Advances in Shock Wave/Boundary Layer Flow Control in Supersonic Inlets (Postprint)

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Date: 2025-12-17T11:20:56+00:00

Abstract

Air-breathing hypersonic vehicle inlets exhibit complex flow phenomena including boundary layer transition, flow separation, and shock wave/boundary layer interaction. A profound understanding and effective control of these phenomena are critical for achieving efficient operation and performance enhancement of hypersonic vehicles. This paper first reviews the research progress on passive and active flow control technologies in supersonic inlets, describing their effectiveness and limitations in controlling shock wave/boundary layer flows. Meanwhile, as hypersonic vehicle development advances toward wider speed ranges, larger flight envelopes, and higher Mach numbers, traditional active and passive inlet flow control technologies struggle to meet the performance-on-demand requirements under wide-range operating conditions. Consequently, multi-field coupling control methods represented by plasma actuation have become a current research hotspot for supersonic inlet flow control. However, due to limitations in existing experimental testing methods, it is difficult to conduct detailed investigations into the fine-scale flow control mechanisms of plasma-actuated shock wave/boundary layer interactions, leaving many aspects worthy of exploration. While providing this review, the article also offers relevant recommendations for future research.

Full Text

Introduction

Energy deposition in the discharge region can increase the local speed of sound of nearby fluid and reduce flow separation. At low Mach numbers, the actuator consists of two electrodes with a specific gap. The thermal effect from rapid heating of gas near the electrodes is the primary cause of shock wave intensity reduction, with temperatures exceeding 3000 K. The resulting flow structures, such as shock waves and control bubbles, are passively carried downstream by the supersonic flow. Experimental results demonstrate that boundary layer flow separation can be effectively suppressed. Research indicates that arc plasma energy deposition acts directly on the flow field, making surface pulsed arc discharge more suitable for wide-frequency flow control compared to c64 actuation.

Surface Pulsed Arc Plasma Actuator

[Figure 1: see original paper] illustrates the surface pulsed arc plasma actuator for shock wave-boundary layer flow control. The actuator developed by __I,M et al., which uses a streamwise array of surface pulsed arc actuators to apply flow control to shock wave-boundary layer interaction induced by a compression ramp, features higher operating frequencies and a broader bandwidth. As shown in [Figure 1: see original paper], experimental results reveal significant potential in the field of shock wave-boundary layer interaction control. Arc plasma energy deposition increases momentum and energy in localized flow regions. The unsteady characteristics and mechanisms of shock wave-boundary layer interaction control using arc plasma energy deposition have been investigated.

Experimental Investigation of Flow Control Process

The unsteady behavior during high-frequency surface pulsed arc actuator array control of shock wave-boundary layer interaction was experimentally studied by L8,M et al. The inlet Mach number was Ma = 2.0-2.3 with a total pressure of P_0 = 0.5 MPa. The test section upper wall was equipped with designed arc plasma generators. To maintain a constant interaction region between the applied high-frequency pulsed plasma and the shock wave-boundary layer, different ramp angles were installed to generate incident shocks on the lower wall while keeping the incident shock position fixed.

Time-resolved changes in plasma interaction with the shock wave-boundary layer are shown in [Figure 2: see original paper]. Energy depositions of 100 mJ and 400 mJ were applied with a time interval of Δt = 10-15 s. At t = 0, high-frequency pulsed plasma is generated. When the supersonic flow passes through the "blockage," a pressure differential induces a thermal jet from the wall. Due to rapid thermal diffusion (approximately 5 s), the plasma continuously moves downstream with the flow and diffuses into the mainstream. At approximately t = 30-40 s, the plasma-induced thermal bubble reaches the shock wave-boundary layer interaction location. The strong flow-induced shock front has moved out of the observation window. The thermal bubble control causes the resulting separation shock to weaken uniformly and triggers a series of oblique shock oscillations. When the control bubble passes through the interaction region, the high pressure induced by thermal effects propagates upstream and interacts with the adverse pressure gradient caused by the incident shock. At t = 80-100 s, as the perturbation completes, the flow field essentially recovers to its pre-actuation structure. The primary effect of incident shock strength variation is to alter the recovery time of the flow field after the thermal bubble leaves the interaction zone.

