

Plasma-Assisted Control of Mach-2 Flowfield over Ramp Geometry

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Abstract. This study examined the effect of Reynolds number on plasma-assisted flow control ahead of a compression ramp geometry in Mach-2 supersonic flow. The experiments were conducted in the supersonic wind tunnel SBR-50 at the University of Notre Dame. Stagnation temperature and pressure were varied as $T_0=294\text{--}500\text{K}$ and $P_0=1\text{--}3\text{bar}$ to attain Reynolds number ranging from $3.4\times 10^5\text{--}2.2\times 10^6$. Ramp pressure measurements, schlieren visualization, and high-speed camera imaging were used for the evaluation of plasma-assisted flow control effects. A linear dependency was found between the ramp pressure change per averaged plasma power and Reynolds number.

1. Introduction

Plasma-based flow actuators are gaining a good deal of research attention. When plasma-assisted flow actuation is applied to surface flow control on a supersonic vehicle, it can modify the aerodynamic characteristics of said vehicle. It has several advantages over conventional mechanical actuators [1-3], two of which are a short response time due to electrical actuation that will realize quick flow-control operation and the simplicity of the device structure will prevent any mechanical failure by eliminating movable parts. Especially in case of high speed vehicles such as supersonic transports, the quick-response feature will be highly beneficial to the prevention of delay in generating an aerodynamic moment. In case of supersonic transports, a vehicle will travel several kilometers if the aerodynamic control is delayed for one second, and it will deviate from the designated orbit. However, if the delay in aerodynamic control can be reduced by plasma-assisted flow control, it will be highly useful in keeping the desired orbit and thereby minimize fuel consumption for trajectory modification. Therefore, plasma-based aerodynamic control is considered to be promising in realizing efficient and more secure flight.

Flow control techniques in supersonic flow were examined by Leonov et al. and they found that the near-surface electrical discharge was useful for surface flow modification, shock formation, and flow modification purposes [3-5]. They also found great utility in combustion and flameholding inside scramjet engines [6, 7]. Therefore, it is expected that plasma-based flow control is promising both for internal flow control and for flow modification around a supersonic vehicle. In this work, the main research interest is plasma actuation ahead of a body-flap geometry, which has been found to be beneficial to the pitching moment control of high-speed vehicles. Watanabe and Suzuki investigated



the Mach-7 hypersonic flow control ahead of 20-degree ramp geometry [8, 9]. A schematic drawing of this plasma-assisted flow control is illustrated in Fig. 1. In these studies, plasma actuation was found to be beneficial when a pair of electrodes was installed ahead of ramp geometry, which is a simplified form of space vehicle and its body flap. As in Fig. 1(a), electrodes are located ahead of flap/ramp geometry to generate plasma that leads to flow separation and subsequently changing the pressure distribution over flap/ramp geometry as illustrated in Fig. 1(b). When plasma actuation was applied to the 20-degree ramp geometry, pitching moment acting on the ramp surface can be controlled by 10-20 percent within 0.09 seconds. Hence, it is clear that plasma-based flow actuation is highly effective in high-speed flow.

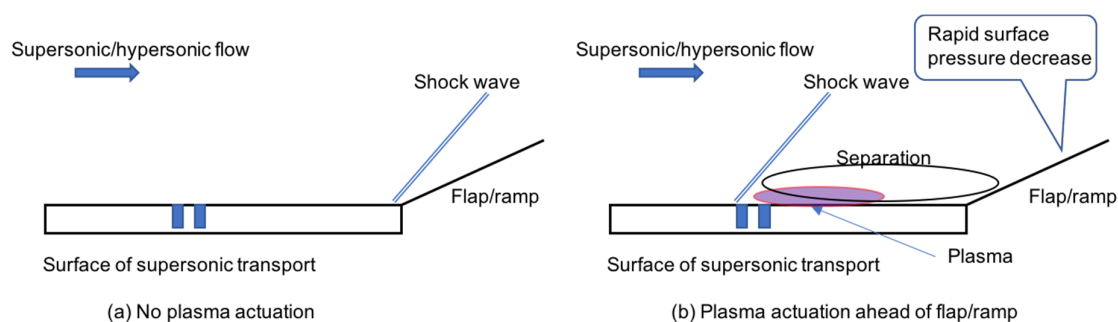


Figure 1. Plasma-assisted aerodynamic control ahead of flaps for supersonic/hypersonic transport.

