Oblique shock wave reflection at plasma array presence

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Abstract. This work discusses the effect of a filamentary plasma array on shock wave (SW) reflection pattern and on a shock-induced separation zone geometry. It includes experimental and computational components both. The experimentation was performed in the supersonic blowdown test rig SBR-50 at the University of Notre Dame at flow Mach number M=2, stagnation pressure P₀=1.7-2.7 bar and stagnation temperature T₀=300 K. Oblique shock wave generator composed of a symmetric solid wedge was installed on the top wall of test section while the filamentary plasma generator was arranged on the opposite wall. Thus, the main SW originating from the wedge impinged the plasma area. As a result of the SW-plasma interaction, the flowfield was significantly modified, including a shift of the main SW upstream and redistribution of wall pressure over the test section. The computational analysis allowed a 3D reconstruction of the SW interaction with the plasma array. The physics of SW-plasma array interaction are also discussed.

1. Introduction

This work aims to study the shock wave - boundary layer interaction, the redistribution of the surface pressure on a flat wall and the dynamics of an air flow structure under the impact of an arranged plasma array on the surface of a supersonic air duct. The plasma array is generated by means of a Quasi-DC electrical discharge, which generates a filamentous pattern between the surface electrodes with a cross-flow orientation [1]. The control of shock wave (SW) interaction with a boundary layer (BL), other SWs, and separated flows in a supersonic/hypersonic airflow is of fundamental and engineering interest for aerospace applications.

The air conditioning in supersonic inlets is one of the major problems in high speed propulsion [2, 3, 4]. Inlet flow control is necessary to mitigate flow separations on the compression surfaces and to prevent air inlet malfunction [3]. It is commonly supposed that the most effective mechanism leading to the prevention of separation is the formation of a vortex in the stream, which transfers the momentum of the gas from the central flow to the BL [5, 6]. Typical control schemes include fixed or movable mechanical elements and valves [7], air injectors or collectors [8], wall jets [9], etc. Problems with these methods include extra pressure losses and long response time, longer than the gasdynamic time. Instantaneous energy deposition by electrical discharges allows for faster system response and a predefined time sequence through electronic control, which introduces additional advantages of this technique for flow control. The authority of electrical discharges for supersonic flow control is well regarded in many
available publications [10, 11, 12, 13, 14]. Several research groups tested different types of discharge including spark discharge [15, 16] and arc discharge [17, 18, 19]. The computational efforts based on 3D unsteady Navier-Stokes equations with plasma modeled as an array of lengthwise heat sources recently demonstrated adequacy of such simplifications comparing to the experimental data [4, 20]. It helped to find an optimal range of plasma power and position in terms of achievable effect, effectiveness of the method, and response time of the system to the plasma actuation.

In this study, a quasi-DC plasma was employed to provide rapid control of the shock train in $M = 2$ duct with a compression ramp, continuing previous efforts of the group [1, 4, 20].

2. Experimental Arrangement

Tests were performed at the SBR-50 supersonic blowdown test rig at the University of Notre Dame. The facility test section has an initial cross section of $Z \times Y = 76.2 \times 76.2$ mm and length of $X = 710$ mm, with a $1\degree$ expansion of the top and bottom walls to compensate for boundary layer growth. The facility was operated at $M = 2$ with stagnation pressures in the range $P_0 = 1.7 - 2.7$ bar in this test series, stagnation temperature $T_0 = 297$ K and steady-state run time $t = 0.5 - 1$s. The upper wall of the test section was arranged with a $10\degree$ wedge with a height of 6.6 mm to generate a planar shock wave impinging in the plasma region on the bottom wall. The leading edge of the compression wedge was located $x = 92$ m downstream of the nozzle exit and the bottom wall was arranged with three electrodes impeded in ceramic at $x = 149$ mm, with two ground rails to elongate the plasma to grounding on the bottom wall. Optical access was provided through quartz side windows. An overview of the test arrangement is presented in figure 1.

![Figure 1. SBR-50 facility test arrangement.](image)

