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Supersonic Cavity-Based Flow Control Using a Quasi-DC Discharge

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Abstract. The Quasi-DC (Q-DC) discharge is studied as an active flow control authority on a rear-facing cavity in a supersonic duct by creating an oblique shockwave that impinges the cavity. This geometry simulates the geometry of a typical scramjet flameholding scheme. The tests were performed at the University of Notre Dame in the SBR-50 supersonic blowdown rig with dried air at M=2. Schlieren imaging is used to view the flow field with and without the Q-DC discharge in operation. A significant change in the flow field structure is observed. Pressure sensors detect a pressure increase throughout the entire rear-facing cavity while the Q-DC discharge is operating. This reveals that the cavity redistributes the pressure increase from the shockwave as a result of the flow within the cavity being subsonic. As a result of this pressure absorption and redistribution, the impinging shockwave created by the Q-DC is almost completely absorbed. This absorption is confirmed by the schlieren images. The data reveal that the discharge power is the dominating influence, as compared to electrode/discharge geometry, on the pressure increase produced in the cavity. There is a nearly linear correlation between the power of the discharge and the pressure increase produced directly behind the discharge, in the cavity, and on the ramp of the cavity (to varying magnitudes). It is suggested that the 11 electrode system may be slightly more effective than the 7 electrode system.

1. Introduction

Plasma-based flow control techniques have been studied extensively in recent decades. Electric discharges provide high-frequency capabilities and a robust, surface-flush installation for active flow control such that it can add momentum/energy into the boundary layer without obstructing the flow while it is not in operation. The large majority of plasma-based flow control studies focus on the use of dielectric barrier discharges (DBDs), but this type of discharge is not powerful enough to provide flow control authority in a highly compressible flow. There have been non-DBD plasma-based flow control studies most of which focus on shockwave generation and control of shockwave/boundary layer interactions [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. The quasi-DC (Q-DC) discharge has proven its potential as a flow control technique in high-density supersonic duct driven airflows, such as the environment typical of a scramjet [7, 8, 11, 12, 13, 14]. The velocity of the core flow in a supersonic duct flow is an order of magnitude faster than the combustion propagation speed of a typical gaseous hydrocarbon fuel (e.g. ethylene) making it difficult to maintain combustion. The prevailing method/geometry used for flameholding in scramjet engines is a rear-facing cavity. The rear-facing cavity creates a subsonic region of flow which provides an environment in which the flame will not be blown downstream. Supersonic duct flow is not favorable for fast mixing of the fuel and oxidizer for a non-premixed flow.

The interaction between the core flow and the cavity flow is limited to the free shear layer which does not provide sufficient mixing between the two if fuel from the core flow is wanted to enter the cavity. In order to overcome this, fuel can be injected simultaneously into the core flow upstream of the cavity and into the cavity. This overcomes the lack of mixing between the two flow regions, and the heat released from combustion can be sufficient to ignite and maintain combustion in the core flow. The Q-DC discharge provides a method for enhancing multiple aspects of off-design flow conditions in a supersonic combustion environment. The strong spanwise non-uniformity of the Q-DC discharge can provide enhanced mixing and the discharge can potentially be used for fast/cold re-ignition. The Q-DC discharge can also potentially be employed as a method to enhance the interaction between the core flow and the cavity flow.

The Q-DC discharge as it is applied to a supersonic duct driven airflow has been studied extensively [7, 8, 13, 14]. The discharge produces a rapid and local heating of the gas leading to a pressure increase which forms an oblique shockwave. This shockwave impinges the rear-facing cavity on the opposite wall leading to a pressure increase in the cavity and a significant change in the flow structure of the cavity [15]. In addition, the strong spanwise non-uniformity of the discharge may provide streamwise vorticity which would enhance the mixing of the fuel and oxidizer. The work performed for this paper focuses on the characterization of the effect of plasma power and electrode geometry on the pressure increase produced in the cavity.