Although a number of studies have focused on plasma-assisted supersonic flow control, most of them are done on the lab-scale basis, and thereby it is still necessary to clarify the scale effect, i.e. Reynolds number effect, before applying the plasma-assisted flow control method to practical-scale problems.

In light of the background above, experimental investigation was carried out in Mach-2 supersonic flow. The objective of this work is to examine the effect of Reynolds number on plasma-assisted flow control ahead of a ramp by correlating Reynolds number with parameters such as plasma power and ramp pressure change.

2. Experimental facility and instrumentation

2.1. Supersonic wind tunnel

The experiments were carried out in the supersonic blow-down wind tunnel SBR-50 at the University of Notre Dame. A photographic view of the wind tunnel facility is shown in Fig. 2. The test section is connected to a vacuum tank. A Mach-2 supersonic nozzle, plenum chamber with an ohmic heater, and high-pressure reservoir are connected to the upstream side of the test section. The plenum chamber pressure can be adjusted by a wind tunnel control panel, but the actual stagnation pressure is identified based on the static pressure at the nozzle exit. In the present configuration, Mach-2 supersonic flow is realized at the test section, which has 76.2 mm x 76.2 mm rectangular cross section at the nozzle exit and a 1-degree inclination along the upper and bottom walls to avoid choking the flow. The wind tunnel offers the stagnation temperature from room temperature up to 800 K. The stagnation pressure can be controlled ranging from 0.1 to 5 bars. The flow duration is 1 second at maximum. In the present work, the stagnation pressure P_0 was changed from one atmospheric pressure up to 3 bars and the stagnation temperature T_0 was varied from 294 to 500 K. By changing stagnation temperature and pressure, various Reynolds number conditions were achieved with Reynolds number ranging from 3.4×10^5 to 2.2×10^6 based on the characteristic distance, 55 mm, measured from the nozzle exit to the leading edge of the ramp surface along the flat test-section wall. While the flow at the test section was steady, plasma-assisted flow control was applied for 0.1 second.

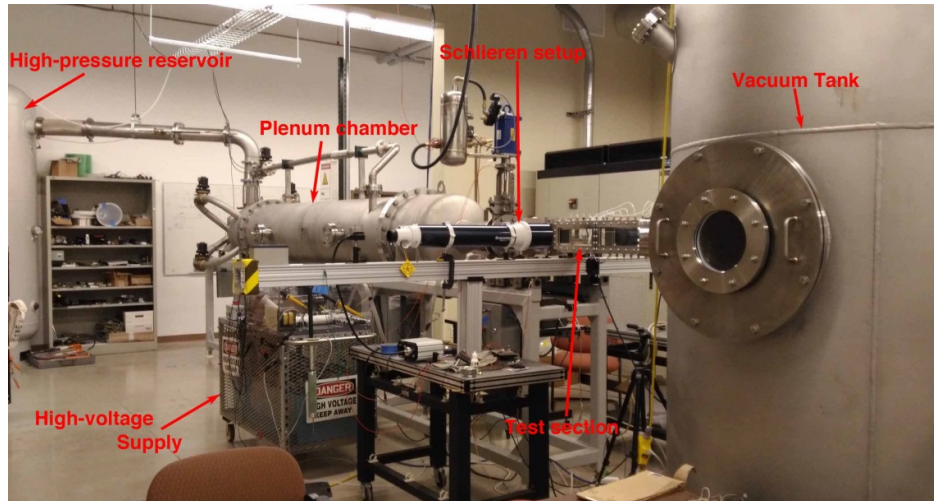
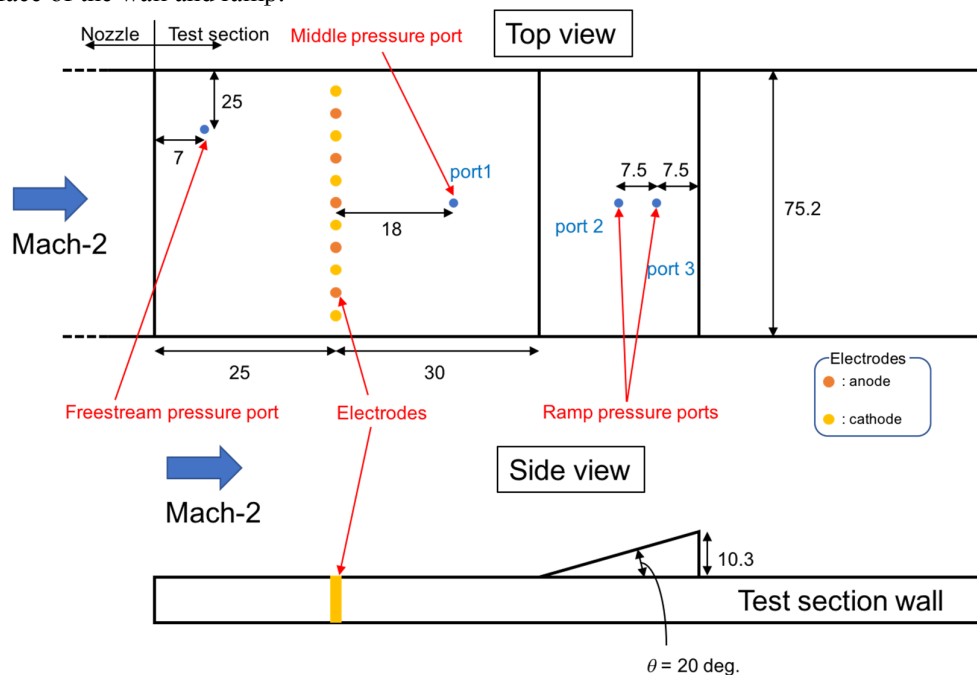


