of hypersonic boundary layer is more in-depth. Fujii studied the control effects of the wavy wall surface on the hypersonic boundary layer transition of a sharp cone with a 5° half cone angle under the condition of incoming flow $Ma=7.1$ [55]. By reasonably designing the wavelength of the corrugated rough band (about 2 times the height of the boundary layer), the boundary layer transition was effectively delayed. According to Fujii's experience, the control of transition of wavy wall surface to hypersonic boundary layer depends on the total temperature of incoming flow and the wavelength of wavy rough band to a great extent. Bountin et al. [86] also conducted experimental research on the stability of wavy walls in Mach 6 boundary layer. The plate model with wavy surface and locations of ICP and ALTP sensors and its section are exhibited in Fig. 11. The experimental results showed that the channels between wavy walls are prone to slight flow separation and reattachment, with certain interference to the flow field outside the boundary layer. However, the second mode instability wave along the wavy wall is effectively suppressed, and the laminar flow in the boundary layer is prolonged. In terms of the control mechanism, Bountin [86] agreed that the control effects of delaying transition produced by the wavy wall mainly are corrected with the basic flow, rather than directly acting on the second mode. However, in the process of his experiments, new unstable waves are noticed on the wavy wall, and the specific reasons for them are still uncertain.

In 2019, Peking University made new progress in using wavy walls to delay the hypersonic transition. Si et al. [87] attempted to weaken the local heating spot of aerodynamic heating by controlling the strength of the second-mode instability. The results provided the information that the wavy-wall can suppress the second-mode instability to a certain degree and eliminate the local heating spot before the transition is completed. Figure 12 exhibits the model Si et al. used.

As shown in Fig. 13(a), the regular periodic structures are second-mode waves. In contrast, there is no significant second-mode structure in Fig. 13(b), which means that the second-mode wave is depressed by the wavy wall. For the wavy-wall case displayed in Fig. 14(b), the hot spots have been eliminated completely.

This simple passive control method has the potential to be used in hypersonic vehicles, but its effects at different Mach numbers and Reynolds numbers still need to be further verified.

To sum up, for the negative effects in the off-design state, almost all passive control methods cannot avoid it. Passive control methods have such limitations not only in the

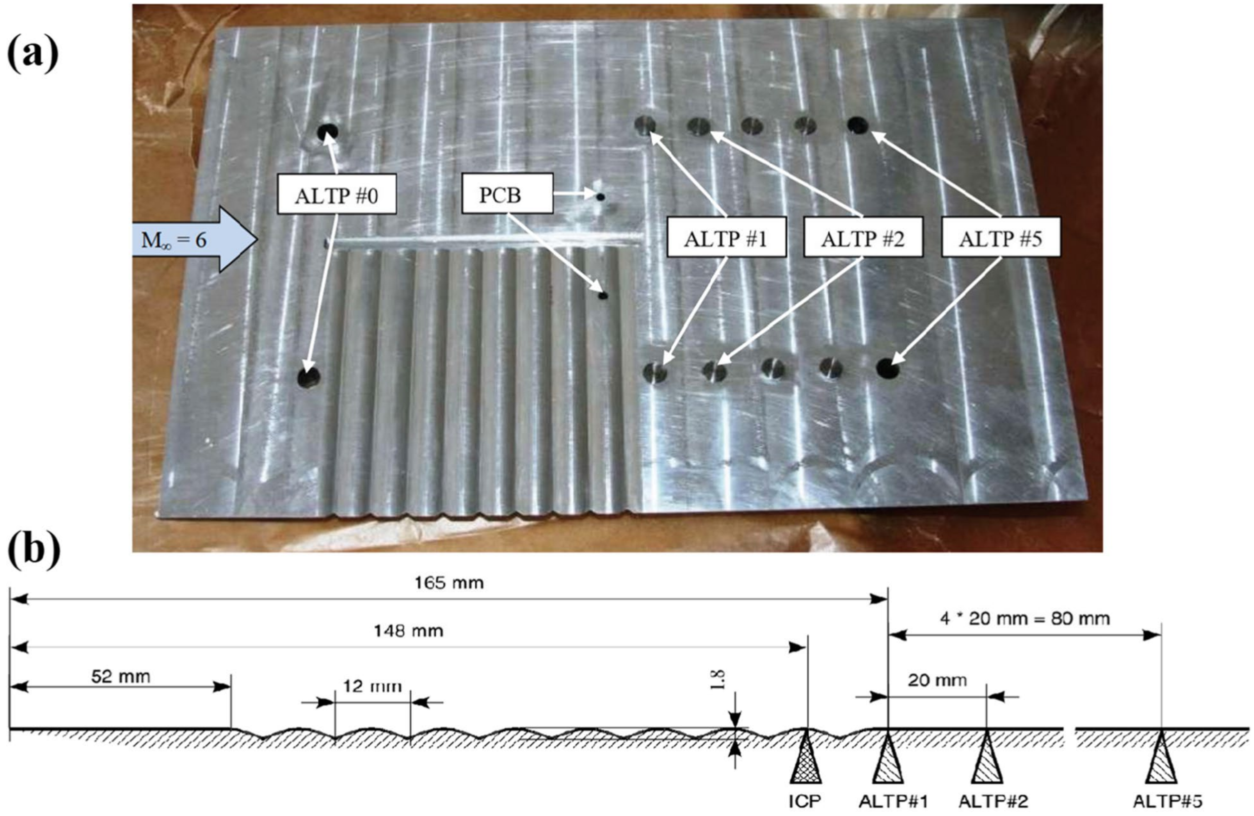


Fig. 11 Wavy wall model and sensor distribution by Bountin et al. [86]

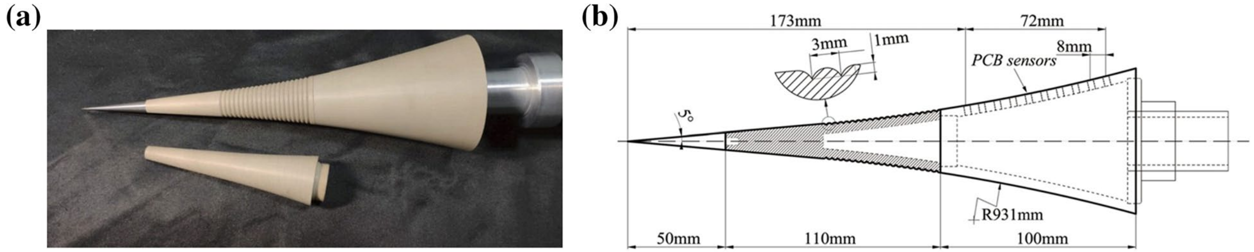


Fig. 12 Wavy wall model and sensor distribution by Si et al. [87]

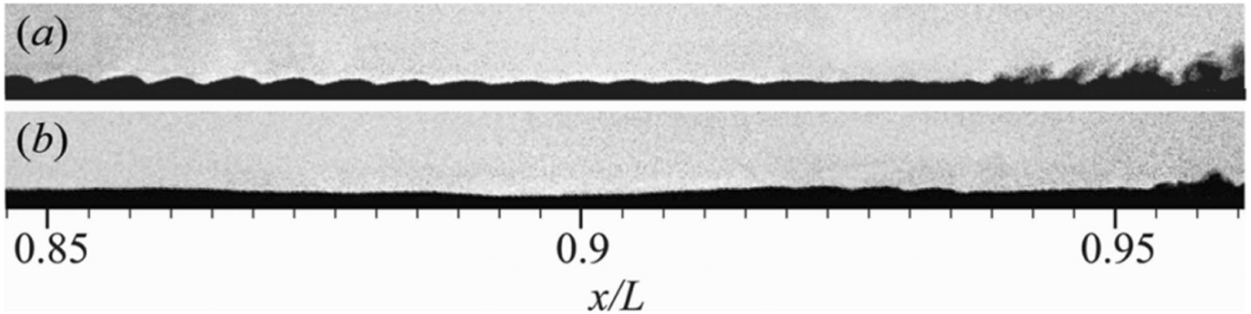


Fig. 13 Rayleigh-scattering flow visualization at $Re_{\mathrm{unit}} = 9.3 \times 10^6\,\mathrm{m}^{-1}$. The flow is from left to right. **a** Smooth wall. **b** Wavy wall [87]

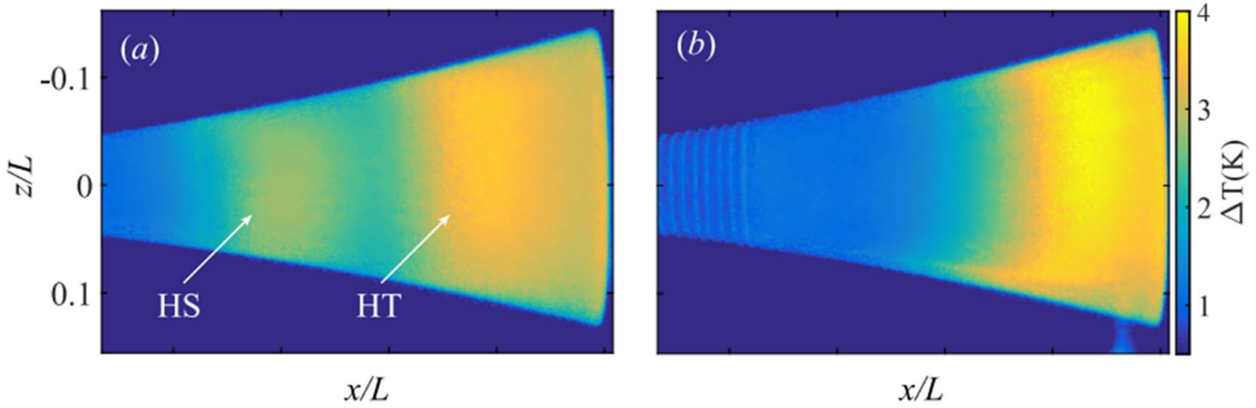


Fig. 14 Contours of surface temperature rise at four different unit Reynolds numbers: $Re_{\text{unit}} = 9.3 \times 10^6\,\text{m}^{-1}$

field of hypersonic boundary layer transition control, but also in the whole field of flow control, which also makes active transition control methods rise since the twenty-first century.

3.2 Active control

Although passive control can meet the demand to a certain extent and some achievements have been formed in engineering applications, it is difficult to achieve good results in wide speed range and working conditions due to the fixed installation position and geometric profile. In addition, it cannot be controlled in real time and most passive transition control devices often produce additional resistance and other problems.

Besides, researchers also realized that the energy injection cost paid by active flow control methods is worthwhile compared with the benefits obtained by the hypersonic transition control. Therefore, in recent years, some active flow control methods have begun to rise [88, 89].

At present, there are many methods that have achieved some exciting results or showed great potential for hypersonic flow control, including active blowing control, CO_2 injection active control technology, wall cooling/heating, local plasma discharge, and so on [90–92].

3.2.1 Active blowing (suction) control

Since the beginning of the twenty-first century, the NASA Langley Research Center has used Hyper-X model to study the active blowing control method of hypersonic boundary layer control in Mach 6 and Mach 10 wind tunnels [93]. The research objects involve a variety of opening models and blowing and sucking layouts, and different hypersonic transition control results have been obtained. The Hyper-X precursor blowing (sucking) model is displayed in Fig. 15 [94].

In the study on the active boundary layer control devices, the rough elements for passive control of the boundary layer are replaced by various blowing module assemblies. However, the experience gained from a large number of passive transition device control experiments still needs to be followed. Berry et al. [94] designed 9 active control unit configurations, as shown in Fig. 15, corresponding to 4 blowing (suction) modes, namely straight groove blowing, straight groove belt suction blowing, sawtooth groove blowing and porous blowing. A total of 14 blowing configurations were screened, and the results revealed that all configurations were effective for generating transition starting position movement. When the blowing pressure ratio is 5, the sound velocity jet condition at the nozzle can just be ensured. In order to move the transition start position near the boundary layer control device, a pressure ratio of 40 or higher is required so as to provide effective control. The sawtooth configuration requires the minimum blowing pressure ratio to produce effective transition movement. The H4 configuration with a single row of larger holes is the best in the concept of circular holes. The experimental results suggested that the active boundary layer control method for hypersonic air-breathing vehicles is feasible. At the same time, a comparative study on the effects of active and passive control methods was carried out for the same controlled object under Ma10 condition. Figure 16 displays the comparison of typical results of shock wave system. Compared with the control results of passive forced transition device, the active blowing

