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Effect of DC-discharge geometry on ignition efficiency in supersonic flow

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Abstract. The plasma-assisted combustion is considered as a prospective approach for ignition of a hydrocarbon fuel and flameholding in a supersonic airflow. Stable flameholding of gaseous and liquid hydrocarbon fuel was achieved by means of surface Q-DC discharge without employing mechanical flameholders in a supersonic combustion chamber. However, a high level of electric power, typically required to realize this method, may limit its application in a real apparatus. The current experimental and computational efforts continue the study of a distributed plasma system with the aim of reduction the total energy consumption and extending the life cycle of the electrode system. In the work described in this paper, the interaction of two separated plasma modules was investigated. The fuel ignition caused by individually controlled plasma modules was explored showing a significant effect of the plasma filament length on ignition efficiency.

1. Introduction

The plasma-assisted ignition and flameholding based on surface DC discharge is known as a realizable method to stimulate combustion in a supersonic flow [1-2]. In work [3], the feasibility of plasma actuators was investigated for ignition of hydrocarbon fuel in high-speed airflows. From the viewpoint of entire system design, it was demonstrated that the plasma torch employing air or oxygen for plasma generation is effective for ignition and flameholding in a scramjet. The work [4] considers the mechanism of ignition due to generation of hot zones of highly excited gas with peak temperature up to 5000 K at a low total input power about 2kW. Results from these studies suggest that the DC torch is more effective in producing a flame than the AC torch with a similar levels of input peak power for the configurations tested. In work [5], various configurations of fuel mixtures used for injection into the plasma torch were considered. It was found that stability of plasma-stimulated combustion significantly depends on the chemical composition of injected mixture: for example, stability of the plasma jet drastically improved with the addition of a small amount of O2 to the feedstock. In Ref [6], plasma jets were used for ignition of the liquid fuel (kerosene). Results of this study indicate that the critical factor affecting the ignition of liquid hydrocarbon fuel in the scramjet is the mixing of the fuel with oxidizer. One of the possible ways of mixing improvement, ignition, and flame-holding can be use the plasma actuator based on Q-DC discharge [7]. It was applied for ignition of gaseous hydrocarbon fuel in a wide range of flow conditions without employing mechanical
flameholders in a supersonic combustion chamber. The complication in employment of plasma-based actuators for ignition and combustion support in high-speed airflow is typically associated with high power consumption. In order to develop the technology, an intensive work is carried out to reduce the total power deposited in the discharge keeping the ignition to be still feasible. The reduction in power intended for plasma generation not only reduces the power requirements for entire system, but also extends the lifetime of the electrodes, which is especially important at long-term use without an option for emergency replacement of the units. Reduced power budget also positively affects the volume and weight associated with the power supply of the combustion support system in a flying vehicle.

The typical discharge power in a series of previous experiments was about 12-18 kW for model combustor with 60x70mm cross-section and Mach number M=2 flow [7], which is a reference point for the current research described in this paper. Previously it was shown that distributed plasma system, consisting of two plasma modules, accelerates the combustion process comparing to a single plasma module [8]. These test series, to some extent, verify the two-stage mechanism of plasma-assisted ignition and combustion [9]. The current experimental and computational work continues to investigate the plasma-based system based on distributed electrodes arrangement, which beneficial in terms of total energy consumption and potentially allows the extending the life cycle of the electrode system.