Figure 2. Supersonic wind tunnel SBR-50 at the University of Notre Dame.

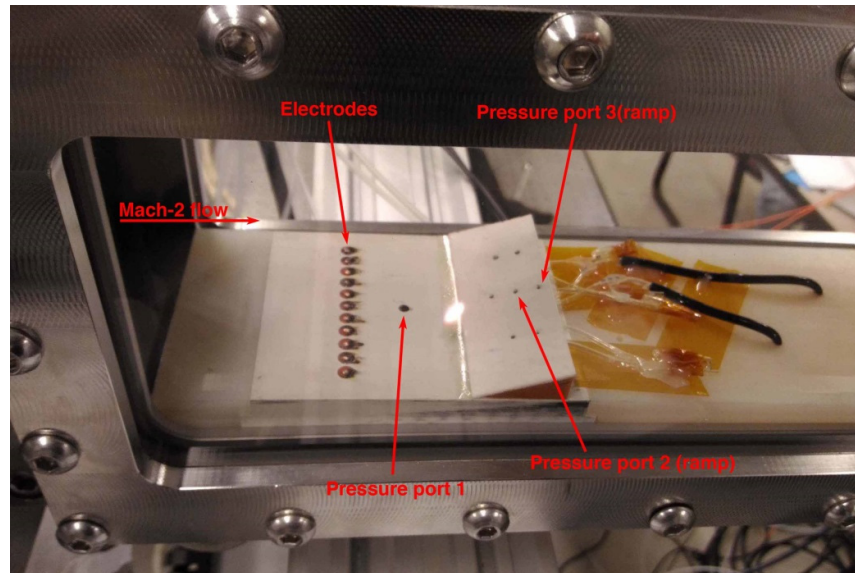
2.2. Ramp model

Schematics of the ramp model are illustrated in Fig. 3. It has 11 electrodes flush mounted on the wall in the transverse direction, 5 of which are anodes and the others are cathodes. A 20-degree ramp with 12 mm height was attached with the leading edge 30 mm downstream of the electrodes as illustrated in Fig. 3(a). The ramp surface was made of an alumina ceramics plate with 1-mm thickness. It has pressure ports along the center line, with their location indicated in Fig. 3(a). The ramp angle was set to 20 degrees to match up with a previous experiment in reference [9] that was tested at higher Mach number.