2. Experimental Facility

The experiments performed for this work were carried out using the SBR-50 supersonic blowdown tunnel. The tunnel was equipped with a Mach 2 Laval nozzle arranged inline with the rectangular test section. The cross-section at the nozzle exit is Y×Z=76.2 mm (width) × 76.2 mm (height) with the top and bottom walls expanding at a 1° half angle over a length of X=610 mm as measured to the beginning of the diffuser. The test section is a modular design which allows for pieces to be interchanged/designed for each experiment and for the side walls to be quartz to allow for excellent optical access. The top and bottom walls are inserts, made of stainless steel or nylon, and are equipped with 48 pressure taps (24 on the top and 24 on the bottom) which are connected to a 16 channel PSI 9116 pressure scanner. This provides a time series of static pressure measurements along the length of the test section sampled at 400 Hz. Schlieren imaging and high-speed imaging with a Photron Fastcam are used for viewing the flow field and Q-DC discharge, respectively. The basic configuration of the SBR-50 test section with an electrode array and planar walls is shown in Fig. 1.

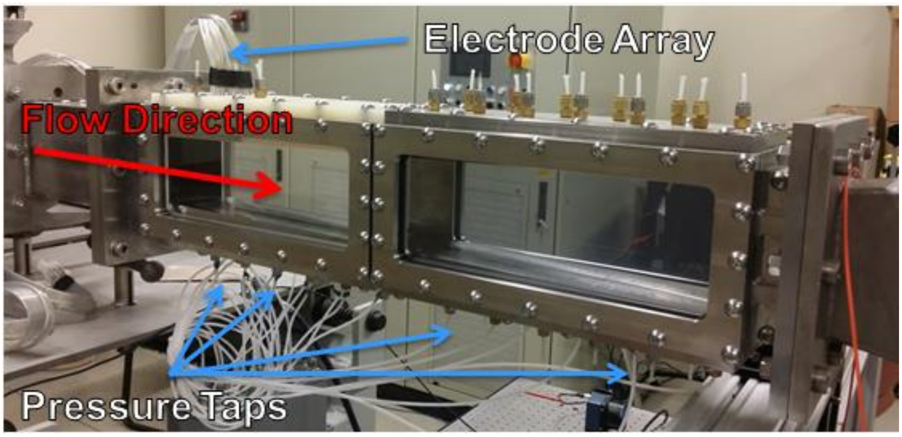

Fig. 1. SBR-50 test section at the University of Notre Dame equipped with planar walls.

An array of 7 or 11 brass electrodes are installed on the top wall with alternating anode and cathode in the spanwise direction (eg. ACACACA). This is used as a controllable shockwave generator and has been studied extensively in this facility [13, 14]. The wall insert is made of nylon, as shown in Fig.

1, and has a ceramic insert with the electrodes flush mounted on the test section surface. The wall insert with the electrode configuration is better shown in Fig. 2 along with the electrical diagram.