2. Experimental setup

The experiments were performed in supersonic wind tunnel PWT-50 of JIHT RAS. Flow parameters were as follows: Mach number M=2, static pressure $P_0=170$ torr, and stagnation temperature $T_0=300K$. Detailed description of experimental facility could be found in work [3]. Fuel injectors were flush-mounted on the wall in the test section and provided fuel supply perpendicular to the flow. In our experiments, ethylene injection was used in a range of mass flow rates $G_{\text{fuel}}=0.5-4\,\text{g/s}$. Two ceramic inserts with $\Omega1.5$ mm electrodes are located downstream of the fuel injectors to create a quasi-direct current (Q-DC) discharge near the wall. Each insert has 8 electrodes placed in pairs (anode-cathode), with a distance between the centers of the electrodes in one pair of 5mm and the distance between the electrodes from the adjacent pairs is 7mm. Both electrode systems were powered independently of each other through two fast high-voltage solid-state switches. The main idea of testing the described system was to organize two low-power electric discharges that cannot ignite the fuel separately, but, when working together, they provide stable ignition and combustion. This approach is based on the concept of a two-stage combustion mechanism in a supersonic flow [5]: first, a cold flame is realized that promotes the production of active particles, and after a while (in supersonic flow conditions, we can talk about the distance traveled by the elementary volume of the mixture) the hot flame arises, which is characterized by active heat release and ensuring the growth of pressure. The reduction in the power of one of the plasma actuators or even its shutdown can be the next step, since it is expected that the combustion mode requires a lower discharge power in comparison with moment of fuel ignition.

![Figure 1](image.png)

**Figure 1.** Wall of test section: 1 – $\Omega1.5$ mm fuel injectors with 0.5-4g/s ethylene flow rate, 2 – electrodes of first actuator, 3 – electrodes of second actuator
3. Experimental results for simultaneous operation of two actuators

3.1. Interaction of two actuators

The first series of experiments was performed without fuel injection to test the operation of the actuators - each individually, as well as their joint work to explore the effect of plasma operation of different modules on each other. The following feature was observed during these tests: activation of the first actuator leads to a decrease in the length of the plasma filaments and a voltage reduction on the second plasma module. This can be clearly seen at following test sequence: initially the second actuator (which is downstream) was turned on, after a while, the first one was turned on (which is located upstream). After activation of first actuator the discharge voltage on the second actuator was reduced from 1200V to 700V, and discharge length was decreased in 1.8-2 times. For this experiment, voltage time series for both actuators and images of plasma filament of second actuator at different period of time are presented in figure 2.

![Figure 2](image_url)

**Figure 2.** Typical voltage dependencies on time for first and second actuator (a) and typical discharge images of one loop for second actuator for different time moments (b)

In order to explain this effect, numerical modeling of supersonic flow in a rectangular channel was performed, whose geometric dimensions and flow parameters correspond to the experimental ones. The simulation was performed in the software package FlowVision 3.10.02. The simulation is based on the solution of a three-dimensional nonstationary system of Navier-Stokes equations supplemented by the k-ε model of turbulence using wall functions for modeling the boundary layer. The simulation took into account the work of only the first discharge module, while the discharge was modeled by a three-dimensional heat source inside the imported object with a total heat release close to the experimental one (1kW for one plasma filament or 2kW for one plasma loop). The imported object was located in the zone of the first actuator, and its shape was similar in shape to the discharge filament, 40 mm in length and 1.3 mm in diameter. The calculation was carried out for a thin three-dimensional layer with one half of the one discharge filament to decrease the number of cells and simulation time. The ceramic insertions from figure 1 (zones in which the actuators are located) are marked with purple rectangles in Figure 3. Analyzing the obtained results it is clearly seen (see figure 3) that the temperature of the gas flow downstream the 1st actuator significantly increases in the area of second actuator. But it is important that the temperature significantly depends on distance from actuator and at the distance more than 300mm it is restored close to initial state because of flow turbulence. Temperature increase is accompanied by decrease of the density and the voltage of breakdown for second actuator. This results in a decrease in the discharge length and a drop in power.
3.2. Ignition and flame-holding by two actuators

Experiments with fuel ignition using simultaneous operation of two actuators were performed at following conditions. After start of fuel injection with mass flow rate 3.8 g/s to the supersonic flow the first actuator was activated with pulse duration of 120 ms. The second actuator was enabled 60 ms later with pulse duration of 60 ms, so last 60 ms both actuators operate together. Work of plasma actuators without fuel has no perceptible effect on static pressure distribution along the test section, so all detected changes of static pressure distribution are caused only by combustion. During this experiment it was observed, that operation of only first actuator lead to weak combustion with medium increase of static pressure which is gradually increased along the test section, as it is shown in Figure 4. Additional activation of second actuator leads to significant improvement of combustion process: flame front moves upstream that is clearly seen by time dependency of pressure at 150mm point. This distance is measured from the injection position. And for all other points the pressure increase was detected that may confirm the improvement of combustion completeness. The displacement of the flame front to the first actuator area leads to a change in the nature of its operation. The length of the plasma filaments decreases, and the work of the discharge becomes less stable because the discharge filaments follow the streamlines in the separation zone caused by combustion.