For this test series, instrumentation includes pressure measurements, schlieren imaging, high speed plasma imaging, and electrical measurements. Static pressure data over the test section were measured using a 64-channel pressure scanner (Scanivalve MPS4264) with an acquisition frequency of 800 Hz collecting from 48 pressure locations on the top and bottom walls and from a 16-probe pitot rake at the end of the test section. For detailed pressure dynamics, Kulite sensors (XT-140M series) were applied, flush mounted in the top test insert downstream of the wedge. The schlieren arrangement consisted of a high current pulsed white LED light source (200-300 ns pulse duration) and a Phantom V2512 high speed camera operating with an exposure time of 400 ns and frame rates 25-200 kHz. An inline band spectral filter was applied to attenuate plasma luminosity in schlieren images. Plasma imaging was performed with a Photron Nova S9 FastCam collecting the videostream with an exposure of 4 µs and frame rates 25-200 kHz. Plasma was generated using a custom capacitor-based power supply operating in a current stabilized mode at breakdown voltage of $U_{ps} = 5$ kV. Electrical probes were used to measure gap voltages, current and electric power. Typical electrical parameters for each filament include gap voltage $U_{gap} = 0.8 - 1$ kV, current $I_2 = 3.5 - 4$ A and plasma power about $P_2 = 3$ kW.
3. Test Results
The test results presented in this paper were acquired at a single ramp position at x = 92mm from the nozzle exit to characterize the effect of electric discharge on the flow field structure. During steady state flow in each run, 5 plasma pulses were activated at 10Hz with a 30ms duration of each pulse. High speed imaging showing the dynamics and shape of plasma filaments presented in figure 2 for two cases when the SW generator was not installed on the top wall, figure 2(a), and when it was in place, figure 2(b). Electric breakdown starts to a close point on the grounded rails shown in figure 2(a) schematically, then the plasma filaments elongated up to a maximum length of about 80mm. The transition period corresponds to a gasdynamic time approximately. Once sufficient heat release is achieved, and the shock front moves upstream to the high voltage electrodes, this takes about 1ms. The plasma filaments are then located within a self-consistent separation area that leads to a highly perturbed shape of the plasma filament, seen in figure 2(b). This also allows more energy to be coupled into the flow and the separation area.

Figure 2. Plasma images collected at 4µs exposure time showing different shape at SW off-on, where (a) no impinging SW, (b) SW on. Inter-electrode distance 20mm.

The basic effect of plasma actuation on the shock train generated by the ramp and on the flow-field structure is seen in schlieren imaging in two key regions: (1) compression wedge shock impact on the plasma array and (2) the reflection of this shock back to the upper wall. In figures 3(a) and 3(b), schlieren imaging from a generic plasma control scheme is presented prior plasma actuation, and during plasma actuation to illustrate the general plasma effect. These figures are compiled from images at three downstream locations and were collected at 10kHz with a 200ns exposure time. The flow structure before plasma actuation, shown in figure 3(a), is dominated by a strong oblique SW from the leading edge of the ramp, reflecting behind the electrode area at x=175-200mm and crossing the rear ramp SW before reflecting from the upper wall at about x=290mm. Weak SWs from ceramic insert and electrodes on the bottom wall are also visible along with an expansion wave from the ramp top, closing compression wave from the ramp back wise corner, and an intensification of density fluctuations in the boundary layer after the 1st compression wedge SW impact. When the discharge is activated on, after a transitional period (about 1ms), significant flow structure modification is observed. Figure 3(b) shows schlieren image during
plasma presence, where the 2nd impact of the compression wedge SW is mitigated. The top wall reflection is now at about x=270mm and originates from the plasma filaments (electrodes). Intense gas heating, locally provided by plasma, forms a thermal layer seen in figure 3(b). Local separation of this thermal layer on the bottom wall at around x=180mm is seen in figure 3(b) due to pressure increase from the 1st compression wedge SW impact.

![Schlieren images](image)

**Figure 3.** Schlieren images stitched together from several view locations at $P_0 = 1.7$ bar, $T_0 = 297$ K showing SW structures at (a) no plasma actuation and (b) plasma on.

The effect of plasma on the shock structure configuration is reflected in pressure data showing key pressure ports at repetitive plasma impact and the static pressure distribution along the upper wall of the test section. In figure 4(a), a time series of pressure port readings on the top wall near the reflected shock position are shown. As the shock impinging this area moves upstream, the pressure at $x = 252$ mm increases indicating this sensor now sits behind the new shock front. Figure 4(b) shows a comparison of the top wall pressure distribution where upstream movement of the shock structure is seen along with an upstream movement of subsequent reflections with plasma on. In all cases the pressure tail after the shock reflection is redistributed, but further from impact pressure returns to near baseline values. Due to the discretized nature of the pressure taps, the peak pressure in each case is not fully resolved, so direct comparison of the shock strength is challenging.
Figure 4. Pressure scanner data: (a) pressure effect at repetitive plasma impact; (b) plasma effect on the top wall pressure distribution.

A change in the total pressure losses resulting from plasma actuation were assessed using pressure data taken at the test section diffuser side by a 16 channel Pitot rake arranged crossflow along a centerline between the top and bottom walls; the Pitot rake was connected to the pressure scanner. Pitot ports were spaced $\Delta y = 6.35$mm apart, starting from $y = 3.8$mm from the top wall. The total pressure distribution before plasma actuation, and during plasma actuation are shown in figure 5. The shock train impacts the center of the pitot rake requiring careful assessment for ports before and after the shock train. For these ports, a decrease near the bottom wall is seen during plasma, while the top wall pressure remains roughly constant.

Figure 5. Pitot crossflow pressure data at $P_0=2.7$bar, $T_0=300$K.