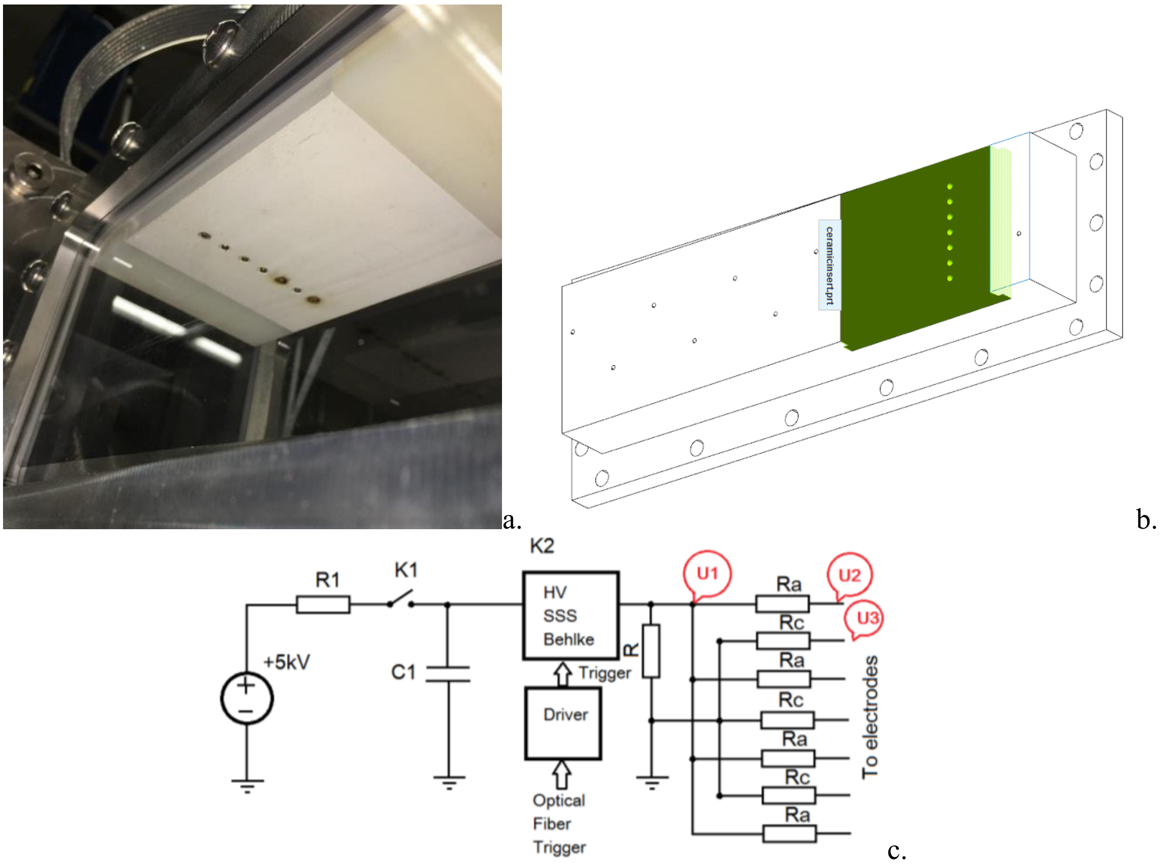

Fig. 2. 7 electrode array used for controllable shockwave generation a) installed in the test section b) 3D rendering showing the ceramic insert c) electrical diagram.

A typical test duration is approximately 1 second, with the Q-DC discharge operated for up to a few hundred milliseconds. This work concerns the application of the controllable shockwave generator used as a flow control authority in a test configuration with a rear-facing cavity on the opposite wall. This geometry is meant to simulate a typical flameholding scheme used for supersonic combustion. The generated shockwave impinges the cavity thus increasing the pressure and changing the structure of the flow field. This method is illustrated in Fig. 3.

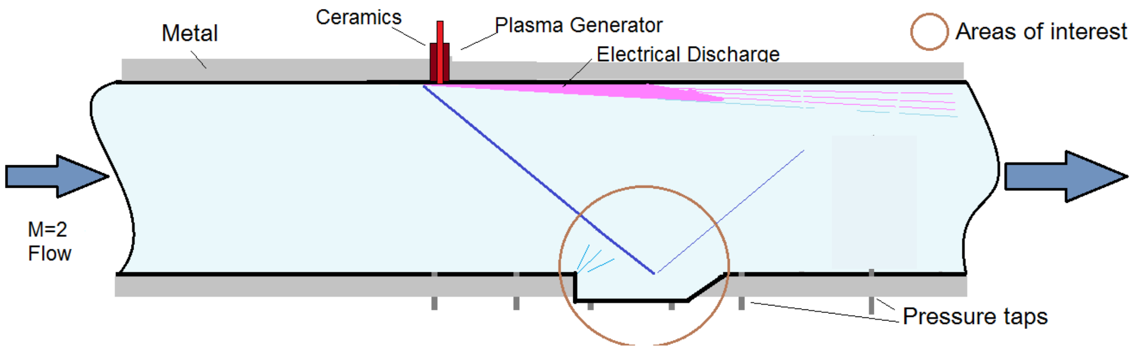

Fig. 3. Experimental configuration of the Q-DC discharge applied to a rear-facing cavity.