The ramp model was fixed in the test section as shown in Fig. 3(b). Both side walls are made of quartz and visualization was conducted through these windows. There are several pressure ports over the surface of the wall and ramp.



(a) Geometry of ramp model (units are in millimeters).



(b) Ramp model assembled with test section.

Figure 3. Ramp model.

2.3. Measurement

Flow visualization, pressure measurement, and measurement of plasma power were conducted in the wind tunnel tests for the purpose of clarifying changes to the flowfield.

2.3.1. Visualization

Flowfield and shock wave visualization were conducted by schlieren method in order to examine the change of flow structure induced by plasma. High-definition images were captured using a Basler camera with 2048×2048 pixel sensor at a rate of 133 fps. Although the imaging rate was low for supersonic flow, the exposure time for each image was <1 μ s. This was achieved using a pulsed NIR laser diode. Using this method essentially “freezes” the flow allowing for a clear instantaneous view of turbulent structures within the flow.

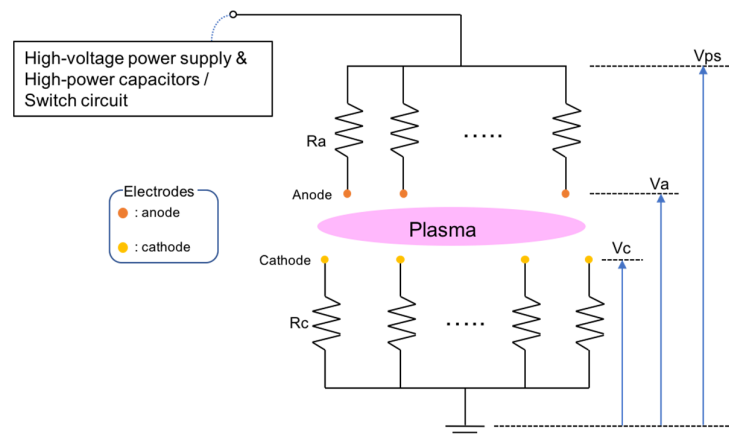
2.3.2. Pressure measurement

Pressure measurements were made using a differential pressure sensor, TE NetScanner™ Model 9116. The reference pressure of this sensor was kept at the atmospheric pressure. Pressure data were recorded at the sampling rate of 400 Hz. In this work, there were 4 pressure ports which were especially important in evaluating the effect of plasma actuation: freestream pressure port, middle pressure port (port 1), and ramp pressure ports (port 2 & 3) as illustrated in Fig. 3(a). The freestream pressure port provides pressure at the nozzle exit, which is used to identify the stagnation pressure value by assuming the designed Mach number of the nozzle to be 2.0. The middle pressure port 1, located between electrode array and the ramp provides pressure value just at the downstream side of electrodes. Pressure ports 2 and 3 are located at the ramp surface. Pressure at these points is the direct indicator of plasma actuation effect over ramp geometry.

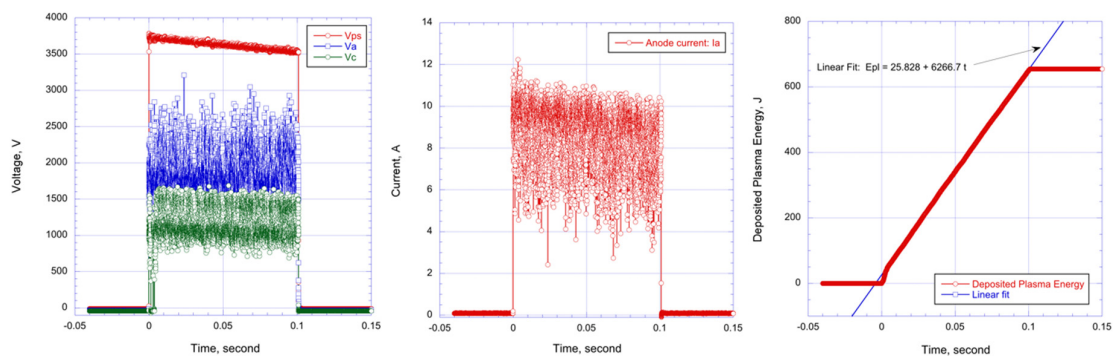
2.3.3. Plasma power measurement

The custom-made power supply [7] for plasma generation in the SBR-50 wind tunnel was used in the present flow-control experiments. Simplified schematics of the electrical circuit and typical waveforms of voltage traces are shown in Fig. 4. In this circuit, a high-voltage power supply and high-power capacitors are connected to 5 anodes through current-limiting resistors, R_a , as illustrated in Fig.