4. Computational analysis
The plasma-SW-flow interaction was simulated numerically using FlowVision CFD software for the configuration presented at the experimental part. The simulation was based on the solution of the three-dimensional unsteady Reynolds averaged Navier–Stokes equations accompanied by the $k-\varepsilon$ turbulence model. The calculation domain includes a thin layer of 10 mm width and contains half of one plasma filament located near a side plane of the calculation domain. The symmetry condition was set to both side
planes of calculation domain. No-slip conditions and wall functions were used on top and bottom boundaries ($y^+$ in range of 10-50). Free supersonic flow exit was set up on the outlet boundary and supersonic flow conditions corresponding to experimental ones were set up on the inlet boundary. Geometry of the test section corresponds to the experimental one. The effect of the plasma filament produced by Q-DC discharge was simulated by volumetric heat sources. This approach demonstrated good consistency of experimental results and simulation data for plasma flow control in different supersonic configurations [4, 20]. The volumetric heat source was 50mm long and 1.5mm in diameter. Power of a full single plasma filament was $W=3$ kW.

![Image](image1.png)

**Figure 6.** Result of CFD simulation. (a) Mach number distribution: plasma off (top) and with plasma (bottom); (b) pressure distribution along the top wall.

Calculated Mach number distributions are shown in figure 6(a) for two cases: baseline - plasma off, and flow with heat source power $W=3$ kW per a single plasma filament. The calculated structure of the shock-dominated flow is in a good agreement with the experimental one. Simulation confirms that the discreet heat release provided by electrical discharge changes the flow structure across the entire test section. Changing of oblique shocks structure caused by plasma activation provides a significant change in pressure distribution along the top wall of the test section, as it is shown in figure 6(b). 3D structure of the structure of shock reflection pattern at plasma filament presence is shown in figure 7. Local heat source produce a long 3D subsonic zone that is closer to flat in front of the discharge. The flow structure behind the discharge is significantly three-dimensional because of uneven heating and hot gas outlet: the gas in this area flows with high speed up to 750m/s and high temperature over 1kK. The generation of a pair of a counter rotating vortices behind the discharge are well-illustrated by figure 7.

![Image](image2.png)

**Figure 7.** 3D structure of flow over plasma filament. Discharge – pink; Mach number distribution is shown by colors, $M=1$ – black; velocity vectors: grey - positive, red-negative in separated area.
It is important to indicate that the adopted approach has some limitations mostly due to a fixed geometry of the discharge. Gas temperature in the discharge area was calculated to be about 16 kK. Such high temperature was caused by formation of the separation zone, which is characterized by a limited heat exchange with the main flow. That is why the discharge shape in figure 2(b) is not straight, but strongly perturbed. Also, obtained back flow in the separation zone can affect (decrease) the discharge length and power which is not taken into account in the computational model.

5. Discussion and Conclusions
The multifilament plasma zone presents a set of longwise subsonic regions surrounded by a supersonic flow. The volumetric expansion zone produces a subsonic flow, where the physical velocity is close to the velocity of the gas in the supersonic core flow. The pressure increases due to the impact of the SW and affects this cone, increasing the pressure of the gas in the subsonic zone. The gas expansion induces a conical SW attached to the root of the plasma filament (electrode). The shape of a “soft” plasma trail complies reducing the reflected SW strength and modifying the separation zone shape [1].

The generation of surface localized discharges in a high-speed flow leads to a substantial change in the structure and parameters of the flow field, including the shock-induced separation zone. Figure 8 shows a scheme of interaction of the plasma-based displacement layer with an impinging SW resulting in a mitigation effect on the reflected SW. The pressure increase concomitant to the impinging SW is mitigated due to presence of longitudinal subsonic zones, which appears in modification of the shape of the displacement layer and separation zone, as is shown in figure 8. As a result, the near-wall layer, produced with the help of the longitudinal plasma array, works as a virtual shape or an active compliant structure.

Figure 8. Scheme of impinging SW interaction with filamentary plasma zone.

The results of an experimental study and concomitant numerical modelling are presented characterizing the effect of a quasi-DC electric discharge located in the reflection region of a compression shock on downstream shock structures and pressure distributions. In schlieren imaging, mitigation of the reflected shock from the ramp is observed, along with formation of a new oblique shock at the location of electrodes. This leads to the formation of a new shock train throughout the test duct, shifted further upstream from the previous pattern. Pressure distribution data and the numerical results similarly confirms this effect. This results in a delay to establish a new pattern of the plasma controlled flowfield. Pressure sensors indicate the delay in the reflected shock position of \( t_{\text{start}} < 1 \text{ ms} \) after electric breakdown with about same time for the decay to reestablish baseline flow after high voltage is switched off.

The plasma-based configuration may potentially be applied to mitigate the reflected SW due to the impinging SW interaction with the plasma-related displacement layer. It is beneficial that the electrical discharge can be switched on/off electronically at any time and synchronized with all other processes, such as a trajectory change or engine thrust modulation. The active compliant structure may aid in shifting
the reflected SW, mitigation of the reflected SW strength, or elimination of the reflected SW for flow control purposes.

The major findings described in this publication are in new details of the SW-plasma array interaction including the dynamics of the plasma-induced SW. It is considered that, under the current test geometry and conditions, the Q-DC electrical discharge generation does not initiate significant losses of total pressure in the duct. The plasma effect on total pressure needs further characterization across a wider range of test parameters and wedge locations.

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