A custom made power supply is used for the operation of the high-voltage, high-power Q-DC discharge. It operates with a steep falling voltage-current characteristic with individual control of each output channel. Varying the output voltage of the power supply, U1, controls the output power of the plasma. The power supply operates in a nearly current-stabilized mode with a fixed ballast resistance on each channel. High-voltage probes and current probes measure the output voltage and corresponding current of the power supply U1, voltage across an anode U2, and voltage across a cathode U3. Typical electrical measurements are shown in Fig. 4. The instantaneous power deposition of the plasma fluctuates in the range of 8-20 kHz (depending on flow conditions) and is a reflection of the unsteady behavior of the plasma filaments. This oscillation is due to the strong coupling of the discharge to the flow. The process of the discharge oscillations is as follows: breakdown occurs across a gap between an anode and cathode, the flow velocity carries the ions downstream which increases the voltage across the gap, a critical length of the plasma filaments is reached and a new breakdown occurs closer to the electrodes [13, 14]. A sample image of the Q-DC discharge showcasing the structure of the plasma filaments is shown in Fig. 5.

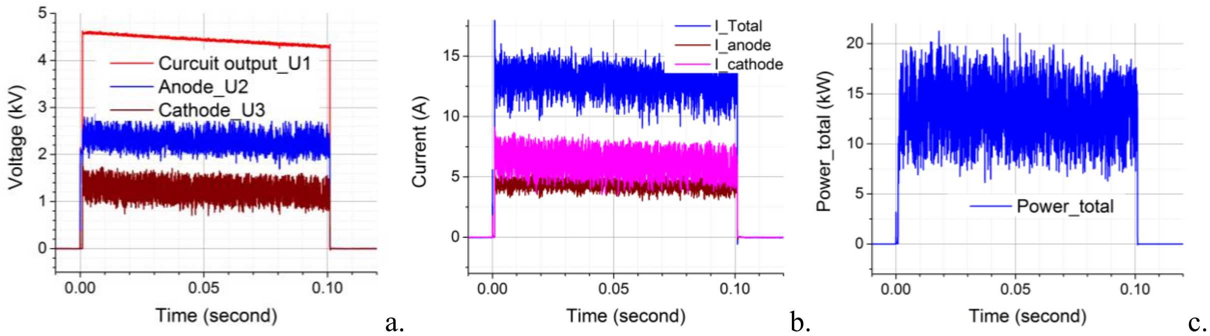

Fig. 4. Representative oscillograms of: a) voltage b) current and c) instantaneous power

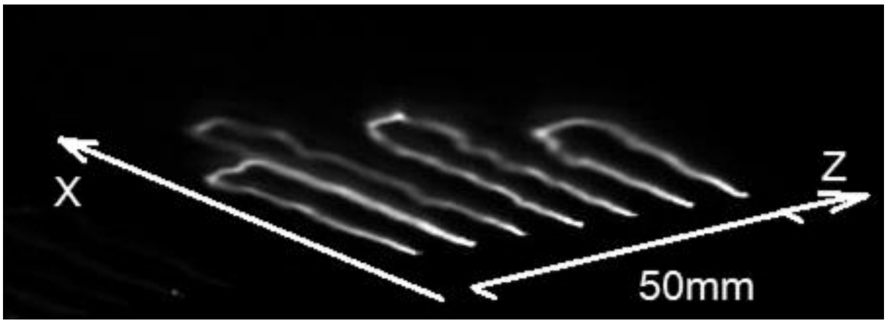

Fig. 5. Standard image of the Q-DC discharge with 4 µs exposure.