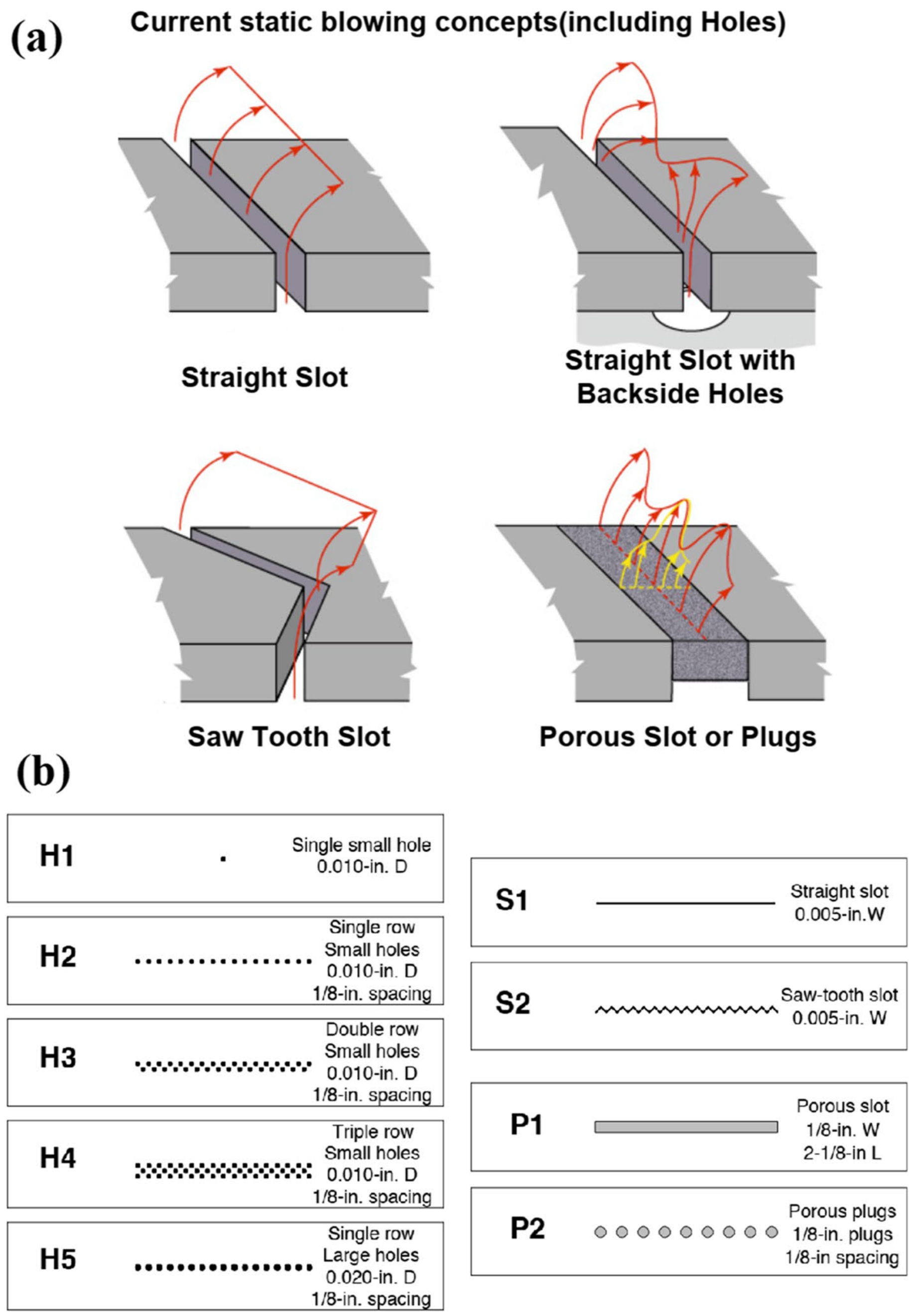


Fig. 15 Hyper-X precursor active blowing (inhaling) model [94]

is accompanied by small jet shock wave and flow separation, and the single jet penetration height cannot be directly compared with the height of the passive control device. The research results suggested that magnifying the jet height by twice is more suitable to equate the active result with the passive result, which provides a better idea for the development of active control methods in the future.

In addition, the type of blowing gas will also affect the control effects. Pappas and Okuno [95] studied the wall blowing effects of air, helium and freon-12 on

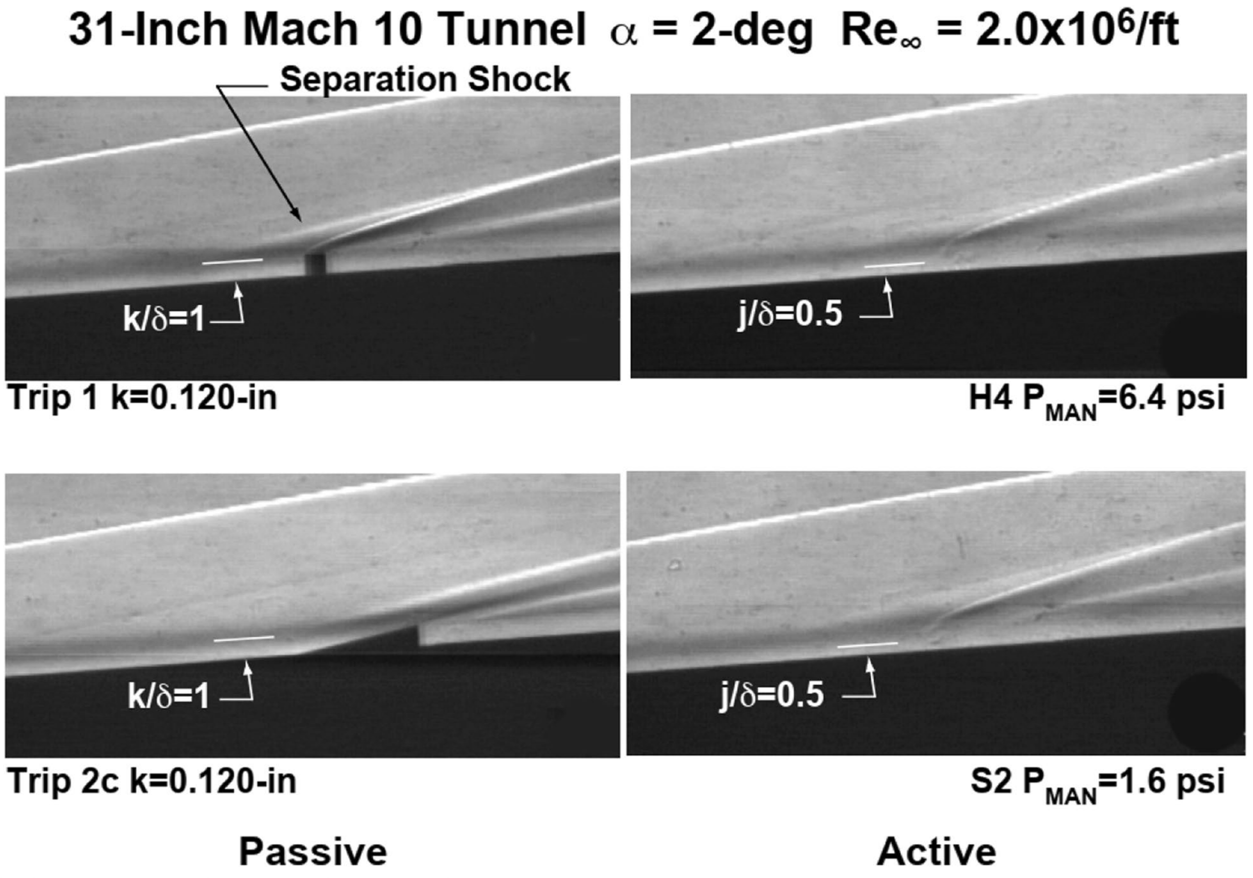
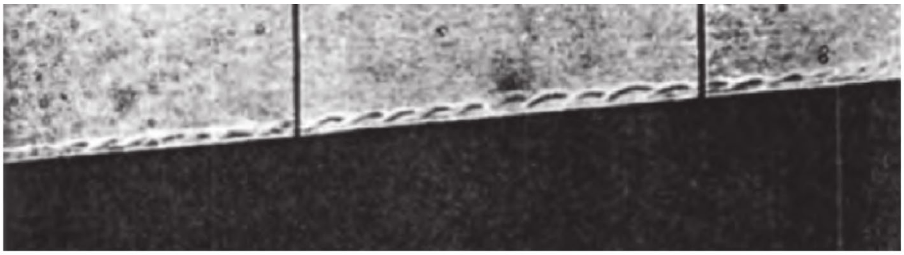
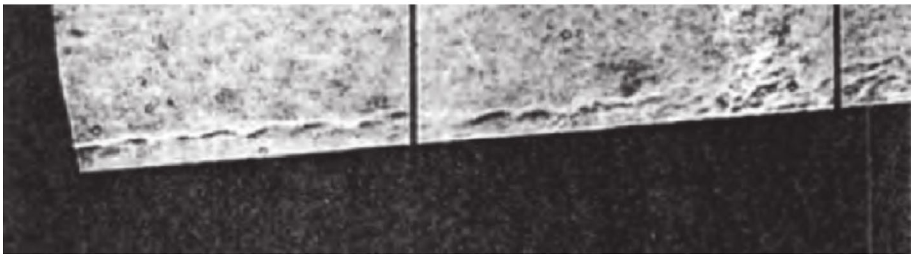


Fig. 16 Flow field and shock wave structure under passive and active control means [94]



(a) No blowing control



(b) With blowing control

Fig. 17 Schlieren diagram of secondary modal instability of conical boundary layer at zero angle of attack [97]. **a** No blowing control. **b** With blowing control

boundary layer transition on a cone model with a half cone angle of 7.5° at NASA's Ames Research Center. The research results illustrated that, under the same mass flow condition, the low-density gas helium has the greatest influence on the transition, and the heavy-density gas freon-12 has the smallest influence. Increasing the mass flow makes the transition position move forward, but the transition does not develop to the jet region.

Demetriades et al. [96] performed a study on the influence of different gas blowing effects on the transition of a cone boundary layer with a half cone angle of 5° in the Ma6 wind tunnel, and the unstable second mode disturbance wave at the outer layer of the boundary layer was observed. With the increase of mass flow rate, the instability of boundary layer intensifies, which leads to the advance of boundary layer flow transition. In addition, they also found that even a small wall blowing flow can result in the amplification and development of unstable disturbance waves in the case of angle of attack, and finally induce boundary layer transition. Schneider [97, 98] investigated and summarized the research on the influence of wall blowing effects on boundary layer transition. It was found that the blowing effects usually induce the transition to advance. The larger the mass flow rate or the lighter the composition is, the greater the transition advance caused by the gas is, and the closer the blowing effect is to the front end of the model, the greater the impacts are, as shown in Fig. 17. Therefore, the jet that appears near the tip has a very large influence on the transition of the boundary layer, which also provides a reference for the arrangement of other active flow control actuators.

The above reviews mainly focus on wall blowing, while wall suction mainly has the effects of delaying transition. Some studies displayed that this method can enhance the stability of boundary layer mainly by reducing boundary layer thickness and eliminating or weakening boundary layer velocity [99].

For wall blowing and suction control, it is quite difficult to analyze the control mechanism of blowing and suction on the hypersonic boundary layer by experiment alone. Combined with the numerical simulation research, blowing and suction are mainly adjusted by modifying the velocity profile of the boundary layer, adjusting the shape of the boundary layer, and then adjusting the movement of the fluid in the boundary layer, which could achieve the effects of controlling the transition of the boundary layer [100].

Although this technology can achieve a relatively good control effect, it is difficult to control its impacts on the aircraft/model profile at high Mach numbers, and it is easy to produce shock waves and other disturbances that interfere with the control effects or affect the boundary layer flow.

3.2.2 CO_2 injection active flow control technology

The results of Clarke and McChesney [101] illustrated that the relaxation effects of chemical reaction can damp the sound waves whose frequency is near the reciprocal of relaxation time, which opens a new door for suppressing/delaying hypersonic boundary layer transition.

In the wind tunnel test, Adam et al. [102] accidentally discovered that, when the test gas is CO_2, the transition position of the boundary layer is greatly delayed. At the same time, as the concentration of incoming CO_2 increases, the transition delay becomes more significant under certain high temperature/high enthalpy conditions.

The internal mechanism can be explained as follows. Since the transition of the hypersonic boundary layer is usually dominated by the second mode, and the second mode is an acoustic disturbance, the non-equilibrium effects on the flow can attenuate these acoustic disturbances [103].

Similarly, in the comparative study of blowing effects on different media gases in the boundary layer, researchers discovered the unique boundary layer transition control ability of CO_2 gas based on the principle of chemical reaction.

Leyva et al. [104–106] used shock wave wind tunnel system to study the effects of injecting CO_2 into hypersonic boundary layer on transition. The results demonstrated that when injecting CO_2 into boundary layer, the Reynolds number of boundary layer transition is higher than that of other injected media. The mechanism is that the vibration mode excited by CO_2 interacts with the acoustic mode in the boundary layer, and the carbon dioxide vibration relaxation absorbs the energy of the acoustic mode disturbance wave, which attenuates the amplitude of the second mode instability wave, thus delaying the boundary layer transition. Leyva et al. [105] also found that the greater the CO_2 injection rate in the boundary layer is, the more obvious the delay effects are.

John D. Schmisseur [107] summarized and prospected the active control technology research for CO_2 gas to suppress hypersonic boundary layer transition in 2015, and he pointed out that CO_2 injection active flow control technology has the advantages of sufficient gas source, convenient access and adjustable flow rate.

Here, the novel findings of the numerical simulation work must be mentioned. When the temperature is high to a certain level, the three dissociation modes of CO_2 can be excited, and the effects of the delay transition are better at this time [108]. Combined with the experimental research details, the mechanism of CO_2 injection control can be further clarified.

The vibration and dissociation of CO_2 molecules can absorb most of the energy near the second mode frequency, thus making the second mode wave grow slowly, and inhibiting the transition. Obviously, the higher the boundary layer temperature is, the better the control effects are. The threshold of temperature is the excitation temperature of CO_2 vibration.

However, from an engineering point of view, it is difficult to apply this measure under hypersonic conditions. A series of issues such as the introduction of air source and the installation of injection devices need to be considered. Similarly, the injection of CO_2 gas will also bring disturbances that we do not want to see.

3.2.3 Wall cooling/heating

In actual situations, the surface of the thermal protection system of hypersonic vehicle has uneven heat flow distribution or sometimes local ablation occurs, which has brought attention to the wall cooling/heating control methods.