4(a). 6 cathodes are wired to the ground level through current-limiting resistors, R_c , which are also illustrated in Fig. 4(a). Total voltage supplied from the power supply circuit, denoted by V_{ps} , was recorded with an oscilloscope, Agilent Technologies DSO-X 4024A, through high-voltage probes at 800,000 samples per second. Anode and cathode voltage, V_a and V_c , were also measured together with V_{ps} and typical voltage traces are shown in Fig. 4(b). These voltage values were used to identify averaged discharge power. In this work, averaged plasma power P_{pl} was calculated as follows: (1) calculate total current I based on anode current I_a as $I = N_a I_a = N_a (V_{ps} - V_a) / R_a$ where $N_a = 5$ is the number of anodes and $R_a = 1 \text{ k}\Omega$ is the resistance of each anode resistor. It is also possible to find the total current I based on cathode current, but it is less accurate because the wind tunnel facility itself is at the ground level voltage and a small portion of the current is lost by going through the metal walls of the wind tunnel. Therefore, in this work, total current I was calculated based on the anode current. (2) Then, plasma power at each moment W_{pl} is calculated by $W_{pl} = (V_a - V_c) I_a$. (3) By integrating W_{pl} , deposited plasma energy $E_{pl} = \int W_{pl} dt$ is obtained. Since the slope of E_{pl} during plasma actuation was found to increase almost linearly, the averaged plasma power P_{pl} was finally calculated by applying linear fitting to E_{pl} plot. In case of typical plot shown in Fig. 4(b), the averaged plasma power was found to be 6.3 kW.



(a) Schematics of electric circuit and parameters.



(b) Typical plots of electric parameters. (left plot: voltage traces, center plot: calculated anode current, right plot: deposited plasma energy and result of linear fit)

Figure 4. Schematics of circuit and typical traces of electric parameters.

3. Experimental result and discussion

The wind tunnel tests were conducted by varying stagnation pressure, stagnation temperature, and power supply voltage to attain various Reynolds number conditions. In the present study, stagnation

temperature and pressure were varied as $T_0=294\text{-}500\text{K}$ and $P_0=1\text{-}3\text{bar}$ to attain Reynolds number ranging from 3.4×10^5 to 2.2×10^6 . Quasi-steady plasma actuation results were observed in all test cases.

A pictorial view of a typical plasma-based flow control test is shown in Fig. 5. It is clearly seen that bright discharge zone was generated ahead of the ramp and the purple light emission from the vibrational mode of nitrogen molecules was observed during plasma actuation.

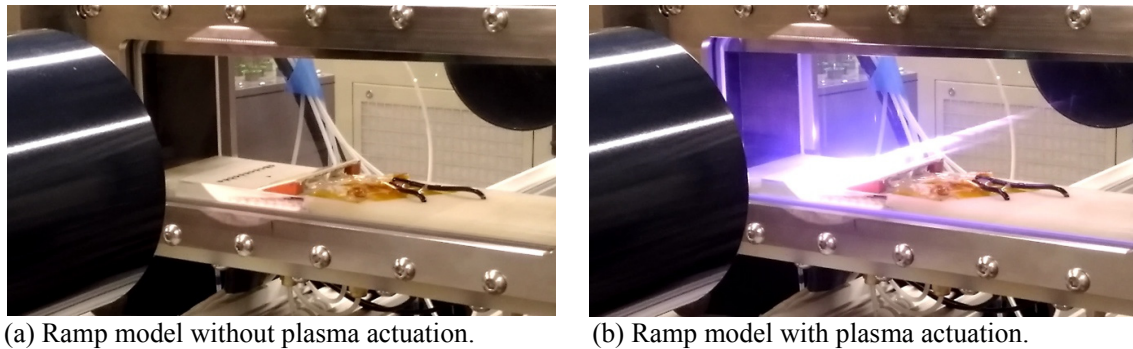


Figure 5. Photographic view of typical plasma-assisted flow control test.