3. Experimental Results

Schlieren imaging provides a qualitative insight of how the Q-DC discharge affects the flow field. Figures 6 and 7 show the flow field at the front edge of the cavity and at the ramp on the downstream side of the cavity, respectively, with and without the Q-DC discharge in operation. The schlieren images have an exposure time of 50 µs, which essentially renders the schlieren images as time averages due to the speed of the flow. The bottom portion of the cavity is inaccessible for schlieren imaging due to the steel frames which hold the windows in place, as are some other portions due to the aperture of the schlieren system. Red lines denote the edges of the schlieren system and frame in Fig. 6. Figure 6b shows the plasma related shockwave impinging the cavity and interacting with the cavity/free shear layer resulting in a much weaker reflected shockwave. A new shockwave forms at the front edge of the cavity as a result of the Q-DC generated shockwave increasing the pressure in the cavity. As a part of the change in the flow field, the free shear layer shifts up toward the core flow slightly. The angle of the compression shock from the ramp, with respect to the ramp surface, increases as is shown in Fig. 7.

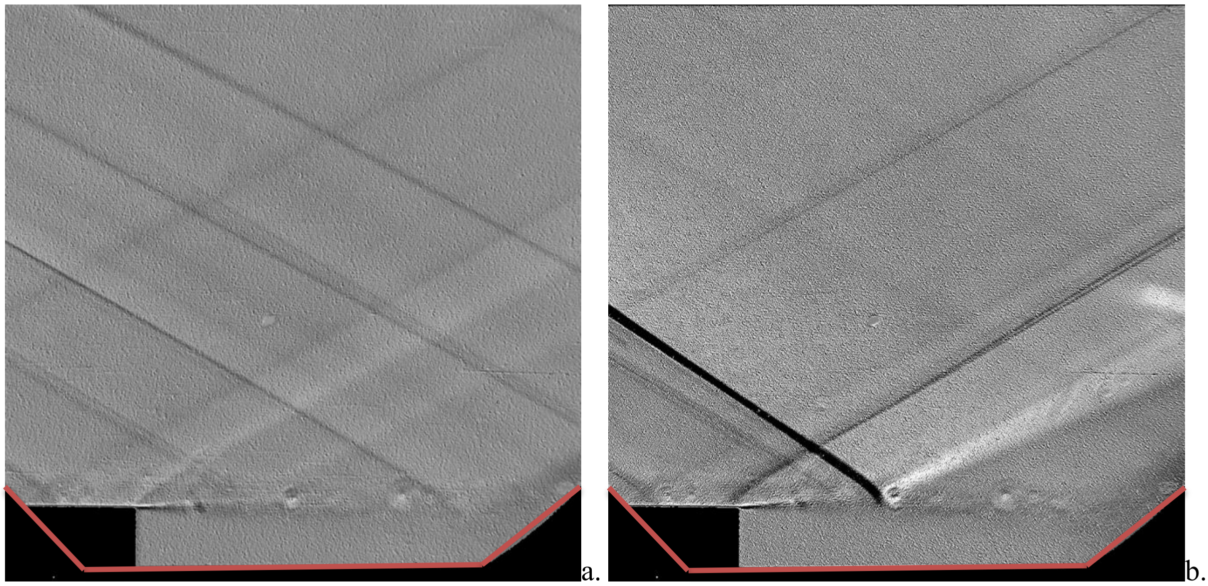

Fig. 6. Schlieren images of the top portion of the rear-facing cavity with plasma a) on b) off.