Experimental studies in the last century have confirmed that by reducing the wall temperature, the heat dissipation rate of the boundary layer can be suppressed, thereby inhibiting the occurrence of transition [102].

Wall cooling [29] can stabilize T-S wave, but it will make the second mode tend to be unstable. Cooling leads to the thinning of boundary layer, which makes it more sensitive to roughness.

The thermal protection system of hypersonic aircraft is usually composed of materials with different properties, thus resulting in uneven heat flow distribution on the surface. Therefore, local wall heating or cooling may achieve better results.

Soudakov et al. [109] placed a local heating/cooling unit on the surface of a cone, and it was found that local cooling would delay the transition at Ma6, and local heating would make the transition happen earlier. Fedorov et al. [110] also maintained that local cooling can suppress the amplitude of the second mode and delay the occurrence of transition through wind tunnel test research, and local temperature distribution on the surface of the experimental model is shown in Fig. 18.

What's more, the research made by Zhao et al. [111] revealed that wall cooling can delay boundary layer transition, but wall cooling has limited laminar flow control effects on the high-speed three-dimensional boundary layer, compared with two-dimensional boundary layer.

For the control mechanism, wall heating or cooling is to cause changes of the boundary layer's thickness and the corresponding position of sound velocity line, which will lead to changes in velocity evolution of disturbance wave phase in boundary layer and migration of synchronous points, thus achieving the purpose of controlling transition.

However, this type of control method is difficult for experimental study, and requires high technical requirements for heat transfer and insulation in the control process, so it is also difficult for it to be used in engineering application.

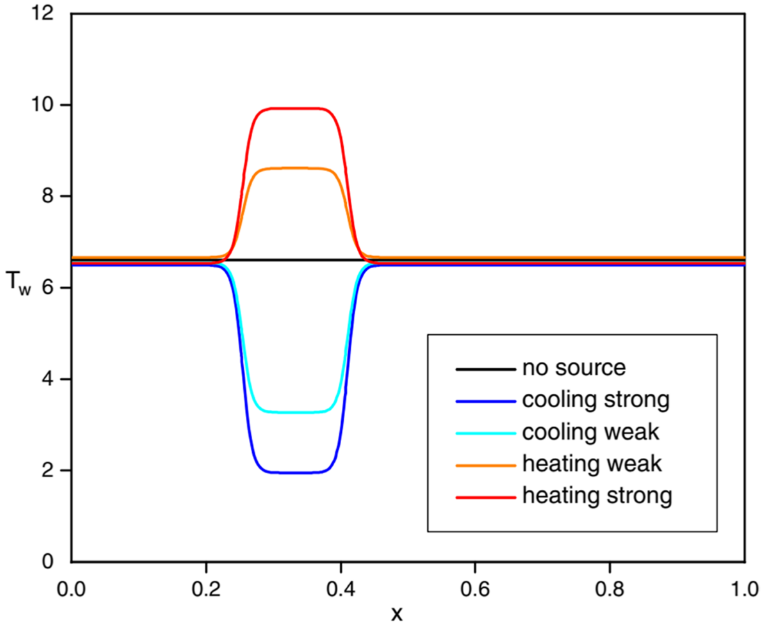


Fig. 18 Wall temperature distributions for the cases given in Ref. [110]

3.2.4 Local plasma discharge

As early as the 1990s, the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences invented a method of glow discharge to control disturbance and study wave development in supersonic flow [112]. According to Kosinov et al. [113], the disturbance introduced by glow discharge into the mainstream has the essence of acoustic disturbance, which proved that glow discharge has the potential to induce transition.

In 2001, Maslov et al. [114] applied the same disturbance method to hypersonic speed flow, and it was discovered that Tollmien-Schlichting wave excited by sound wave at the leading edge of a flat plate can affect the receptivity of hypersonic boundary layer, which indicated that glow discharge is possible to be applied as an active control method in hypersonic boundary layer transition research.

Heitmann et al. [115] used a non-intrusive pulsed YAG double-pulse laser to generate glow discharge plasma on the surface of the model, and it was further converted into acoustic disturbance in the hypersonic boundary layer. The artificial disturbance further excites the second mode unstable wave in the hypersonic boundary layer. By comparing the disturbance growth amplitudes of natural transition, forced transition and linear theory, Heitmann et al. discovered that the disturbance growth rate of unstable waves obtained by experiments is not consistent with the theoretical prediction, which further reflected that plasma discharge can be used as an active controlled artificial disturbance to exert more flexible control on boundary layer transition.

Casper et al. [116] studied in detail the development process of pulsed glow discharge on the nozzle wall of Purdue University Ma6 quiet wind tunnel, and gave the change of pressure field. In Casper et al.'s experiments, controlled disturbances were created by pulsed-glow perturbations based on the electrical breakdown of air and a disturbance first grew into a second-mode instability wave packet that is concentrated near its own centerline. Weaker disturbances spread from the center. The waves grow and become nonlinear before breaking down to turbulence. The breakdown begins in the core of the packets where the wave amplitudes are the largest. The second-mode waves are still evident in front of and behind the breakdown point and propagate in the span-wise direction. The turbulent core grows downstream, thus resulting in a spot with a classical arrowhead shape. Behind the spot, a low-pressure calm region develops. These can lay a foundation for the subsequent exploration of internal mechanism.

Recently, in the experiments carried out by Lee Cunbiao et al. [117, 118] of Peking University, glow discharge was introduced as an artificial disturbance under the condition of Ma6. Firstly, an artificially introduced disturbance in the first-mode frequency range can excite a specific second-mode wave, one of the high-order harmonics of the added disturbance. A clear harmonic relationship between the first-mode and second-mode waves was found, and the phase lock phenomenon between them was found for the first time.

Secondly, 105 kHz glow discharge in the second-mode frequency range was introduced into the boundary layer of the flat plate, and the second mode wave was evidently excited. At the same time, the amplitude of the first mode has also been significantly enhanced, and the position of boundary layer transition has been significantly advanced, which proved that glow discharge has a broad prospect in the application of hypersonic boundary layer transition control, as a controllable active flow control method. Figure 19 displays the glow discharge image created and power supply and Fig. 20 displays the results of promoting transition.

Combined with the experimental results of various test methods, the internal mechanism can be explained. There are two reasons for making the transition happen earlier. On the one hand, the increase of the amplitude of the second mode significantly changes the effects of the average flow. On the other hand, the second mode instability interacts with the first mode via a phase-lock mechanism, which leads to the rapid amplification of the first mode [118].

4 Prospect of hypersonic boundary layer transition controlled by plasma actuation

Plasma active flow control technology has the advantages of fast response, wide frequency band (response time less than 0.1 ms, frequency band 0.01-100 kHz), simple structure, no moving parts, simple adjustment of actuation parameters, low energy consumption and convenient realization of feedback control, which can solve the problems rapidly and accurately, such as plasma actuation in the control of high angle of attack flow separation [119], airfoil dynamic stall [51, 52], nacelle flow separation [120], and so on.

From the perspective of boundary layer disturbance and sensitivity, previous researchers have demonstrated the feasibility of applying glow discharge to transition control [117, 118]. However, glow plasma discharge is a weak discharge mode with very small current (generally 1-100 mA), which produces limited aerodynamic effects, while obtaining considerable control effects on hypersonic boundary layer control. At present, plasma aerodynamic actuation has been successfully applied to shock wave/boundary layer interference flow control in boundary layer control, and a breakthrough has been

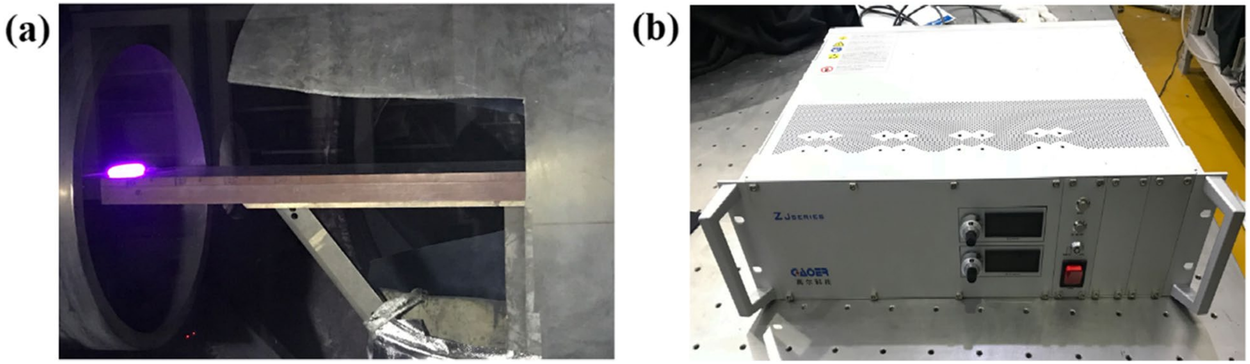


Fig. 19 Glow discharge created by Lee Cunbiao et al. and its generating power supply [118]

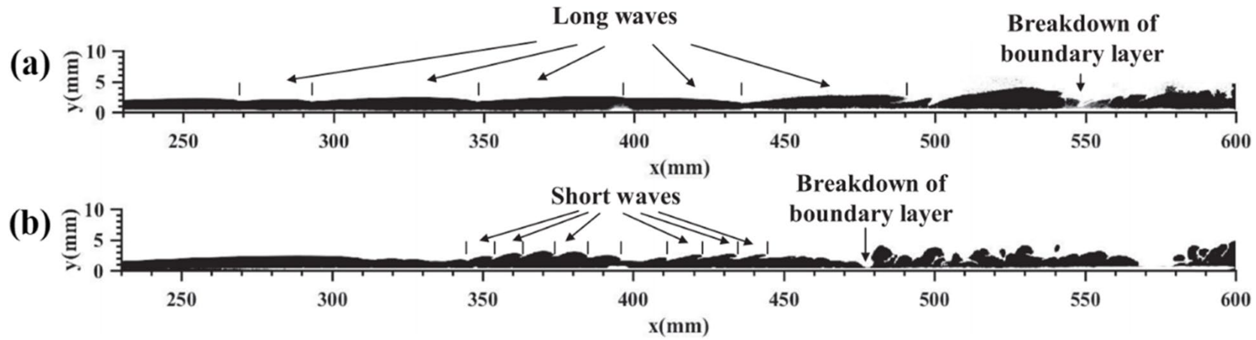


Fig. 20 Rayleigh-scattering results (side view of the centerline): **a** natural transition and **b** 105 kHz discharge [118]

made under the condition of higher Mach number [121], which was expected to make better control effects of hypersonic boundary layer transition.

In the following, in order to inspire researchers in this field, the authors will demonstrate the feasibility and introduce work prospect on plasma flow control in hypersonic boundary layer transition combined with the actual situation of the author's research team. There are three aspects, namely plasma aerodynamic actuation and its control principle, feasibility analysis of hypersonic boundary layer transition control, and follow-up key experimental research work.

4.1 Plasma aerodynamic actuation and its control principle

According to different discharge principles, the common plasma aerodynamic actuation methods can be divided into surface dielectric barrier discharge (DBD) actuation, surface arc discharge actuation and plasma synthetic jet actuation [122, 123]. The surface dielectric barrier discharge actuation can generate near-wall jet and accelerate the flow of the boundary layer, and is mainly used for the suppression of flow separation and reduction of friction drag in subsonic flow control. The surface arc plasma actuation that is heated and flowed by arc discharge plasma is mainly used for changing local flow sound velocity and thermal resistance and weakening shock wave intensity in supersonic flow control. The plasma synthetic jet actuation rapidly heats the gas in the cavity through discharge to generate high-speed jet, which is suitable for subsonic and supersonic flow control to suppress separated flow and control shock wave/boundary layer interference. The typical flow evolution process of different plasma aerodynamic actuation is shown in Fig. 21.

In 2006, the author's research team put forward the physical basis of plasma flow control. The physical principle of plasma actuation to regulate flow was summarized into three aspects [124]. (1) "Dynamic effect": Plasma formed or injected by ionization in the flow field moves directionally under the action of electromagnetic field, and neutral molecules are induced to move through the momentum transport between ions and neutral molecules to form plasma actuation; (2) "Impact effect": When some air or external gas in the flow field is ionized, local temperature rise and pressure rise are generated, and even shock waves are generated to form plasma actuation; (3)"Physical property change": The plasma in the flow field changes the physical property, viscosity and heat conduction of the airflow, thus changing the flow field characteristics. Under traditional aviation conditions, the effects of physical property change are secondary, but under hypersonic flight conditions, this effect may be highlighted. Dynamic effects, impact effects and physical property changes are consistent with the connotations of acceleration effects, heating effects and chemical effects.