Figure 3. Simulation of influence of 1st actuator operation on flow parameters in the area of location of second actuator. Flow is directed from left to the right. Density field is presented for all cross-section of test section, velocity and temperature are presented for layer near wall and the images are enlarged in y-direction at 2 times.

Figure 4. Pressure distribution during combustion for experiment with serial activation of plasma actuators
Obtaining active combustion in the case of operation of two actuators was expected based on the results of previous experiments. Also it was expected that turning of second actuator after obtaining active combustion with separation zone in the area of first actuator will keep the combustion quality at the same state because of important role of separation zone with Q-DC discharge as a plasma-chemical reactor. So turning off second actuator should reduce the power consumption of discharge system without decreasing the combustion efficiency. To test this hypothesis the following experiment was performed. Ignition of 3.8 g/s ethylene into the supersonic flow with Mach number M=2 was organized using two actuators and after obtaining the regime of active combustion with separation zone in the area of first actuator the second actuator was disabled. Time dependencies of electrical characteristics of both actuators are presented in Figure 5. After activation of first actuator (I=2A for one loop, U=0.9-1.2kV, total power W=4.2kW) medium pressure increase was detected. Next activation of second actuator 40 ms later (I = 3A for one loop, U=300-400V, total power W=1.8kW) results in pressure increase and change in character of 1st actuator operation. Length of discharge decreases together with voltage drop that can be seen in figure 5 (0.05-0.08 s). But after turning off the second actuator it was obtained that pressure caused by combustion restores to the values obtained at activation of only first actuator. And it is clearly seen in figure 5, voltage drop of first actuator also restored to the state before second actuator activation. So in the presented case, second actuator plays significant role for obtaining stable effective combustion even after the displacement of the flame front to the first actuator area. For a detailed explanation of this result, additional research is required.

**Figure 5.** Time dependencies of electrical characteristics for both actuators.

### 4. Detailed investigation of single actuator

#### 4.1. Single actuator operation mode

As it was described in part 2, each series of electrodes consists of 4 pairs with a gap of 5 mm between the electrodes in a pair and a gap of 7 mm between the electrodes of neighboring pairs. It was expected that such distances between electrodes in pair and neighboring pairs will provide barrier for the interaction of separated plasma loops. And as a result of such geometry of electrodes the configuration of plasma filaments presented in Figure 6(a) should be realized. But actually such configuration was realized only for short time after discharge activation. At the later time moments the plasma filament which is located close to neighboring earth electrode, could reconnect to this electrode. As a result the operation mode with shared ground electrode is realized. It was found that reconnection has no significant effect on the 1st loop which stays connected to the initial electrodes. But for the second loop reconnected to another ground the inter electrode gap increases, that lead to the increase of discharge length, voltage drop and power impact to the discharge, as it is shown in Figure 6(b-c). This mode also has a double current in one ground electrode, and this is a stable configuration, because the reconnection of second loop to initial ground electrode was not detected.
Figure 6 Change of plasma actuator operation mode. (a) Initial discharge configuration after activation of discharge (b) Stable configuration with shared ground electrode (c) Time dependence of voltage drop on discharge