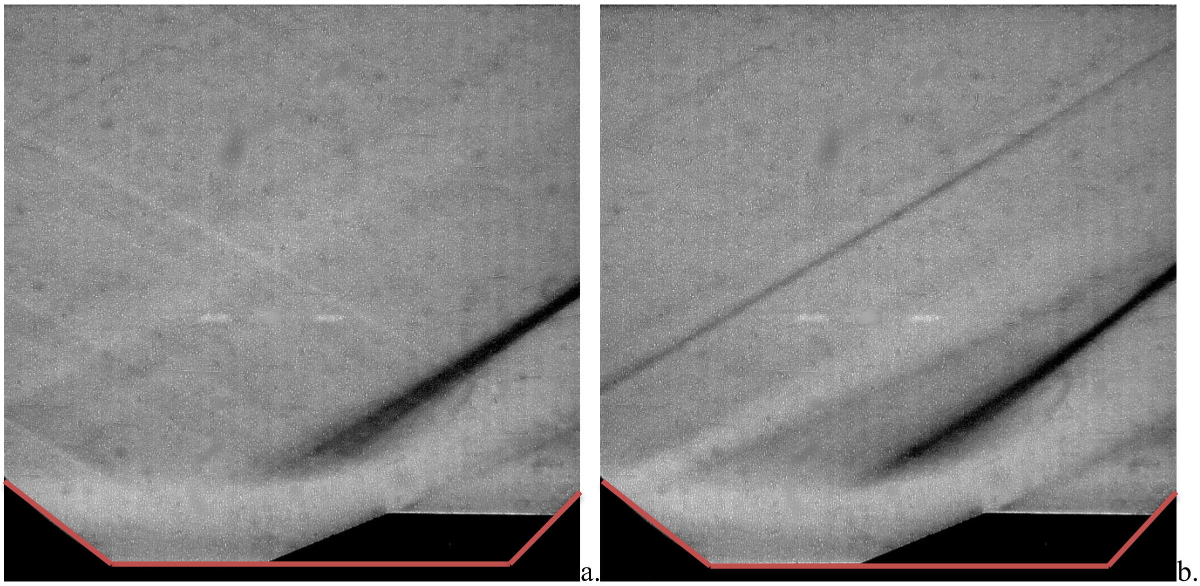

Fig. 7. The ramp at the downstream side of the cavity with plasma a) off b) on

The 16 channel pressure scanner provides static pressure distributions in the test section. Figure 8 shows the pressure distribution along the upper and bottom walls with 5 anodes and 6 cathodes in operation for the Q-DC discharge. Datasets are shown before the plasma is turned on, during plasma operation, and after plasma operation. The static pressure throughout the cavity increases during plasma operation in Fig. 8a. The cavity flow is a subsonic region which absorbs the pressure increase on the downstream side of the shockwave and redistributes it throughout the subsonic region. There is a sharp increase in pressure immediately downstream (x<20 mm) of the electrodes on the top wall where the plasma is influencing the flow the most. This is followed by a region along the top wall (50 mm<x<200 mm) where the pressure decreases due to separation and heating of the flow. The compression shock due to the ramp in the cavity produces a shockwave for which a pressure increase is seen without plasma operation approximately 290 mm downstream of the electrodes. When the plasma is turned on the pressure at this location decreases while the pressure increases at the neighboring upstream region. This indicates the compression shock due to the ramp changes angle, as shown in Fig. 7, most likely due to a lower Mach number and stronger pressure in the cavity. These same measurements were made for only 2 anodes in operation for the discharge and are shown in Fig. 9. The plasma shockwave generator with 2 anodes operating has the same effect but a lesser magnitude as when 5 anodes are operating. Since the cavity is a subsonic region, the power of the discharge rather than the geometry should be the dominating factor. This is confirmed in Fig. 10, where the pressure is measured directly behind the plasma generator, in the cavity, and on the ramp for 7 and 11 electrode arrays with varying power. The pressure increase due to the Q-DC shockwave generator is nearly the same linear trend for the 7 and 11 electrode arrays, with the 11 electrode array producing slightly more of a pressure increase. This may be due to the longer filaments of the 7 electrode array releasing its power over a larger area and some of this pressure increase may reach the opposite wall too far downstream to interact with the cavity. The 11 electrode system is slightly more effective than the 11 electrode system. As it is considered, the 11 electrode system has a smaller area of influence and can produce a larger pressure increase with equal power. It should be noted that the data points labeled as A1 in Fig. 10 are anomalous. The discharge did not connect across the gap which is in line with the pressure tap at that location.