Numerical Simulation

To investigate the effects of different actuation parameters on incident shock-boundary layer interaction and the underlying mechanisms, a phenomenological-based model was developed with a radiation dissipation term for correction. Using this arc plasma model for a 24° wedge angle, [Figure 3: see original paper] shows the flow control process of surface pulsed arc plasma with a power density of 1.25×10^9 W/m^2. The numerically predicted dynamic movement of the separation shock agrees well with experimental results. Initially, turbulent kinetic energy in the flow domain concentrates at the shock-boundary layer interaction region, with the bottom wall boundary layer also observable. After the pulsed arc discharge ends, the maximum turbulent kinetic energy appears at the bubble top, exceeding the mean bubble turbulent kinetic energy by over 10,000 m^2/s^2. At t = 25–30 s, after passing through the shock-boundary layer interaction region, the turbulent kinetic energy dissipates and decreases. At t = 50–60 s, the control bubble alters the boundary layer structure during downstream propagation and affects the downstream shock-boundary layer interaction.

Parametric Study of Frequency and Power Effects

Building upon single-pulse arc plasma flow control research, the effects of actuator operating frequency and discharge power on control effectiveness were investigated. The freestream Mach number remained at Ma = 2.5 with total pressure $P_0 = 0.5$ MPa. Following the experiments of L8,M et al., as shown in their experimental setup, the high-frequency pulsed arc plasma streamwise actuator array consisted of multiple units with 20 mm spacing between adjacent actuators. Each actuator unit comprised a pair of tungsten electrodes. The distance between the last actuator of the arc plasma streamwise array and the leading edge of the half-cylinder was 15 mm.

The discharge pulse width remained at 5 s. The overall flow control process was similar to the field evolution under the 1.25×10^9 W/m^2 excitation condition described previously. However, due to lower energy density in the arc plasma excitation region, the fundamental flow control mechanism for shock-boundary layer interaction can be attributed to the impact effect of the plasma energy deposition block.

[Figure 4: see original paper] presents the temperature and streamwise velocity distributions at different moments for this power density condition. At t = 5 s when the pulse discharge ends, the average temperature is approximately 1000 K, with peak values near 1500 K. Consequently, the initial velocity of the energy deposition block is lower than the mainstream, with a counterflow velocity approaching 200–300 m/s, though the downstream recirculation zone remains unaffected at this stage. At t = 20 s, the recirculation zone volume within the shock-boundary layer interaction region decreases. As the plasma energy deposition block leaves the interaction zone, the separation shock exhibits obvious fluctuations. In the numerical schlieren images, shock waves and separation bubbles can be clearly observed. Shock waves from different discharge cycles merge to form an equivalent compression wave system. Compared with the single-pulse excitation process, the flow field can achieve continuous control of shock-boundary layer interaction through high-frequency pulsed arc discharge, as evidenced by the average temperature in the wedge region enclosed by the shear layer, bottom wall, and half-cylinder leading edge exceeding 2000 K.

[Figure 5: see original paper] shows the instantaneous numerical schlieren after two excitation cycles at a constant frequency of 40 kHz. Increasing the pulsed arc discharge power directly increases the electrical energy consumed per discharge, enhancing the plasma energy deposition and thereby strengthening flow control capability. The separation shock exhibits reduced density gradient values compared with single-pulse excitation.

[Figure 6: see original paper] displays the density gradient for a higher power condition of 100 mJ at 40 kHz. After several excitation cycles, a thermal excitation surface parallel to the bottom wall forms, providing continuous thermal perturbation to the boundary layer flow. The closely connected shock waves within the same excitation cycle enhance the actuator’ s flow control capability.

Conclusion

Shock wave-boundary layer interaction represents the primary flow characteristic within inlets, and developing efficient, dynamically adjustable control technology is critical. Traditional active/passive methods such as vortex generators and boundary layer suction/bleed cannot satisfy future vehicle requirements for wide operating ranges. Current experimental measurement techniques cannot provide detailed resolution of the multi-state, multi-physical-chemical coupling processes in supersonic plasma actuation, limiting mechanistic understanding. Engineering practice currently relies on phenomenological modeling methods. Further research must address:

1. The multi-state, multi-field, and high-temperature aspects of plasma physics under complex environmental conditions, as existing methods cannot effectively reveal the interaction mechanisms between plasma and shock wave-boundary layer interference.
2. Refined measurement techniques for the multi-state and multi-physical-chemical coupling processes in supersonic plasma excitation.
3. Integration with existing flow control techniques to enable effective flow regulation support for wide-speed-range, large-altitude-domain efficient operation of supersonic inlets.

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