A snapshot image of a typical plasma filament, observed between electrodes and the ramp, is shown in Fig. 6. Periodical change in the transverse plasma filament location was confirmed in the images, but the change in streamwise plasma filament position was negligible. This can be because there was a separation zone formed ahead of the ramp which is on the downstream side of the electrodes. Therefore, the transverse filament was trapped inside the separation and exhibited periodical change.

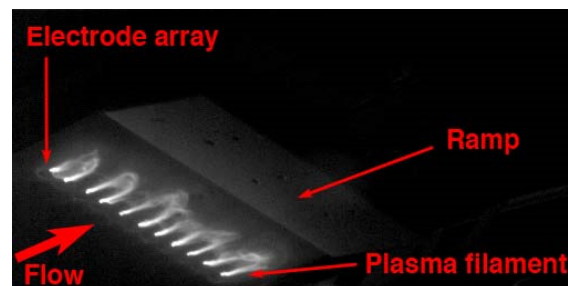


Figure 6. Typical plasma filament image from high-speed visualization.

From Fig. 6, it is suggested that significant flow heating took place because of the plasma filament and thereby it is expected that flowfield change was induced ahead of the ramp. Schlieren images are shown in Fig. 7, which exhibit significant change in shock positions. Similar change in the shock position was also observed in all the test cases. Prior to plasma actuation, the shock wave at the ramp was formed at almost 45 degrees to the flow. This shock wave was generated almost at the leading edge of the ramp but the shock front was a slightly ahead of the tip. This is because the ramp angle, 20 degrees, is very close to the shock detachment angle at Mach-2. While the plasma was turned on, the shock location shifted upstream and formed just ahead of the discharge. In Fig. 7(a), the shock wave at the ramp is almost 45 degrees to the flow, which is slightly smaller than the shock angle, 53 degrees, obtained from oblique shock relation. Similarly, in Fig. 7(b), the plasma-related shock wave formed at the electrodes is almost 34 degrees to the flow, which is also slightly smaller than the Mach angle: 30 degrees. The difference in actual shock angles from those obtained from theoretical relation can be caused by the flow acceleration due to 1-degree inclination of wind tunnel walls and also because of significant flow heating that took place at rear side of the shock waves.

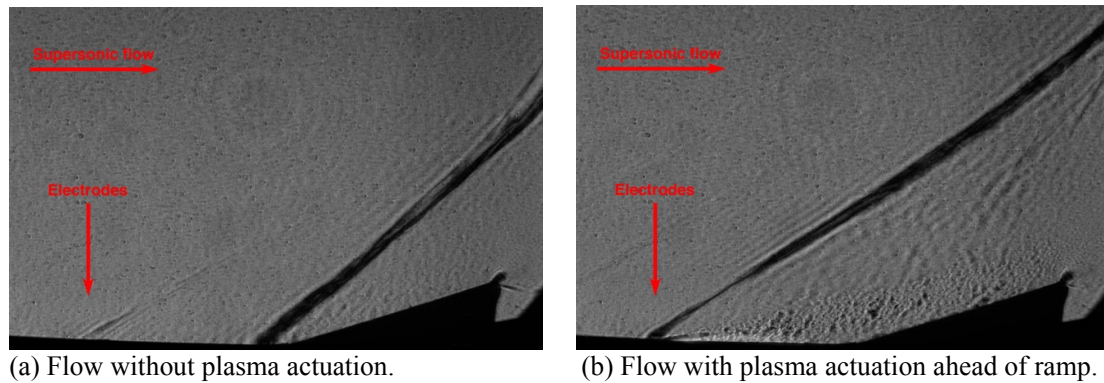


Figure 7. Snapshot images of typical flow actuation test.