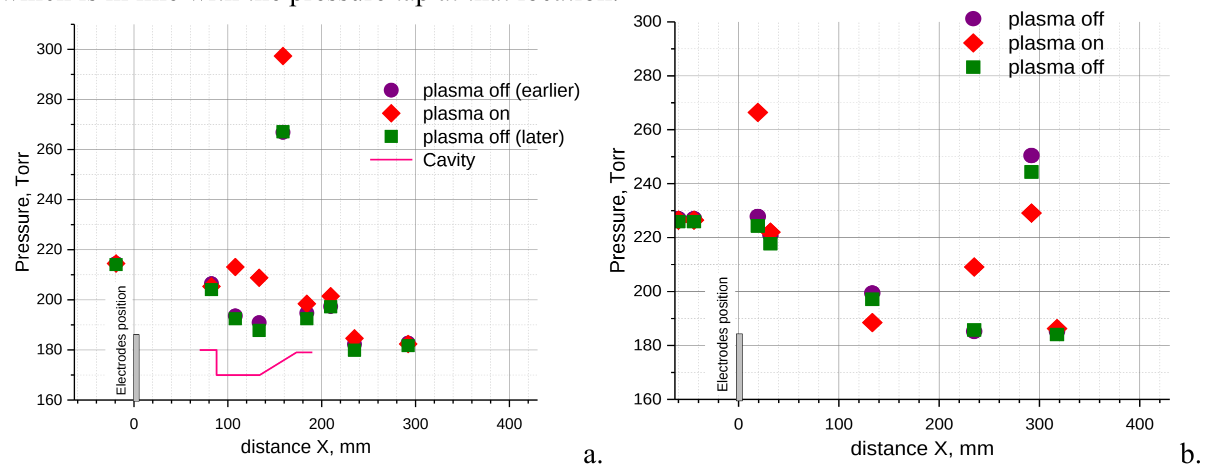

Fig. 8. Static pressure distribution along a) bottom wall with cavity b) top wall with plasma generator with 5 anodes on.

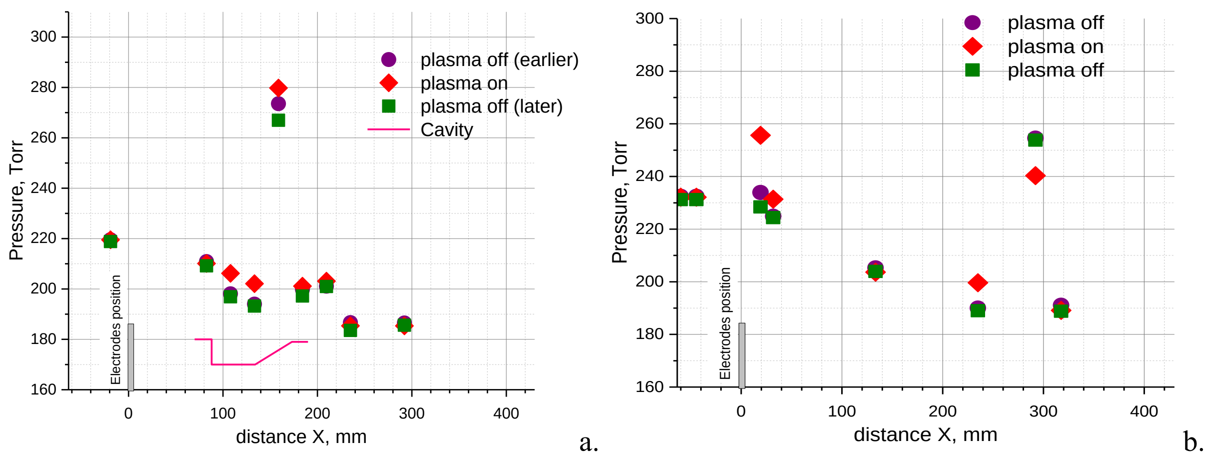

Fig. 9. Static pressure distribution along a) bottom wall with cavity b) top wall with plasma generator with 2 anodes on.