After more than 10 years of development, relatively considerable control effects have been achieved in stall separation control and anti-deicing of typical wings, shock wave/boundary layer interference control and separation flow suppression of inlet and compressor with plasma actuation. On the basis of flow control effects and multi-physical field coupling simulation model, the principle of plasma flow control was summed up [123]. The main connotation includes three aspects. "Impact actuation" uses short pulse discharge to increase the peak power of discharge, generate strong temperature rise and pressure rise, and form strong pulse disturbance or even shock wave; "vortex control"

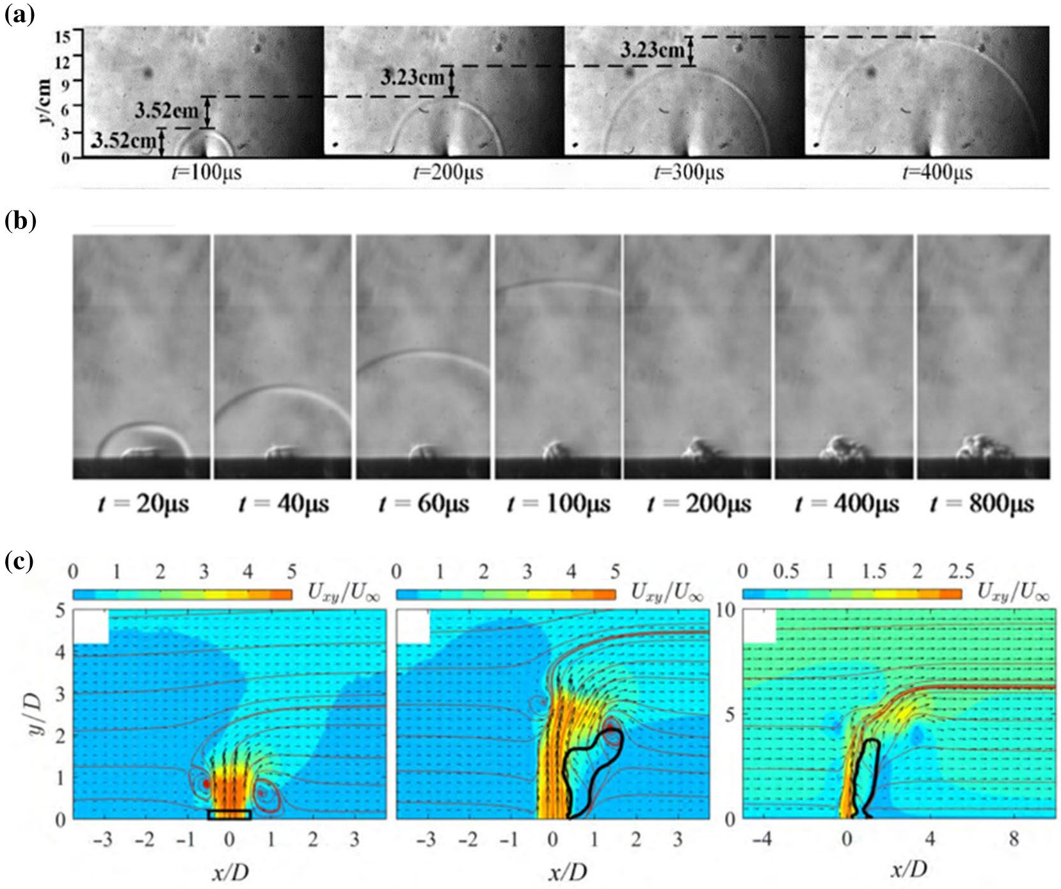


Fig. 21 Typical flow visualization results of different plasma aerodynamic actutation induced flow fields [123]. **a** Dielectric barrier discharge. **b** Arc discharge. **c** Plasma synthetic jet

generates vortex in the process of interaction with cross flow, and promotes the mixing of boundary layer and mainstream through the transport effect of vortex, thus improving the kinetic energy of near-wall flow and inhibiting flow separation; "frequency coupling" makes the pulse frequency of plasma actuation close to the characteristic frequency of flow field.

From the perspective of the nature of flow control, once the multi-physics coupling effects of plasma actuation and flow field were resolved, the flow control effect can be improved, and the power consumption can be reduced [125].

4.2 Feasibility analysis of hypersonic boundary layer transition control by plasma actuation

The key scientific problem of regulating hypersonic boundary layer transition by plasma actuation is the unsteady coupling mechanism of plasma actuation and boundary layer flow. The core of this mechanism is how plasma actuation excites or suppresses the internal instability of flow, and then promotes transition and delays transition macroscopically, including how to suppress the unstable waves and cross-flow instability of different modes and delay flow transition by plasma actuation, how to induce unstable waves and cross-flow instability to produce vortex structure with sufficient scale to promote transition, how to directly induce bypass transition, and so on. Due to experimental cost and difficulty, the research on the unsteady coupling mechanism of plasma actuation and flow is a long-term process, and plasma flow control in boundary layer transition under hypersonic conditions will also face huge challenges.

Although the transition under hypersonic conditions is complex, the plasma actuator suitable for high-speed flow field developed vigorously in recent years, which is expected to realize effective experimental measurement, and get the desired transition control effects combined with detailed boundary layer measurement methods.

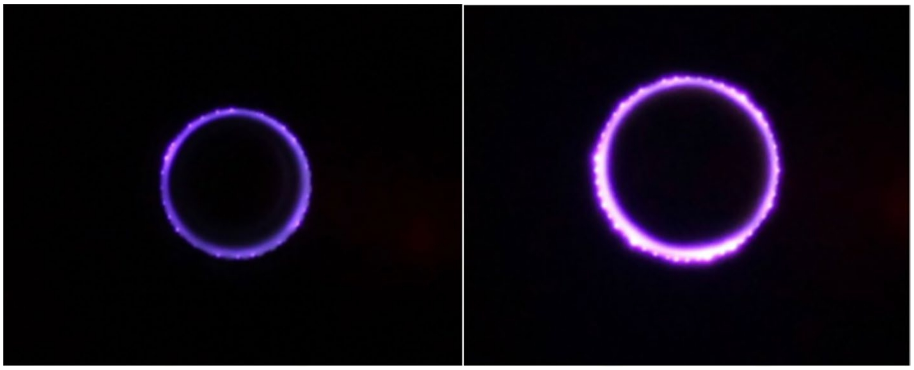
4.2.1 Dielectric barrier discharge actuator

The most important disadvantages of dielectric barrier discharge (DBD) actuators in flow control applications are low induction speed and insufficient control capability.

The research results conducted by Post and Corke [126] indicated that the maximum velocity peak value of DBD plasma actuator is about 10 m/s [127, 128]. Higher voltage input will not increase the generated plasma kinetic energy, but cause gas and electrode surface heating. At the same time, it will also cause the transition from glow discharge to arc discharge and the breakdown of barrier medium.

But in recent years, the control ability of DBD actuator in hypersonic flow has been explored with the development of actuator technology.

In 2013, Corke et al. used the DBD array at Mach 3.5 on a sharp-tipped 14° right-circular cone to explore the possibility of delaying cross-current transition of DBD actuation, and it was expected that the subcritical wavenumber plasma roughness would produce a similar transition delay as the passive roughness [129].



(a) m=32 tip to accelerate transition (b) m= 48 tip to delay transition

Fig. 22 Circumferential DBD discharge image of cone tip [131]. **a** m = 32 tip to accelerate transition. **b** m = 48 tip to delay transition

The advantage of the plasma roughness is that it can be designed to produce a range of azimuthal wavenumbers. Therefore, it is feasible to use DBD actuation to achieve delaying transition under supersonic conditions.

Nishihara et al. [130] demonstrated the feasibility of hypersonic flow control by low-temperature, repetitive nanosecond pulse discharges under Ma = 5 with the energy of 7.3–7.8 mJ/pulse, which also reflected that a remarkable advantage of DBD actuator applied to active flow control of high-speed flow field is that it consumes less power.

Based on the research made by Corke et al.,[129] in 2018, Thomas J. Juliano et al. [131] conducted an experimental research on AC-DBD (Alternating current dielectric barrier discharge) plasma-actuated flow control of hypersonic crossflow-induced boundary-layer transition in a Mach 6 quiet tunnel. A lift-off photolithography process was developed to create dielectric-barrier-discharge plasma actuators on Macor nose tips. Finally, the actuator with a wavenumber nearly equal to the most naturally amplified wavenumber was observed to accelerate transition. The actuator designed to delay the transition did not demonstrate a clear effect. Figure 22 exhibits the discharge image of DBD actuators to accelerate and delay the transition designed by Thomas J. Juliano et al.

Future tests will implement improved plasma actuators to ensure that roughness effects do not obscure the controller's effect.

With the in-depth exploration of the plasma actuation characteristics, the internal control mechanism is expected to achieve a breakthrough. In 2020, Zhang et al. [132] discovered that an asymmetrical DBD plasma actuator that was powered by sinusoidal AC waveforms with an AC voltage of $V_{p\text{-}p} = 16\,\text{kV}$ at a high voltage frequency of a few kHz can generate ultrasound in quiescent air, and the frequency of this induced ultrasound is approximately 100 kHz that is much higher than the sinusoidal high voltage frequency of a few kHz. The schlieren result is displayed in Fig. 23.

Further, the mechanism of how AC-DBD induces sound waves has been inferred and proposed. It is hypothesized that the streamer discharge in the positive-going cycle could generate some high amplitude current pulses, which can rapidly cause the heat generation [133] and the change of the gas density and pressure in the vicinity of

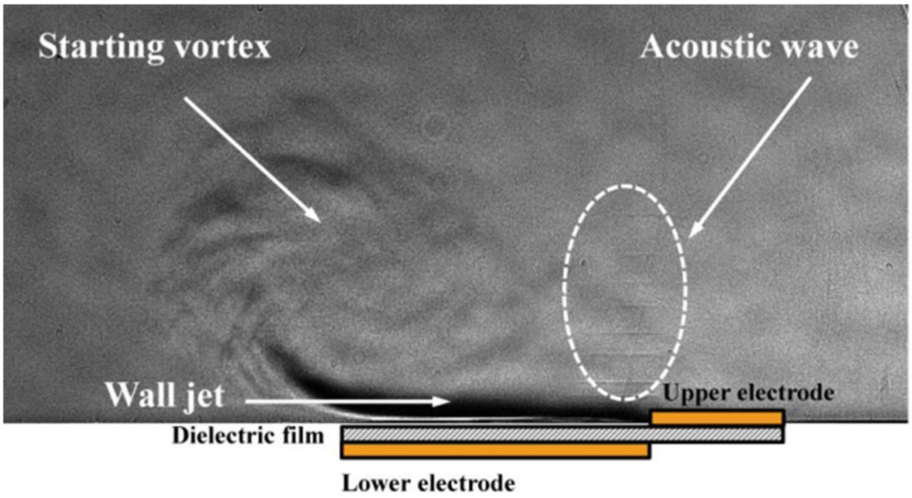


Fig. 23 Acoustic waves induced by AC-DBD actuation [132]

the surface of the AC-DBD plasma actuator. Then, acoustic waves are generated due to the pressure oscillation.

This provides conditions for the disturbance of the AC-DBD actuation injected into the flow field and the interaction of the second mode wave in the hypersonic boundary layer, which will further promote the mechanism study on the DBD actuation to control the transition of the hypersonic boundary layer.

It is foreseeable that in the transition control of the hypersonic boundary layer, the dielectric barrier discharge plasma itself acts as an energy-controllable disturbance, and it is not difficult to achieve the effects of promoting the transition. As for the transition delaying control, the special actuator setting has a certain experimental basis and theoretical analysis basis, which is expected to be realized in future wind tunnel experiments, while there is still a long way to go. After all, DBD actuation is a kind of small disturbance. The follow-up research mainly focuses on the interaction between the disturbance and the hypersonic boundary layer and the excavation of the characteristics of acoustic disturbance caused by DBD actuation.

4.2.2 Arc discharge actuator

The arc discharge actuator is mainly composed of high temperature resistant ablation electrodes arranged on the insulating plate. The difference is that the two electrodes are arranged on the same side of the insulating plate without dielectric barrier between them, compared with the DBD actuator. The actuator electrodes can be made into many different shapes, and the electrode pair and arrangement can be changed on the basis of the application needs.

At present, it is considered that the mechanism of arc discharge plasma actuator in high-speed flow control is the local density and sound velocity change caused by rapid gas heating effects. This will play a role in the transition control of the hypersonic boundary layer, and local temperature changes will have important impacts on the stability of unstable waves.

The experiment made by Leonov et al. [134] compared the arc discharge and glow discharge, the results of which implied that a weak shock wave will be formed at the arc discharge, but the pressure increase caused by the plasma discharge is not much more obvious than that caused by the glow discharge. Therefore, Shin et al. [135] and Menier et al. [136] held the view that electrostatic force also plays an important role in the flow control of plasma based on DC discharge besides gas heating effects. With the increase of input power, the control effects of plasma in dispersion discharge mode will be enhanced. When being transitioned to arc discharge, excessive power input will cause the separation of supersonic boundary layer, which showed that the arc discharge with large energy injection has the ability to induce transition advance.

The authors' research group has used a single pulse energy of 70 mJ surface arc discharge at Mach 3 to verify the forced transition capability of high-energy surface arc discharge. When the actuation frequency is 60 kHz, the flow directly transitions to turbulence at the actuation position [137]. The flow display results of forced transition are illustrated in Fig. 24.

However, high energy will bring problems, such as high cost and low efficiency. In order to overcome the shortage of high power required by arc discharge, Tang et al. [138] proposed a method to control supersonic shock wave/boundary layer interference flow by exciting the shock wave induced by high frequency and small energy array arc actuation. Through the relay action of array actuation, the original strong oblique shock wave is transformed into a flow weak compression wave front, which weakens the shock wave intensity and unsteady behavior. The significant control effects have been achieved in wind tunnel experiments at high Mach numbers and this method is expected to achieve efficient transition control effects under hypersonic conditions.

On this basis, a span-wise pulsed arc discharge array (SP-PSDA) was used by Tang et al. The author's research group controlled the transition of the flat plate boundary layer at Mach 3, and the microscopic flow structure was visualized by the nanoparticle planar laser scattering (NPLS) technology. The results indicated that surface arc discharge plasma actuation can make the transition position happen earlier [139]. Figure 25 exhibits the effects of surface arc actuation on promoting the transition and the evolution of flow field structure.