4.2. Influence of discharge length on ignition

It was found that a configuration with a shared grounded electrode is capable to ignite the fuel mixture in several conditions then two non-interacting operated loops of one electrode row can’t ignite the fuel, but both configurations have the same energy impact into the discharges. Next series of experiments were carried out to verify the influence of discharge length and local power increase due to the double current to the filament attached to the shared ground. For this purpose two following geometries of electrodes were used. To organize two independent loops with 5mm gap between electrodes (mode 1) two separate loops were spaced apart from each other by a distance of 19 mm, which made it possible to exclude the possibility of a breakdown into shared ground (see figure 7a). Second circuit (mode 2) was realized using 5 mm distance between adjacent loops, and the gap between the electrodes was 7 mm (see figure 7b). In order to prevent the breakdown of discharge to the non ground in this case, the arrangement of electrodes was changed by the following way: pair cathode + pair cathode/anode, so gap between two cathodes was 5 mm. Also ballast load for limitation of discharge current was installed on cathode side of discharge gap (normally it was installed on anode side). Also the possibility of fuel ignition in the supersonic flow by one plasma loop with 7mm gap between electrodes was tested (mode 2b).

Comparison of three presented cases was performed at fuel mass flow rate 3.8g/s. Stable ignition of fuel was obtained for all tested cases. Pressure distributions along the test section for main cases are presented in Figure 8. Two significantly different variations of combustion activity were obtained during series of experiments. First one is characterized by low pressure increase during significant distance of 300 mm after discharge, and only after point of 320mm the significant pressure gradient was detected. This point corresponds to the separation area induced by oblique shock from the top wall of test section, as it is shown in simulation results in Figure 3. In this case the discharge has a stable operation and long straight filaments. The second variation is characterized by immediate pressure increase directly after discharge area and increase of pressure gradient along the length of test section after point of 320mm. In this case the discharge has an unstable length, shape and position of discharge filaments because of operation inside the separation area caused by flame front. It was found that obtaining of second variation of combustion is possible at following conditions: 6.5kW of power necessary at mode1, 5.6kW of power necessary at mode2 and 3.5kW of power was used in mode2b. The typical discharge power in a series of previous experiments was about 12-18 kW for similar
experimental conditions [7], so obtained reduction of power required for realization of stable active combustion is significant. Apparently, obtained reduction of power caused by an increase in the discharge length that provides the increase of the interaction time of the plasma with the elementary volume of the mixture.

![Figure 7. Geometrical configurations of tested plasma actuators.](image)

**Figure 7.** Geometrical configurations of tested plasma actuators.

- **Mode1** – two plasma loops with 5mm discharge gap,
- **Mode2** – two plasma loops with 7mm discharge gap.

![Figure 8. Pressure distribution along the test section for different discharge regimes at fuel mass flow rate 3.8g/s.](image)

**Figure 8.** Pressure distribution along the test section for different discharge regimes at fuel mass flow rate 3.8g/s.

**Conclusions**

Experimental study of distributed plasma system for ignition and flameholding of ethylene in supersonic flow was performed. It was found that the first plasma actuator affects the operation of the second one: the activation of the first actuator leads to the voltage drop on second actuator on ~40%, and discharge length decreases in 1.8-2 times. For understanding of this effect, the numerical simulation of the supersonic flow with volumetric heat source in the location of the first actuator was performed. It was found that this heat source leads to decrease the density and velocity of gas in the area of second actuator that results in decrease the discharge length and the average discharge voltage. The tests of distributed plasma system demonstrate that activation of second actuator after ignition by the first actuator improves of combustion efficiency. However, a following turn-off of the second actuator leads to the restoration of the flame front position and the distribution of wall pressure over the test section.

The detailed study of operation of a single actuator shows that the reconnection of one discharge loop to the ground electrode of adjacent loop results in increase the discharge length and power deposition in the discharge. To verify the effect of discharge length on ignition and combustion pattern, the comparison of plasma actuators with different discharge gap (5mm and 7mm) was performed. It was found that, for intensive combustion, the actuator with 2 plasma filaments (4 electrodes) and 5mm gap should provide the power deposition of 6.5kW and 5.6kW for a weak
combustion. However, operation of the actuator of same geometry but 7mm gap results in intensive combustion already at 5.6kW. To observe the intensive combustion, the minimal plasma power of 3.5kW was achieved using one plasma loop (2 electrodes activated) with 7mm discharge gap that is significantly lower than typical discharge power in the experiments with plasma-assisted combustion.

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