Since there was significant change in shock locations, it is expected that there was a significant pressure change at the rear side of the electrodes and along the surface of 20-degree ramp. Typical pressure variation is shown in Fig. 8. A pressure rise was observed on the downstream side of the electrodes, which is a consistent result with previous research without the ramp [3]. However, a significant pressure drop was observed along the surface of the ramp at ports 2 and 3. This is evidence that the plasma actuation ahead of a ramp/flap can control pressure force and thereby cause a change in the pitching moment acting on the flaps. The pressure plot in Fig. 8(a) also suggests that the pressure curves of port 2 and 3 are almost identical and hence, separation ahead of the ramp was negligible when there is no plasma actuation. In the following discussion, the ramp pressure drop was evaluated based on the pressure at port 2 and quantified according to the definition of pressure drop illustrated in Fig. 8(b).

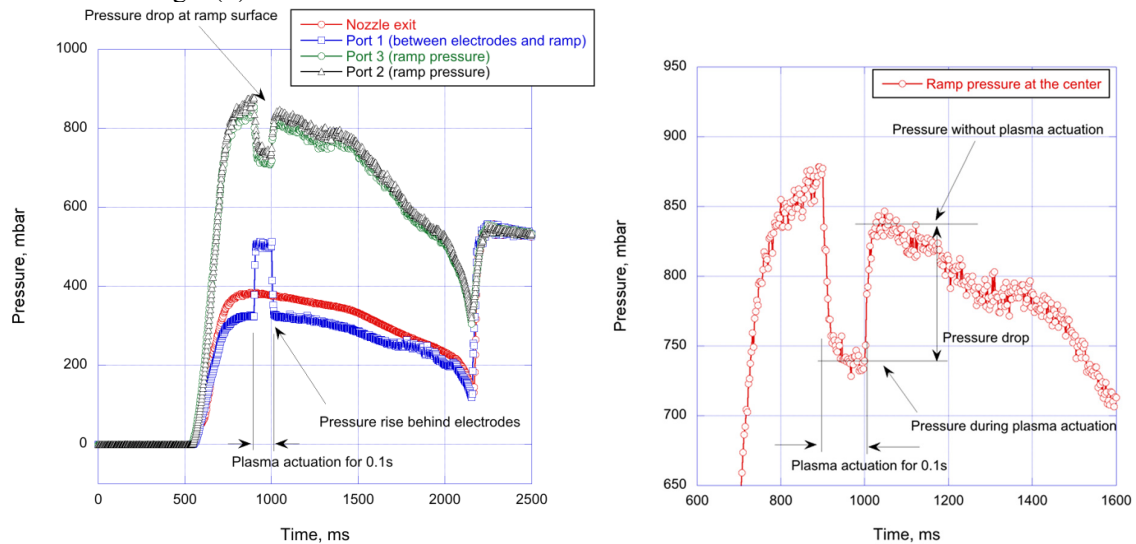


Figure 8. Pressure plot in typical test.

In this work, Reynolds number was varied by changing stagnation pressure and temperature independently. Averaged plasma power was also changed based on various flow conditions and it ranged from 4-12 kW. The averaged plasma power variation with Reynolds number is shown in Fig. 9. Since the tests were done at constant pressure condition and at constant temperature conditions, these results are plotted respectively in Fig. 9; red circle denotes $P_0=1.7$ bar constant pressure tests,

blue rectangle for $T_0=294$ K tests, green triangle for $T_0=400$ K tests, and black rectangle for $T_0=500$ K tests. From Fig. 9, there is a trend that average plasma power increases with an increase in Reynolds number. This would be because, when the temperature T_0 is constant, the Reynolds number increase is attained by the increase in pressure P_0 and thereby increase in air density. Under a higher density environment, it is obvious that heat generation is realized in thicker air and it caused higher plasma power consumption. From the aerodynamic viewpoint, higher Reynolds number makes the boundary layer thickness smaller. This will cause the plasma filament to be kept close to the wall. Since the filament is formed inside the boundary layer and separation zones, smaller boundary layer volume would realize more dense plasma region to attain higher plasma power values.