At last, a conceptual model of the hairpin vortex generation process was proposed to preliminarily reveal the control mechanism of the forced boundary layer transition using SP-PSDA. Furthermore, the model was divided into three stages: production and lift-up of the high-vorticity region, the formation of Λ vortex, and the hairpin vortex evolution.

Also at Mach 6, the author's research group also verified the transition promotion effects of surface arc discharge on a 7° half-angle cone. The control effects were mainly reflected in that the surface arc discharge promoted the growth of the second mode wave, and eliminated the characteristics of the second mode wave at a certain forward flow direction, thus making the flow become turbulent in advance. Figure 26 illustrates the power spectrum distribution at a certain flow direction position.

Above experimental studies have proved that the surface arc actuation may achieve better results in promoting the transition of the hypersonic boundary layer. In the

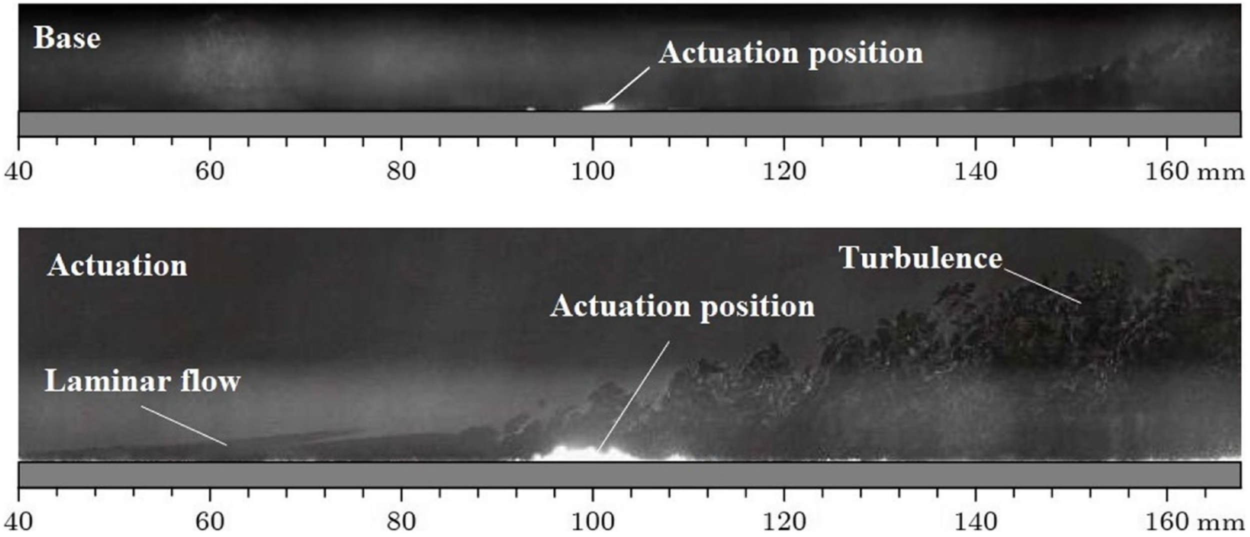


Fig. 24 Verification of the boundary layer transition control effect of high-energy surface arc discharge at Mach 3 [137]

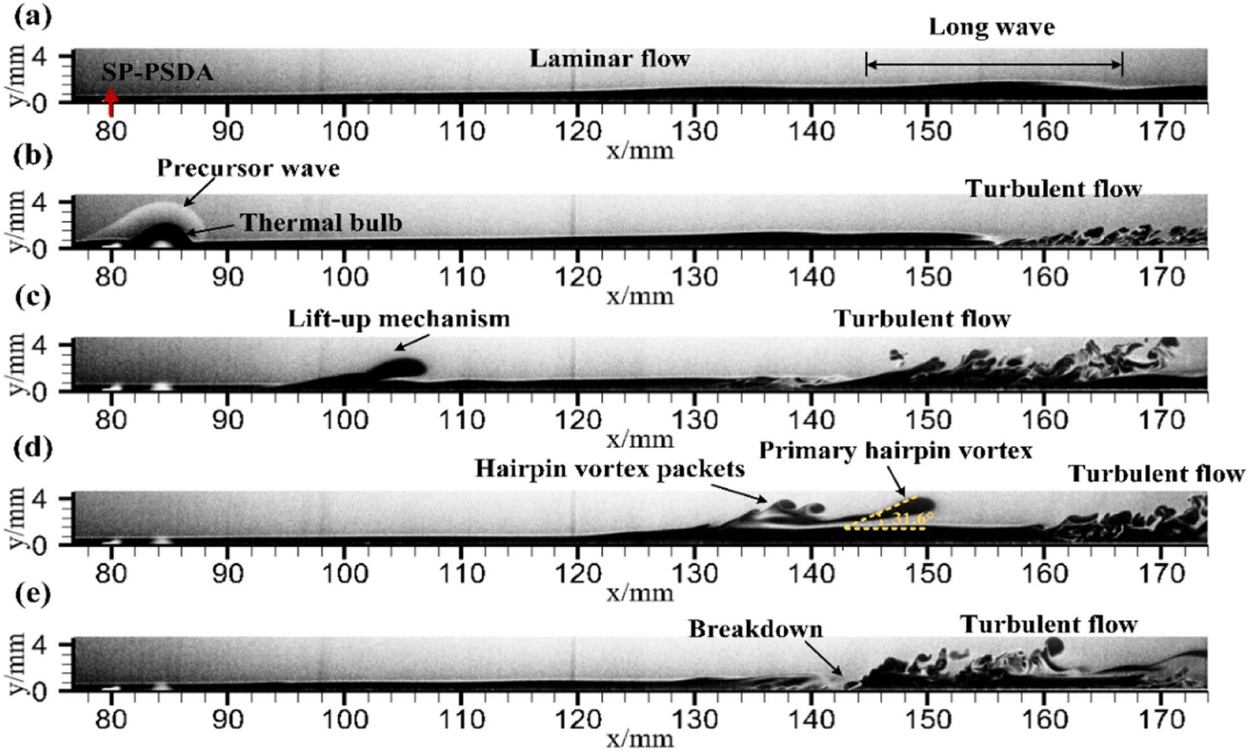


Fig. 25 The time evolution of flow field structure under SP-PSDA actuation: **a** base; **b**-**e** actuation [139]

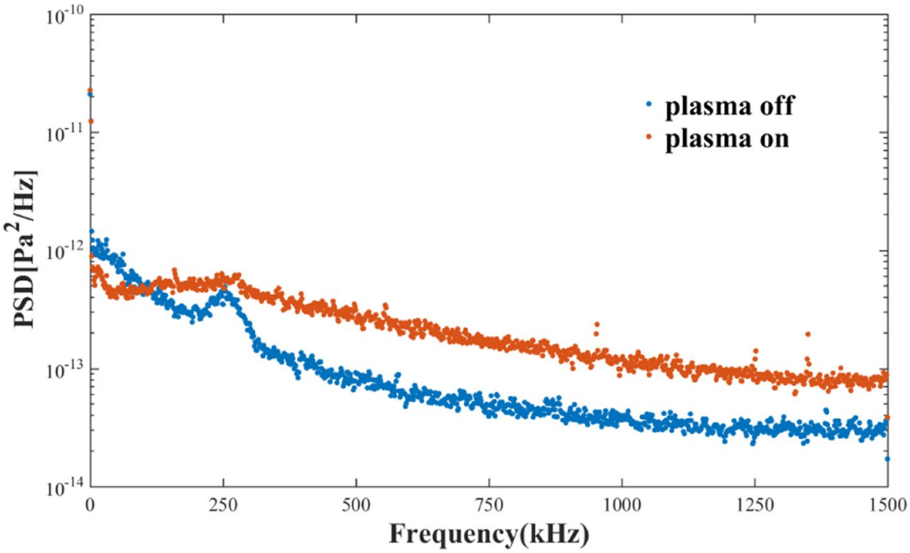


Fig. 26 The distribution of power spectral density of modal wave in a certain flow direction

follow-up, attention should be paid to the study of parameter law, aiming to form a functional relationship between the injected energy and the effects of promoting transition.

4.2.3 Plasma synthetic jet actuator

Compared with the dielectric barrier discharge plasma actuator, surface arc plasma actuator and traditional synthetic jet actuator, the plasma synthetic jet actuator is the only new actuator that combines simple structure (electrode and cavity), high jet velocity (> 500 m/s) and wide working frequency band (> 5 kHz) [140], which has attracted much attention in the field of low speed and supersonic active flow control [141, 142].

The plasma synthetic jet actuation mainly controls the external flow through four major disturbance characteristics: shock wave, vortex ring, high-speed jet and weak suction, as displayed in Fig. 27.

In higher speed flow control applications, the experimental results of Ref. [135] showed that, in the supersonic flat plate flow with $Ma = 3$, plasma synthetic jet can cause local separation and the thickening of boundary layer. The “penetration” distance to the boundary layer can reach 6 mm. Based on the hypersonic boundary layer transition control effects corresponding to different rough element heights, this distance is enough to affect the stability of the boundary layer, and achieve considerable control effects, which makes the plasma synthetic jet a new active control method with the application prospects for hypersonic boundary layer transition control.

Under the hypersonic flow conditions, the disturbance generated by the plasma synthetic jet actuator should be carefully analyzed. Within a certain range of injected energy, since the shock wave velocity is lower than the mainstream velocity, the shock wave can only propagate downstream. After the jet is ejected, the velocity ratio will be relatively low, and the penetrating ability will be weak. It is possible to basically remain attached to the wall. Therefore, the plasma synthetic jet actuator may only be equivalent to a virtual vortex generator, so as to produce an obvious contra-rotating

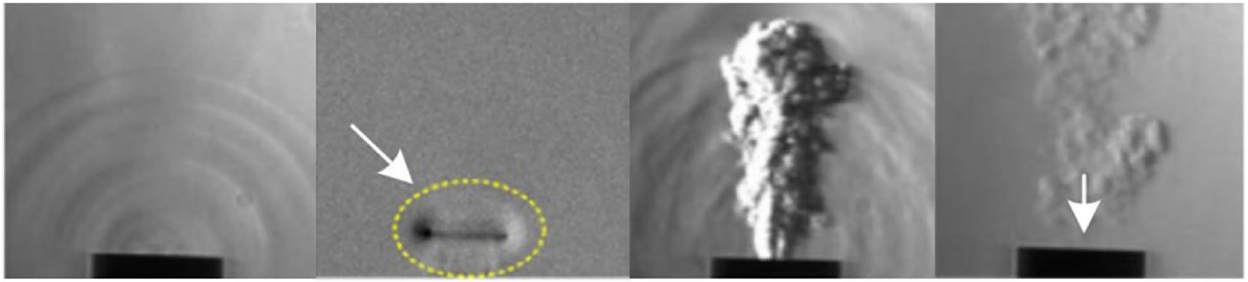


Fig. 27 Disturbance of plasma synthetic jet actuator to flow field [143, 144]

vortex pair structure [145]. However, the up-washing and down-washing effects of these vortex structures may produce the same effect as wall blowing: To modify the velocity profile of the boundary layer, and ultimately achieve the effects of promoting transition. The weak suction effects of the plasma synthetic jet should be specially studied in the hypersonic boundary layer, because the suction effects may bring about the effects of delaying transition [146].

Besides, the working characteristics of the plasma synthetic jet actuator are affected by the size of the energy deposition, the size of the actuator cavity and the outlet. In addition, only relying on gas discharge heating limits the relative temperature rise that is generated by the actuator under high temperature conditions.

In view of these limitations, Luo et al. [147] created the self-sustained suction-blowing synthetic dual jet actuator that was used to control the supersonic/hypersonic flow field. It can suck fluid from the high-pressure area of the high-speed airflow and discharge the gas from the low-pressure port to produce a self-sustaining circulating jet. Numerical simulation has verified its control effects of the hypersonic compressible boundary layer flow separation in the inlet [148]. Subsequent development and research can focus on “plasma self-sustained blowing synthetic jet actuator”, which can absorb the advantages of low energy consumption and physical property changes for plasma actuation.

Therefore, using plasma synthetic jet actuation to control the hypersonic boundary layer transition is much promising. However, it should be noted that the plasma synthetic jet itself is a cavity, so the impacts on the boundary layer should be considered, which may affect the subsequent engineering applications.

4.3 Follow-up key experimental research work

4.3.1 Overall planning

Firstly, the effects of boundary layer transition control under hypersonic conditions were verified. To prove the control ability of various plasma actuation methods, the author’s team has carried out effect verification experiments at Mach 3 and Mach 6, and achieved a satisfactory transition promotion effect [137]. From the NPLS flow field display results, the transition mechanism under the condition of relatively large energy injection was similar to bypass transition, which needs further study. For the results of the supersonic boundary layer transition induced by high repetition frequency and low energy actuation, how the plasma affects the unstable wave of the first mode is still unclear. From the unstable wave power spectrum measured in the hypersonic wind tunnel experiment, the plasma can interact with the unstable wave in the boundary layer at hypersonic speed.

Subsequently, from the perspective of promoting transition, investigating the influence law of parameters is the main research direction, especially the parameters of plasma actuation itself, such as actuation frequency, actuation voltage, and single-pulse injection energy. For example, being inspired by relevant works of Peking University, introducing frequency actuation of the same order of magnitude as characteristic unstable wave and trying different energy injection may be the key to obtain a more ideal control effect.

Compared with promoting, delaying transition is more challenging. First, for the natural transition of basic models such as cone and flat, trying the idea of small disturbance mainly to innovate the layout of the DBD actuator and see if it can induce the growth of the first mode wave can interact with the second mode wave, thus achieving surprising control effects of suppressing transition, while it is quite difficult. For the cross-flow transition, the research can be continued on the basis of the research conducted by Thomas J. Juliano et al.