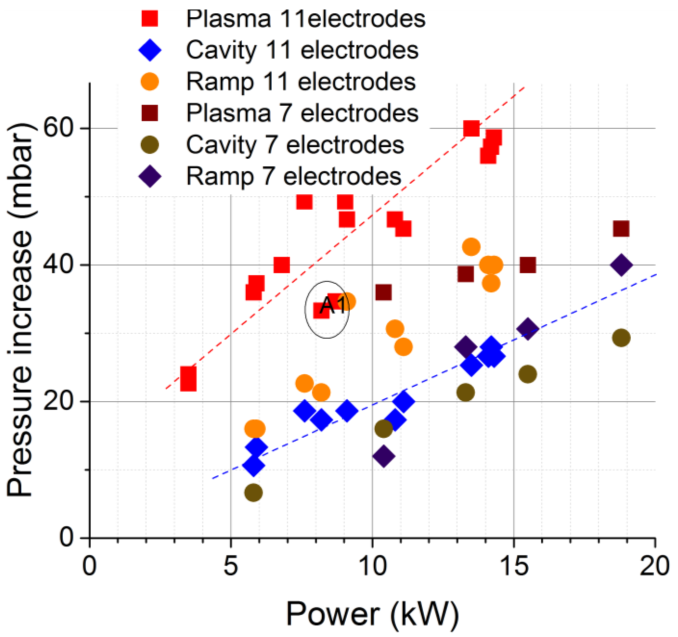

Fig. 10. Pressure increase as a function of average power for two different electrode arrays.

4. Summary

The quasi-DC (Q-DC) discharge was studied as a control authority to a supersonic flow with a rear-facing cavity, a geometry that imitates a typical flameholding scheme for a scramjet engine. The Q-DC discharge was used to generate an oblique shockwave which impinged a rear-facing cavity on a planar wall opposite the electrode array. Schlieren imaging shows the generated shockwave interaction with the cavity and the free shear layer which developed between the cavity and core flows. The cavity is a subsonic region that absorbs and redistributes the pressure increase of the shockwave. This causes the static pressure in the cavity to increase and the cavity to slightly enlarge which creates a new shockwave at the front edge of the cavity. This new flow field structure slightly moves the free shear layer up towards the core flow. Different electrode geometries and powers were tested, revealing that the plasma power is the dominating factor for increasing the pressure in the cavity rather than electrode geometry. The cavity absorbs any pressure increase and redistributes it throughout the entire recirculation flow because it is a subsonic flow region. Thus having a wider area of influence on the cavity is not as important as the power of the electrical discharge. There is a nearly linear relation between power of the Q-DC discharge and pressure increase experienced by the cavity. It is suggested that the 11 electrode system is slightly more effective than the 7 electrode system. This is due to formers ability to produce a larger pressure increase with equal power along with its ability to be better targeted due to its smaller region of influence produced from shorter plasma filaments.

The Q-DC discharge can be used in this arrangement to positively influence the combustion environment of a scramjet engine at off-design conditions. Increasing the pressure in the cavity increases the amount of oxidizer present in the cavity. This allows for more fuel to be in the cavity, if the same stoichiometric ratio is to be used, and thus can increase the heat release in this region. The upward shift of the free shear layer into the core flow can increase the entrainment of fuel for non-premixed fuel injection along the wall in which the cavity is installed. More studies need to be done in order to fully characterize the capabilities and flow control authority of the Q-DC discharge with this flow geometry. Future studies will include varying flow temperature, implementing the Q-DC discharge into a metal wall (as opposed to the nylon and ceramic wall used thus far), moving the impingement location of the shockwave, and placing the discharge on the same wall as the cavity.

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