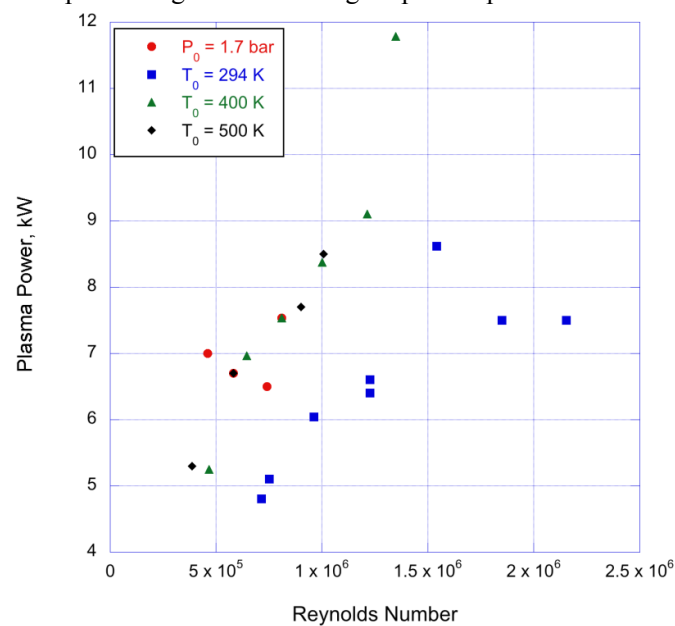


Figure 9. Averaged plasma power variation with Reynolds number.

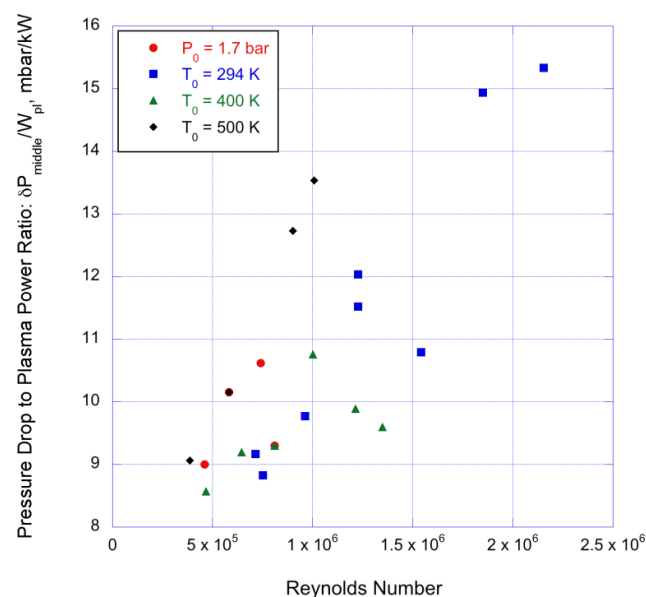


Figure 10. “Pressure drop per plasma power” variation with Reynolds number.

Although the ramp pressure drop and Reynolds number did not exhibit a distinct correlation, the quantity ramp pressure drop per averaged plasma power, which is a kind of pressure drop efficiency per power, showed linear dependency on Reynolds number as shown in Fig. 10. At constant temperature conditions, the increase in Reynolds number is realized by increasing the freestream pressure and density. Therefore, it is reasonable that, at higher Reynolds number, the pressure change will be greater than the flow with smaller freestream pressure. According to the experimental results, plasma power increases with increase in Reynolds number but the pressure drop increase seems to be much greater than those of plasma power. Since pressure drop per averaged plasma power is a kind of indicator for how efficiently plasma actuation is conducted, it is concluded that, in the present experimental conditions, the plasma actuation is more efficient at higher Reynolds number.

4. Conclusion

Plasma-assisted flow control ahead of 20-degree ramp geometry was examined with Mach-2 supersonic wind tunnel experiments and the effect of Reynolds number on flow control properties was also investigated. It was found that ramp pressure drop per averaged plasma power depends almost linearly on Reynolds number variation and, therefore it is concluded that plasma actuation is more efficient at higher Reynolds number flows.

Acknowledgements

This work was supported by Grant-in-Aid for Young Scientists (B) No. 16K18307. The first author appreciates the FlowPAC Institute, University of Notre Dame, for providing opportunity to use SBR-50 wind tunnel for this work.

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