Secondly, excavating the acoustic disturbance phenomenon of plasma actuation in the flow field, including AC-DBD actuation, may be a breakthrough, and the mechanism of plasma acoustic disturbance and the second mode wave can be explored by adjusting the parameters.

Finally, the jet flow was tried to observe if the velocity perturbation can eliminate or weaken the inflection point of the boundary layer velocity profile, thus achieving the purpose of enhancing stability and delaying transition. Based on these gradual research, the effects of delaying the transition are expected to be obtained.

It can also start from the control mechanism of the passive transition control method that delays transition at present, aiming to investigate whether plasma actuation can replace the passive control method under certain parameter settings under a certain combination of fixed parameters. However, if there is a control effect in this way, the internal mechanism is difficult to explain.

According to the above work, the corresponding transition path was studied, through the accumulation of experimental parameter combinations. It was determined whether the plasma actuation parameters can be changed to achieve different transition paths for different kinds of actuation style (dielectric barrier discharge actuation, arc discharge actuation, plasma synthetic jet actuation). In addition, the theoretical analysis was combined to summarize the effects of plasma aerodynamic actuation on boundary layer flow and related dimensionless law. The coupling mechanism between them can further reveal and enrich the intrinsic physical mechanism of hypersonic boundary layer transition. At the same time, the control method was optimized, and a universal wind tunnel experimental control scheme can be given to provide a data basis for subsequent flight tests.

4.3.2 Outlook of experimental strategy

In terms of control strategy, in addition to the basic research and mechanism research discussed above, the research in combination with engineering background is also very important. Hypersonic vehicles often encounter physical damage or high temperature ablation in actual flight, thereby forming irregular bulges or depressions on their thermal protection system [149], which is not easy to simulate in wind tunnel experiments, because once this irregular structure is formed during flight, it is impossible to change its own structure, and the experimental research for actual flight conditions is still insufficient. However, we can try active flow control methods in this situation to realize real-time control under specific conditions, so as to affect the stability of the boundary layer before and after these irregular bulges or depressions. Additionally, it can also be considered to apply corresponding passive control in some transition scenes where hypersonic vehicles do not need special active parameter adjustment control, and apply plasma actuation in situations where flexible control is required, so as to develop active and passive combined control and realize the maximum utilization of resources.

In terms of experimental technology, we should focus on solving the problem of low-pressure discharge, namely discharge stability. The stability of gas discharge is very important to realize the regulation of plasma parameters and obtain stable plasma treatment effect, while there are many factors affecting the stability of discharge and the mechanism is complex. During the discharge, the stability of discharge is affected by current density, electrode structure and material, plasma-sheath interaction, external electromagnetic field, gas flow and mass and energy transport process of different kinds of charged particles in plasma. Especially in the field of hypersonic plasma flow control, the high gas velocity and low gas pressure pose great challenges to the stability of plasma discharge. In addition, minimizing the influence of the existence and arrangement of actuators on the stability of boundary layer is also a problem that should be considered at all times. On the basis of solving these problems, array actuation can be developed to improve the control effects. Of course, this will face great challenges.

In terms of specific experimental schemes and methods, from the perspective of energy injection, the focus is on nanosecond-pulsed plasma discharge. Nanosecond pulse actuation can produce rapid temperature rise and pressure rise locally in the flow field. In terms of the type of plasma disturbance, AC plasma actuation is the focus of research. The experiments have displayed that AC discharge can generate acoustic waves [132]. As for the experimental measurement technology, it is necessary to focus on the development of measurement methods that can reflect the time series flow field, such as high-precision flow display technology. In the selection of measurement technology, it is necessary to prevent the measured control effect from being "averaged", because plasma actuation is not always constant actuation and some actuation methods are pulsed. What's more, we should devote ourselves to the study of high-frequency actuation, especially introducing disturbances with similar frequencies to the first mode and the second mode waves. Here, radio frequency plasma actuation can be considered.

Being inspired by ablation, plasma synthetic jet relies on gas discharge heating to produce mass jet by gas-liquid mixing, so a new method of plasma mass injection for forced transition can be developed. Trying to combine CO_2 injection with plasma synthetic jet to form plasma synthetic CO_2 jet may be a good attempt.

Considering the ionization of boundary layer gas for the high temperature gas effects at high speed, Lorentz force effect produced by magnetic fluid control principle can adjust boundary layer velocity profile for ionized gas, and then exert influence on flow stability. The electron density and conductivity in the boundary layer of aircraft are low, the actual control effect may not be obvious, the engineering implementation is expensive, and the cost performance and feasibility of magnetic fluid control can be reevaluated in the research above $Ma = 10$, because the ionization effects of gases below $Ma = 10$ are not obvious [29].

Theoretically, transition control should be combined with transition prediction research. Hypersonic wind tunnel experiments are expensive, so LST theoretical analysis, direct numerical simulation and other means should be used to guide experiments to prevent unnecessary trial and error. Furthermore, it is necessary to study the nonlinear dynamics of plasma discharge and the nonlinear development of disturbance during transition. The nonlinear dynamic process in plasma system not only affects the discharge mode and mode conversion mechanism of plasma, but also leads to physical phenomena such as chaos. In addition, the strong coupling effect between flow field and chemical reaction field (such as the interaction between plasma jet/shock wave and hypersonic boundary layer), large changes in local environmental pressure (such as the evolution of flow state from laminar flow to turbulent flow under different transition paths), strong electric field disturbances (such as high-voltage pulsed discharge plasma) and complex chemical reactions (such as relaxation effect) will also lead to the plasma system showing nonlinear dynamic behaviors related to these strong disturbances, due to the high-speed gas flow and temperature field that may accompany the gas discharge process [150]. These complex effects inspired us to study how the physical property changes caused by plasma aerodynamic actuation will affect the stability of hypersonic boundary layer, which may play a vital role in establishing the unsteady coupling mechanism between plasma actuation and boundary layer flow.

To sum up, the coupling mechanism between plasma aerodynamic actuation and boundary layer flow is the theoretical treasure to be obtained finally. The future research direction is to investigate the interaction principle between plasma aerodynamic actuation and various unstable disturbances in the boundary layer. To achieve it, hypersonic wind tunnel experiments with high reliability will be carried out, and numerical simulation research and analysis also should be conducted to clarify the action principle of plasma aerodynamic actuation under the condition of hypersonic to broaden the application boundary of plasma flow control.

Obviously, the development direction of plasma flow control will be oriented to hypersonic speed in the future development trend. If plasma flow control technology achieves a breakthrough in hypersonic boundary layer transition control, it will achieve wide-speed range active control from low velocity to hypersonic velocity, which may bring new things to the aerodynamic layout design of the aircraft.

5 Summary and prospect for boundary layer transition control methods

The hypersonic boundary layer transition control technology greatly affects the development of hypersonic aircraft. The research progress of ground experiments from the two categories of passive control methods and active control methods was mainly introduced in this paper, the control effect was sorted out, and the control mechanism was summarized. Also, the advantages and disadvantages of different methods were analyzed as well.

Finally, combined with the actual engineering application, the development direction of these control methods and the focus of future research were prospected on the basis of existing research.

5.1 Rough element

For rough elements, the future will mainly face the background of forced transition, and the matching of different types of rough elements with the intake of new hypersonic aircraft needs to be continued. Besides, the study on irregular protrusions or depressions on the surface of the aircraft during actual flight caused by ablation, physical damage, joints, and the flow behind the rough element need to be focused on later.

5.2 Cavity

For the cavity structure, we must clearly realize that there are inevitable cavities, grooves and other structures on the surface of hypersonic vehicles. The situation that these structures trigger transition and make transition advance is inevitable. How to carry out the work from the control point of view is the direction of our efforts. Li et al. [151] carried out experimental research on the influence of spanwise cavity and discharge hole on the transition of hypersonic flat plate boundary layer. It was observed that the spanwise cavity promotes the transition position at Mach 6. However, the combination of the groove and the discharge hole can delay the transition of the central symmetry plane, which provides ideas for subsequent research. From the control point of view, this combination can reduce the adverse disturbance of the cavity to the downstream without completely delaying the transition.

This interesting result provides a new idea for our choice of transition control method. The combination of different control methods may achieve unexpected control effects. Even in practical engineering applications, some measures can be taken to reduce the unfavorable disturbance for downstream caused by surface ablation and other reasons.

5.3 Porous Wall

The control effects of porous surface will be affected by the opening rate, pore radius, depth, arrangement and cross-sectional shape of the surface. The porosity is one of the most important parameters. The experimental results [81] indicated that the inhibition of porous surface on the second mode increases with the increase of porosity. However, the research on parameter optimization is mainly numerical simulation, and focuses on the analysis of optimal opening rate and hole radius, which still needs experimental verification urgently, and also the center of future research for porous wall.

What's more, the thermal protection material on the surface of hypersonic aircraft is usually braided structure, and its roughness height is generally millimeter or below. The braided material essentially introduces two effects, namely the roughness effect and the porous media effect. Therefore, porous wall technology can be combined with thermal protection technology to realize the innovation of thermal protection materials in the future, thus making the effects of delaying transition better.

5.4 Wavy wall

As a simple passive control method, wavy wall has the potential to be used in hypersonic vehicles, while its control effects at different Mach numbers and Reynolds numbers need to be further verified.

5.5 Active blowing (suction) control

The impacts of active blowing (suction) control devices on the profile of aircraft at high Mach numbers are the focus of future research. If this problem can be better solved, this method is likely to be applied in engineering, because this method is one of the few control methods that can achieve both the promotion of transition and the delay of transition.

5.6 CO_2 injection active flow control technology

For CO_2 injection active flow control technology, on the one hand, the excitation of CO_2 vibrational energy is limited by temperature, and it is difficult to achieve a stable control effect, which should be started from the perspective of molecular science, and some measures should be taken to promote the vibration and dissociation of carbon dioxide molecules. On the other hand, a series of issues such as the introduction of air sources and the installation of injection devices also need to be considered. The miniaturization of air sources and injection devices will be the focus of future research.

5.7 Wall cooling/heating

For wall cooling/heating control method, whether the heat transfer and heat insulation technology in the control process can adapt to the rapid changes of high-altitude physical parameters requires careful research. Besides, how to recycle heat may need to be emphatically considered to improve the cost-effectiveness of the control method.

5.8 Plasma flow control

The current hypersonic boundary layer transition delay control technology is mostly facing to the second mode instability, and there are few studies on the lateral flow stability and the first mode instability, while the control requirements for these instability modes are very urgent [33]. Therefore, as the demand for transition control becomes more refined, exploring the possibility of transition control technology that can control multiple unstable modes will become the focus of research.

As a new type of active flow control method, plasma has certain advantages, with the potential to control a variety of unstable modes and the ability to obtain effects of promoting transition and delaying transition control.

On the contrary, judging from the effects of hypersonic boundary layer flow control achieved by plasma actuation at present, it is still relatively gossamer. For hypersonic boundary layer transition control, passive control is still the mainstream, and some passive control methods are likely to achieve large-scale engineering applications, while combined control is a satisfactory path. The advantages of plasma can be combined to eliminate the negative effects of passive devices, or plasma actuation can be used for supplementary control. The author agreed that this is possible in the current development stage of plasma flow control technology.

In summary, the development of multi-modal transition control technology, with wide speed range, low energy consumption and adjustable effects, is a long way to go. In the future, the accumulation of ground wind tunnel experiments, verification of numerical simulations, in-depth mining of mechanisms, and breakthrough in flight test obstacles are needed to support the thermal protection, aerodynamic characteristics and stability of the propulsion system of a new generation of hypersonic vehicle.

Acknowledgements
Not applicable.

Authors' contributions
All the authors contributed to and approved this manuscript.

Funding
Not applicable.

Availability of data and materials

The data and materials are available upon request.

Declarations

Competing interests

The authors declared that they have no competing interests.

Received: 28 September 2021 Accepted: 29 January 2022

References

1. Luo C, Lei H, Li J et al (2020) A new adaptive neural control scheme for hypersonic vehicle with actuators multiple constraints. Nonlinear Dyn 100:3529–3553
2. Wadhams TP, Mundy E, MacLean MG et al (2008) Ground test studies of the HIFiRE-1 transition experiment part 1: experimental results. J Spacecr Rockets 45(6):1134–1148
3. Kendall JM (1975) Wind tunnel experiments relating to supersonic and hypersonic boundary-layer transition. AIAA J 13(3):290–299
4. Chen J, Yi S, Li X et al (2021) Theoretical, numerical and experimental study of hypersonic boundary layer transition: blunt circular cone. Appl Therm Eng 194:116931
5. Schneider SP (2004) Hypersonic laminar–turbulent transition on circular cones and scramjet forebodies. Prog Aerosp Sci 40(1–2):1–50
6. Nayfeh AH (1980) Stability of three-dimensional boundary layers. AIAA J 18(4):406–416
7. Li X, Fu D, Ma Y (2010) Direct numerical simulation of hypersonic boundary layer transition over a blunt cone with a small angle of attack. Phys Fluids 22(2):025105
8. Chen X, Huang GL, Lee CB (2019) Hypersonic boundary layer transition on a concave wall: stationary Görtler vortices. J Fluid Mech 865:1–40
9. Oddo R, Hill JL, Reeder MF et al (2021) Effect of surface cooling on second-mode dominated hypersonic boundary layer transition. Exp Fluids 62(7):1–18
10. Fedorov A (2011) Transition and stability of high-speed boundary layers. Annu Rev Fluid Mech 43:79–95
11. Schneider SP (2015) Developing mechanism-based methods for estimating hypersonic boundary-layer transition in flight: the role of quiet tunnels. Prog Aerosp Sci 72:17–29
12. Lee C, Jiang X (2019) Flow structures in transitional and turbulent boundary layers. Phys Fluids 31(11):111301
13. Chen JQ, Tu GH, Zhang YF et al (2017) Hypersonic boundary layer transition: what we know, where shall we go. Acta Aerodyn Sin 35(3):311–337 (in Chinese)
14. Yang WB, Shen Q, Zhu DH et al (2018) Tendency and current status of hypersonic boundary layer transition. Acta Aerodynamica Sinica 36(2):183–195 (in Chinese)
15. Huang ZF, Wan BB, Duan MC (2020) Progresses in engineering application research on hypersonic flow stability and transition. Acta Aerodynamica Sinica 38(2):368–378 (in Chinese)
16. Kachanov YS, Kozlov VV, Levchenko VY (1982) Origin of turbulence in boundary layer. Nauka, Novosibirsk (in Russian)
17. Lee C, Chen S (2019) Recent progress in the study of transition in the hypersonic boundary layer. Natl Sci Rev 6(1):155–170
18. Liu XH, Lai GW, Wu J (2018) Boundary-layer transition experiments in hypersonic flow. Acta Aerodyn Sin 36(2):196–212 (in Chinese)
19. Chen WL, Chen GB, Xu F et al (2020) Suppression of vortex-induced vibration of a circular cylinder by a passive-jet flow control. J Wind Eng Ind Aerodyn 199:104119
20. Acarer S (2020) Peak lift-to-drag ratio enhancement of the DU12W262 airfoil by passive flow control and its impact on horizontal and vertical axis wind turbines. Energy 201:117659
21. González-Salcedo Á, Croce A, León CA et al (2020) Blade design with passive flow control technologies. In: Stoevesandt B, Schepers G, Fuglsang P, Sun Y (eds) Handbook of wind energy aerodynamics. Springer, Cham
22. Cattafesta LN III, Sheplak M (2011) Actuators for active flow control. Annu Rev Fluid Mech 43:247–272
23. Collis SS, Joslin RD, Seifert A et al (2004) Issues in active flow control: theory, control, simulation, and experiment. Prog Aerosp Sci 40(4–5):237–289
24. Li J, Zhang X (2020) Active flow control for supersonic aircraft: a novel hybrid synthetic jet actuator. Sens Actuator A Phys 302:111770
25. Aley KS, Guha TK, Kumar R (2020) Active flow control of a high-lift supercritical airfoil with microjet actuators. AIAA J 58(5):2053–2069
26. Huang G, Dai Y, Yang C et al (2021) Effect of dielectric barrier discharge plasma actuator on the dynamic moment behavior of pitching airfoil at low Reynolds number. Phys Fluids 33(4):043603
27. Tadjfar M, Kasmaiee S, Noori S (2020) Continuous blowing jet flow control optimization in dynamic stall of NACA0012 airfoil. Proceedings of the ASME 2020 fluids engineering division summer meeting collocated with the ASME 2020 heat transfer summer conference and the ASME 2020 18th international conference on nanochannels, microchannels, and minichannels, Virtual, Online, July 2020, vol 2. ASME, New York, V002T03A029
28. Yang H, Liang H, Zhao G et al (2021) Experimental study on dynamic stall control based on AC-DBD actuation. Plasma Sci Technol 23(11):115502

29. Kimmel RL (2003) Aspects of hypersonic boundary layer transition control. Paper presented at the 41st aerospace sciences meeting and exhibit, Reno, 6-9 January. AIAA 2003–772
30. Schneider SP (2008) Effects of roughness on hypersonic boundary-layer transition. J Spacecr Rockets 45(2):193–209
31. Lawson SJ, Barakos GN (2011) Review of numerical simulations for high-speed, turbulent cavity flows. Prog Aerosp Sci 47(3):186–216
32. Lau KY (2008) Hypersonic boundary-layer transition: application to high-speed vehicle design. J Spacecr Rockets 45(2):176–183
33. Liu Q, Tu GH, Luo ZB et al (2022) Progress in hypersonic boundary transition delaying control. Acta Aeronaut Astronaut Sin 43(2):125357
34. Whitehead AH Jr (1989) NASP aerodynamics. Paper presented at the national aerospace plane conference, Dayton, 20-21 July. AIAA 1989–5013
35. Tarn TJ, Wu Y, Xi N et al (1996) Force regulation and contact transition control. IEEE Contr Syst Mag 16(1):32–40
36. Grundmann S, Tropea C (2007) Experimental transition delay using glow-discharge plasma actuators. Exp Fluids 42(4):653–657
37. Niermeyer S, Velaphi S (2013) Promoting physiologic transition at birth: re-examining resuscitation and the timing of cord clamping. Semin Fetal Neonatal Med 18(6):385–392
38. Fiorentini L, Serrani A, Bolender MA et al (2009) Nonlinear robust adaptive control of flexible air-breathing hypersonic vehicles. J Guid Control Dyn 32(2):402–417
39. Hermann T, McGilvray M, Naved I (2020) Performance of transpiration-cooled heat shields for reentry vehicles. AIAA J 58(2):830–841
40. Yu X, Li P, Zhang Y (2018) The design of fixed-time observer and finite-time fault-tolerant control for hypersonic gliding vehicles. IEEE Trans Ind Electron 65(5):4135–4144
41. Zhang T, Yan X, Huang W et al (2021) Design and analysis of the air-breathing aircraft with the full-body wave-ride performance. Aerosp Sci Technol 119:107133
42. Uffelman KE, Deffenbaugh FD (1979) Asymmetric transition effects on reentry vehicle trim and dispersion characteristics. Paper presented at the 5th atmospheric flight mechanics conference for future space systems, Boulder, 6-8 August 1979. AIAA 1979–1626
43. Reshotko E (2008) Transition issues for atmospheric entry. J Spacecr Rockets 45(2):161–164
44. Platus DH (1982) Ballistic re-entry vehicle flight dynamics. J Guid Control Dyn 5(1):4–16
45. Lu P, Forbes S, Baldwin M (2013) Gliding guidance of high L/D hypersonic vehicles. Paper perPresented at the AIAA guidance, navigation, and control (GNC) conference, Boston, 19-22 August 2013. AIAA 2013–4648
46. An MY, Wang KC, Campbell CH et al (1996) Space shuttle orbiter aerodynamics induced by asymmetric boundary-layer transition. Paper presented at the 34th aerospace sciences meeting and exhibit, Reno, 15-18 January 1996. AIAA 1996–808
47. Yi SH, Liu XL, Niu HB et al (2020) Experimental study on flow stability of hypersonic boundary layer. Acta Aerodyn Sin 38(1):137–142 (in Chinese)
48. Yost MF, Choi Y, Lerner EW et al (2019) Performance of a generic X-51 waverider – thrust, drag, and trim computed using the MASIV reduced order model. Paper presented at the AIAA propulsion and energy 2019 forum, Indianapolis, 19-22 August 2019. AIAA 2019–3841
49. Sforza PM (2021) Bluntness parameter for hypersonic vehicle design. J Spacecr Rockets 58(5):1548–1551
50. Schneider SP (2008) Summary of hypersonic boundary-layer transition experiments on blunt bodies with roughness. J Spacecr Rockets 45(6):1090–1105
51. Yang H, Liang H, Zhao G (2021) Nanosecond dielectric barrier discharge–based dynamic stall control on an SC-1095 airfoil. P I Mech Eng I-J Sys 235(4):563–576
52. Yang HS, Zhao GY, Liang H et al (2020) Dynamic stall control over an airfoil by NS-DBD actuation. Chin Phys B 29(10):105203
53. Gil P, Smyk E, Gałek R et al (2021) Thermal, flow and acoustic characteristics of the heat sink integrated inside the synthetic jet actuator cavity. Int J Therm Sci 170:107171
54. Borg MP, Schneider SP (2008) Effect of freestream noise on roughness-induced transition for the X-51A forebody. J Spacecr Rockets 45(6):1106–1116
55. Matsuo A, Fujii K (1996) Detailed mechanism of the unsteady combustion around hypersonic projectiles. AIAA J 34(10):2082–2089
56. Tirtey SC, Chazot O, Walpot L (2011) Characterization of hypersonic roughness-induced boundary-layer transition. Exp Fluids 50(2):407–418
57. Reda DC, Wilder MC, Bogdanoff DW et al (2008) Transition experiments on blunt bodies with distributed roughness in hypersonic free flight. J Spacecr Rockets 45(2):210–215
58. Fiala A, Hillier R, Estruch-Samper D (2014) Roughness-induced turbulent wedges in a hypersonic blunt-body boundary layer. J Fluid Mech 754:208–231
59. Bernardini M, Pirozzoli S, Orlandi P (2012) Compressibility effects on roughness-induced boundary layer transition. Int J Heat Fluid Fl 35:45–51
60. Wheaton B, Schneider S, Bartkowicz M et al (2011) Roughness-induced instabilities at Mach 6: a combined numerical and experimental study. Paper presented at the 41st AIAA fluid dynamics conference and exhibit, Honolulu, 27-30 June 2011. AIAA 2011–3248
61. Van Driest ER, McCauley WD (1960) The effect of controlled three-dimensional roughness on boundary-layer transition at supersonic speeds. J Aerosp Sci 27(4):261–271
62. Berry SA, DiFulvio M, Kowalkowski MK (2000) Forced boundary-layer transition on X-43 (Hyper-X) in NASA LaRC 31-inch Mach 10 air tunnel. NASA Tech Memo NASA/TM-2000-210315
63. McGinley CB, Berry SA, Kinder GR et al (2006) Review of orbiter flight boundary layer transition data. Paper presented at the 9th AIAA/ASME joint thermophysics and heat transfer conference, San Francisco, 5-8 June 2006. AIAA 2006–2921

64. Wheaton BM, Schneider SP (2012) Roughness-induced instability in a hypersonic laminar boundary layer. AIAA J 50(6):1245–1256
65. Tang Q, Zhu Y, Chen X et al (2015) Development of second-mode instability in a Mach 6 flat plate boundary layer with two-dimensional roughness. Phys Fluids 27(6):064105
66. Sterrett JR, Holloway PF (1963) Effects of controlled roughness on boundary-layer transition at a Mach number of 6.0. AIAA J 1(8):1951–1953
67. Fujii K (2006) Experiment of the two-dimensional roughness effect on hypersonic boundary-layer transition. J Spacecr Rockets 43(4):731–738
68. Fong KD, Zhong X (2016) DNS and PSE study on the stabilization effect of hypersonic boundary layer waves using 2-D surface roughness. Paper presented at the 46th AIAA fluid dynamics conference, Washington DC, 13-17 June 2016. AIAA 2016–3347
69. Everhart JL, Alter SJ, Merski NR et al (2006) Pressure gradient effects on hypersonic cavity flow heating. Paper presented at the 44th AIAA aerospace sciences meeting and exhibit, Reno, 9-12 January 2006. AIAA 2006–185
70. Everhart JL, Berger KT, Merski NR Jr et al (2010) Aero-heating of shallow cavities in hypersonic freestream flow. NASA Tech Memo NASA/TM-2010-216846
71. Xiao L, Xiao Z, Duan Z et al (2015) Improved-delayed-detached-eddy simulation of cavity-induced transition in hypersonic boundary layer. Int J Heat Fluid Fl 51:138–150
72. Ohmichi Y, Suzuki K (2011) Study on hypersonic flow over flat plate with channels. Paper presented at the 29th AIAA applied aerodynamics conference, Honolulu, 27-30 June 2011. AIAA 2011–3966
73. Chen S (2020) The effect of concave roughness on the hypersonic flat-plate boundary-layer transition. Int J Mod Phys B 34(14n16):2040091
74. Malmuth N, Fedorov A, Shalaev V et al (1998) Problems in high speed flow prediction relevant to control. Paper presented at the 2nd AIAA theoretical fluid mechanics meeting, Albuquerque, 15-18 June 1998. AIAA 1998–2695
75. Maslov AA (2003) Experimental and theoretical studies of hypersonic laminar flow control using ultrasonically absorptive coatings (UAC). ISTC Proj Tech Rep ISTC 2172–2001
76. Shalaev VI, Fedorov AV, Malmuth ND (2002) Dynamics of slender bodies separating from rectangular cavities. AIAA J 40(3):517–525
77. Fedorov AV, Malmuth ND, Rasheed A et al (2001) Stabilization of hypersonic boundary layers by porous coatings. AIAA J 39(4):605–610
78. Brès GA, Inkman M, Colonius T et al (2013) Second-mode attenuation and cancellation by porous coatings in a high-speed boundary layer. J Fluid Mech 726(7):312–337
79. Lukashevich SV, Maslov AA, Shiplyuk AN et al (2012) Stabilization of high-speed boundary layer using porous coatings of various thicknesses. AIAA J 50(9):1897–1904
80. Fedorov AV, Malmuth ND (2008) Parametric studies of hypersonic laminar flow control using a porous coating of regular microstructure. Paper presented in the 46th AIAA aerospace sciences meeting and exhibit, Reno, 1-10 January 2008. AIAA 2008–588
81. Chokani N, Bountin DA, Shiplyuk AN et al (2005) Nonlinear aspects of hypersonic boundary-layer stability on a porous surface. AIAA J 43(1):149–155
82. Maslov A, Shiplyuk A, Sidorenko A et al (2006) Hypersonic laminar flow control using a porous coating of random microstructure. Paper presented at the 44th AIAA aerospace sciences meeting and exhibit, Reno, 9-12 January. AIAA 2006–1112
83. Zhu Y, Gu D, Zhu W et al (2021) Dilatational-wave-induced aerodynamic cooling in transitional hypersonic boundary layers. J Fluid Mech 911:A36
84. Zhu W, Shi M, Zhu Y et al (2020) Experimental study of hypersonic boundary layer transition on a permeable wall of a flared cone. Phys Fluids 32(1):011701
85. Zhu W, Chen X, Zhu Y et al (2020) Nonlinear interactions in the hypersonic boundary layer on the permeable wall. Phys Fluids 32(10):104110
86. Bountin D, Chimitov T, Maslov A et al (2013) Stabilization of a hypersonic boundary layer using a wavy surface. AIAA J 51(5):1203–1210
87. Si W, Huang G, Zhu Y et al (2019) Hypersonic aerodynamic heating over a flared cone with wavy wall. Phys Fluids 31(5):051702
88. Yates HB, Tufts MW, Juliano TJ (2020) Analysis of the hypersonic cross-flow instability with experimental wavenumber distributions. J Fluid Mech 883:A50
89. Yates HB, Matlis EH, Juliano TJ et al (2020) Plasma-actuated flow control of hypersonic crossflow-induced boundary-layer transition. AIAA J 58(5):2093–2108
90. Bathel BF, Danehy PM, Inman JA et al (2008) PLIF visualization of active control of hypersonic boundary layers using blowing. Paper presented at the 26th AIAA aerodynamic measurement technology and ground testing conference, Seattle, 23-26 June 2008. AIAA 2008–4266
91. Joslin RD, Nicolaides RA, Erlebacher G et al (1995) Active control of boundary-layer instabilities: use of sensors and spectral controller. AIAA J 33(8):1521–1523
92. Maslov AA, Poplavskaya T, Bountin DA (2010) Hypersonic boundary layer transition and control. In: Schlatter P, Henningson D (eds) Seventh IUTAM symposium on laminar-turbulent transition, vol 42. Springer, Dordrecht, pp 19–26
93. McClinton CR, Rausch VL, Sitz J et al (2001) Hyper-X program status. Paper presented at the 39th aerospace sciences meeting and exhibit, Reno, 8-11 January 2001. AIAA 2001–828
94. Berry SA, Nowak RJ, Horvath TJ (2008) Boundary layer control for hypersonic airbreathing vehicles. Paper presented at the 34th AIAA fluid dynamics conference and exhibit, Portland, 28 June-1 July 2004. AIAA 2004–2246
95. Pappas CC, Okuno AF (1964) Heat-transfer measurement for binary gas laminar boundary layers with high rates of injection. NASA Tech Rep NASA-TN-D-2473
96. Demetriades A, Laderman AJ, Seggern LV et al (1976) Effect of mass addition on the boundary layer of a hemisphere at Mach 6. J Spacecr Rockets 13(8):508–509

97. Schneider SP (1999) Flight data for boundary-layer transition at hypersonic and supersonic speeds. J Spacecr Rockets 36(1):8–20
98. Schneider SP (2010) Hypersonic boundary-layer transition with ablation and blowing. J Spacecr Rockets 47(2):225–237
99. Wang S, Lei J, Zhen H et al (2015) Numerical investigation of wall cooling and suction effects on supersonic flat-plate boundary layer transition using large eddy simulation. Adv Mech Eng 7(2):493194
100. Wang X, Zhong X, Ma Y (2011) Response of a hypersonic boundary layer to wall blowing-suction. AIAA J 49(7):1336–1353
101. Clarke JF, McChesney M, Scott JE Jr (1966) The dynamics of real gases. J Appl Mech 33(1):237–238
102. Adam PH, Hornung HG (1997) Enthalpy effects on hypervelocity boundary-layer transition: ground test and flight data. J Spacecr Rockets 34(5):614–619
103. Hornung HG, Adam P, Germain P et al (2002) On transition and transition control in hypervelocity flow. In: Proceedings of the ninth Asian congress of fluid mechanics, Isfahan, 27-31 May 2002
104. Leyva IA, Laurence S, Beierholm AW et al (2009) Transition delay in hypervelocity boundary layers by means of CO_2/acoustic instability interactions. Paper presented at the 47th AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition, Orlando, 5-8 January 2009. AIAA 2009–1287
105. Jewell JS, Leyva IA, Parziale NJ et al (2012) Effect of gas injection on transition in hypervelocity boundary layers. In: Kontis K (ed) 28th international symposium on shock waves. Springer, Berlin, Heidelberg
106. Jewell JS, Wagnild RM, Leyva IA et al (2013) Transition within a hypervelocity boundary layer on a 5-degree half-angle cone in air/CO_2 mixtures. Paper presented at the 51st AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition, Grapevine, 7-10 January 2013. AIAA 2013–523
107. Schmisseur JD (2015) Hypersonics into the 21st century: a perspective on AFOSR-sponsored research in aerothermodynamics. Prog Aerosp Sci 72:3–16
108. Leyva IA, Jewell JS, Laurence S et al (2009) On the impact of injection schemes on transition in hypersonic boundary layers. Paper presented at the 16th AIAA/DLR/DGLR international space planes and hypersonic systems and technologies conference, Bremen, 19-22 October 2009. AIAA 2009–7204
109. Soudakov VG, Fedorov AV, Egorov IV (2015) Stability of high-speed boundary layer on a sharp cone with localized wall heating or cooling. In: Knight D, Lipatov I, Reijasse P (eds) EUCASS proceedings series – advances in Aerospace sciences. Progress in flight physics vol 7. EDP Sciences, Les Ulis, pp 569–584
110. Fedorov A, Soudakov V, Egorov I et al (2015) High-speed boundary-layer stability on a cone with localized wall heating or cooling. AIAA J 53(9):2512–2524
111. Zhao G (1999) Effect of wall suction and cooling on the stability of the supersonic and hypersonic three dimensional boundary layer. Acta Aerodyn Sin 17(1):21–29 (in Chinese)
112. Kosinov AD, Maslov AA, Shevelkov SG (1990) Experiments on the stability of supersonic laminar boundary layers. J Fluid Mech 219:621–633
113. Kosinov AD, Maslov AA, Semionov NV (1996) Modified method of experimental study of supersonic boundary layer receptivity. Proc Int Conf on Methods of Aerophys Research: Pt III pp 161–166
114. Maslov A, Shiplyuk A, Sidorenko A et al (2001) Leading-edge receptivity of a hypersonic boundary layer on a flat plate. J Fluid Mech 426:73–94
115. Heitmann D, Kähler C, Radespiel R et al (2011) Non-intrusive generation of instability waves in a planar hypersonic boundary layer. Exp Fluids 50(2):457–464
116. Casper KM, Beresh SJ, Schneider SP (2014) Pressure fluctuations beneath instability wavepackets and turbulent spots in a hypersonic boundary layer. J Fluid Mech 756:1058–1091
117. Zhang Y, Li C, Lee C (2020) Influence of glow discharge on evolution of disturbance in a hypersonic boundary layer: the effect of second mode. Phys Fluids 32(7):071702
118. Li C, Zhang Y, Lee C (2020) Influence of glow discharge on evolution of disturbance in a hypersonic boundary layer: the effect of first mode. Phys Fluids 32(5):051701
119. Yang HS, Zhao GY, Liang H et al (2020) Research progress on influence factors of airfoil dynamic stall and flow control. Acta Aeronaut Astronaut Sin 41(8):23605–023605
120. Jia Y, Liang H, He Q et al (2021) Flow separation control of nacelle in crosswind by microsecond pulsed surface dielectric barrier discharge plasma actuator. Flow Turbul Combust 107:631–651
121. Baldwin A, Mears LJ, Kumar R et al (2021) Effects of Reynolds number on swept shock-wave/boundary-layer interactions. AIAA J 59(10):3883–3899
122. Abbasi AA, Li H, Meng X (2020) Coupled aerodynamic and thermal effects for steady and unsteady plasma actuation. AIAA J 58(1):488–495
123. Li YH, Wu Y (2020) Research progress and outlook of flow control and combustion control using plasma actuation. Sci Sin Technol 50(10):1252–1273 (in Chinese)
124. Wu Y, Li YH (2015) Progress and outlook of plasma flow control. Acta Aeronaut Astronaut Sin 36(2):381–405
125. De Giorgi MG, Motta V, Suma A (2020) Influence of actuation parameters of multi-DBD plasma actuators on the static and dynamic behaviour of an airfoil in unsteady flow. Aerosp Sci Technol 96:105587
126. Post ML, Corke TC (2004) Separation control using plasma actuators - stationary and oscillating airfoils. Paper presented at the 42nd AIAA aerospace sciences meeting and exhibit, Reno, 5-8 January 2004. AIAA 2004–0841
127. Roth JR (2003) Aerodynamic flow acceleration using paraelectric and peristaltic electrohydrodynamic effects of a one atmosphere uniform glow discharge plasma. Phys Plasmas 10(5):2117–2126
128. Leonov SB, Yarantsev DA, Gromov VG et al (2005) Mechanisms of flow control by near-surface electrical discharge generation. Paper presented at the 43rd AIAA aerospace sciences meeting and exhibit, Reno, 10-13 January 2005. AIAA 2005–0780
129. Schuele CY, Corke TC, Matlis E (2013) Control of stationary cross-flow modes in a Mach 3.5 boundary layer using patterned passive and active roughness. J Fluid Mech 718:5–38
130. Nishihara M, Takashima K, Rich J et al (2011) Mach 5 bow shock control by a nanosecond pulse surface dielectric barrier discharge. Phys Fluids 23:066101

131. Yates HB, Juliano TJ, Matlis EH et al (2018) Plasma-actuated flow control of hypersonic crossflow-induced boundary-layer transition in a Mach-6 quiet tunnel. Paper presented at the 2018 AIAA aerospace sciences meeting, Kissimmee, 8-12 January 2018. AIAA 2018–1076
132. Zhang X, Cui YD, Tay CMJ et al (2020) Ultrasound generated by alternating current dielectric barrier discharge plasma in quiescent air. Plasma Sources Sci Technol 29(1):015017
133. Kogelschatz U (2002) Filamentary, patterned, and diffuse barrier discharges. IEEE Trans Plasma Sci 30(4):1400–1408
134. Leonov S, Bityurin V, Savelkin K et al (2002) The features of electro-discharge plasma control of high-speed gas flows. Paper presented at the 33rd plasmadynamics and lasers conference, Maui, 20-23 May 2002. AIAA 2002–2180
135. Shin J, Narayanaswamy V, Raja L et al (2007) Characteristics of a plasma actuator in Mach 3 flow. Paper presented at the 45th AIAA aerospace sciences meeting and exhibit, Reno, 8-11 January 2007. AIAA 2007–788
136. Menier E, Leger L, Depussay E et al (2007) Effect of a dc discharge on the supersonic rarefied air flow over a flat plate. J Phys D Appl Phys 40:695–701
137. Tang BL, Guo SG, Song GZ et al (2020) Experimental study on supersonic plate boundary layer transition under pulsed arc plasma excitation control. Acta Phys Sin 69(15):155201-1
138. Tang M, Wu Y, Guo S et al (2020) Effect of the streamwise pulsed arc discharge array on shock wave/boundary layer interaction control. Phys Fluids 32(7):076104
139. Tang MX, Wu Y, Zong HH et al (2022) Experimental investigation of supersonic boundary-layer tripping with a spanwise pulsed spark discharge array. J Fluid Mech 931:A16
140. Reedy TM, Kale NV, Dutton JC et al (2013) Experimental characterization of a pulsed plasma jet. AIAA J 51(8):2027–2031
141. Zong H, Kotsonis M (2018) Formation, evolution and scaling of plasma synthetic jets. J Fluid Mech 837:147–181
142. Luo Y, Li J, Liang H et al (2021) Suppressing unsteady motion of shock wave by high-frequency plasma synthetic jet. Chinese J Aeronaut 34(9):60–71
143. Zong H, Kotsonis M (2016) Characterisation of plasma synthetic jet actuators in quiescent flow. J Phys D Appl Phys 49(33):335202
144. Zong H, Kotsonis M (2017) Effect of slotted exit orifice on performance of plasma synthetic jet actuator. Exp Fluids 58(3):17
145. Zong H, Kotsonis M (2017) Interaction between plasma synthetic jet and subsonic turbulent boundary layer. Phys Fluids 29(4):045104
146. Zong H, Kotsonis M (2019) Effect of velocity ratio on the interaction between plasma synthetic jets and turbulent cross-flow. J Fluid Mech 865:928–962
147. Wang L, Luo ZB, Xia ZX et al (2012) Review of actuators for high speed active flow control. Sci China Technol Sci 55(8):2225–2240
148. Wang JW (2016) Research on controlling the flow field of hypersonic inlet using dual synthetic jet actuator. Dissertation, National University of Defense Technology
149. Singh AP, Choudhary V, Sharma D (2021) Design and development of hypersonic aerial vehicles. In: Kumar N, Tibor S, Sindhwani R, Lee J, Srivastava P (eds) Advances in interdisciplinary engineering. Lecture notes in mechanical engineering. Springer, Singapore, pp 457–467
150. Ju Y, Sun W (2015) Plasma assisted combustion: dynamics and chemistry. Prog Energy Combust Sci 48:21–83
151. Li Q, Zhao L, Chen S et al (2020) Experimental study on effect of transverse groove with/without discharge hole on hypersonic blunt flat-plate boundary layer transition. Acta Phys Sin 69(2):024703-1

Publisher's Note