

Advanced Ignition in Supersonic Airflow by Tunable Plasma System

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Abstract. The plasma-based technique was studied for ignition and flameholding in a supersonic airflow in different laboratories for a long time. It was shown that flameholding of gaseous and liquid hydrocarbon fuel is feasible by means of surface DC discharge without employing mechanical flameholders in a supersonic combustion chamber. However, a high power consumption may limit application of this method in a real apparatus. This experimental and computational work explores a distributed plasma system, which allows reducing the total energy consumption and extending the life cycle of the electrode system. Due to the circuit flexibility, this approach may be potentially enriched with feedbacks for design of a close loop control system.

1. Introduction

For the purpose of a multi-regime scramjet development, many studies were conducted to explore a plasma-based ignition system, alternative to mechanical one, that could consistently and reliably ignite non-stoichiometric mixtures at low temperature and high speed of atmospheric flight. The most technologies of ignition rely on high energy density electrical discharges to heat and ionize the mixture and initiate combustion due to a mechanism of flame propagation or chemical activation [1-3]. In the case of fuel ignition in a high-speed flow and plasma-based flameholding, there are two main approaches: (1) ignition in separation zone, which then works as a chemical reactor (pilot flame), and (2) application of high power electrical discharges in a free stream or fuel jet. In the model #1, several research groups work under combustion in supersonic flow using different geometrical configurations [4-6]. They utilize plasma only as an igniter of combustible mixture. An example of the second case is the study employed a microwave discharge and its combinations with DC discharge [7]. We advocate a viewpoint that the most successful way for the combustion promotion in high-speed flow includes not only mixture ignition, but also the mixing intensification at non-premixed conditions [8], and control of the flow structure to improve the conditions for a flame stabilization (flameholding) [9].

High power consumption of plasma assisted ignition and flameholding technology may limit its application in a real apparatus. For resolving this problem a distributed tunable plasma system is considered in this work. Two rows of electrodes were flush mounted on the ceramic wall of supersonic test cell downstream of wall-mounted injectors of gas fuel (ethylene in this work). The first electrode row was located closer to the injectors and second electrode series was installed downstream of the first row on distance which prevent the electrical breakdown from the first row to the second one. Both electrode systems were powered independently via two fast high voltage solid-state switches. Main idea of described system is to organize two low-power electrical discharges which can't ignite the fuel



separately but, working together, capable to ignite the fuel. The next step may be in decrease the power of one of plasma actuator or even turning it off, because it is expected that flameholding needs a lower discharge power than the fuel ignition.

In general, this approach is based on concept of two-stage mechanism of fuel ignition in supersonic flow described in Ref. [10]. During the first stage, the plasma induces a fuel reforming, which may be simplified as production of H_2 , CH_2O , and CO . Despite the bright luminescence, this zone does not experience significant temperature and pressure increase. This so-called cold flame [11] appears as a source of active chemical species that initiates (under favorable conditions) the second stage of normal "hot" combustion, characterized by high temperature and pressure rise.

2. Description of experimental facility

The experimental facility PWT-50 of the JIHT RAS was designed as an alternative to a full-scale test rig in accordance with the following requirements: flow parameters are close to those typical for the combustion chamber of scramjet; operating time is much longer than the characteristic gasdynamic time; dimensions of the test section are much greater than the thickness of the boundary layer; gas-dynamic duct has flow expansion zones; amount of fuel injected is small in order to avoid dangerous operation, but is sufficient to observe physical and chemical effects; the number of experiments is 10-50 per working day; usability for the installation of high-voltage equipment and diagnostics. The experimental setup is equipped with a closed test section with a cross-section $Y \times Z = 72 \times 60 \text{ mm}$. The flow parameters are as follows: initial Mach number $M = 2.0$ or 2.3 , static pressure $P_{st} = 100\text{-}250 \text{ Torr}$, Reynolds number $Re = (4\text{-}10) \times 10^6 \times L$, thickness of the boundary layer does not exceed 1mm in the test region, typical gas flow through the channel $G_{air} = 0.6\text{-}0.9 \text{ kg/s}$, duration of the steady-state phase $t = 0.2\text{-}0.5 \text{ s}$, the total enthalpy of the flow is $H_{tot} \leq 300 \text{ kW}$. Flow parameters vary from run to run insignificantly, which ensures high repeatability of the test results. A detailed description can be found in publication [12].

3. Details of numerical simulation

Numerical simulation (CFD) of the flowfield provides extended information on flow parameters and structure, which is challenging to acquire experimentally due to a limited set of diagnostic tools. In particular, an essentially three-dimensional distribution of fuel cross test section and along the combustion test cell is needed for a proper analysis of the chemical processes. To resolve this issue, as well as to evaluate the influence of the discharge on the supersonic flow, a three-dimensional nonstationary simulation of the supersonic flow in the test cell was performed, taking into account the direct injection of the fuel through the wall-mounted nozzles. The calculations were performed using software package FlowVision 3.10. Flow simulation was carried out by solving a three-dimensional time-dependent system of Navier-Stokes equations using a modified $k\text{-}\epsilon$ model of turbulence (URANS approach).

From experiments, there is known the value of static pressure in the subsonic part of the fuel injector, as well as the diameter of orifices and the static pressure in the test section of the channel. The fuel injector consists of 10 orifices with a diameter of $\phi 1.5 \text{ mm}$ and a distance of 5 mm between the centers, located on the same line across the channel. Under the conditions corresponding to the experimental ones, the modeling of fuel injection into core flow for a range of flow rates $G_{fuel} = 1\text{-}7 \text{ g/s}$ was performed. As a result of simulation the calibration curve was obtained for the fuel flow rate versus the pressure in the injector. The simulation visualizes the distribution of fuel near the wall of supersonic duct. The calculation grid was adapted to obtain good spatial resolution for fuel jets in the area of the test section wall, where the injector was installed. Number of cells was 4.2 million. Calculations were performed for half of the channel using the "symmetry" boundary condition to reduce the number of calculated cells and accelerate the calculation. Simulation results for cases with ethylene injection of $G_{fuel} = 1 \text{ g/s}$ and $G_{fuel} = 3 \text{ g/s}$ are presented in Figure 1. It is clearly seen that the discrete structure of the air-fuel mixture remains in the area of placement of the first plasma generator, and disappears to the place of location of the second plasma generator. Thus, relating to the fuel jets, the location of electrodes may be actually important for the first discharge module only. For the first discharge module, the composition of the

mixture has a periodic structure and varies significantly from the poor to the rich condition over the cross section. Based on results of simulation, the composition of the mixture allows to expect fuel ignition starting from $G_{\text{fuel}}=1.5$ g/s. It should also be noted that the air-fuel mixture in the region of the second plasma module can be considered suitable for plasma-stimulated combustion only starting from $G_{\text{fuel}}=2$ g/s, because at lower flow rates the mixture is lean yet. These data should be considered as a lower estimate because, in a real test cell, oblique shocks, caused by joints of sections and optical windows, and its interaction with boundary layer increase the level of turbulence in a near-wall region, which leads to a faster mixing.

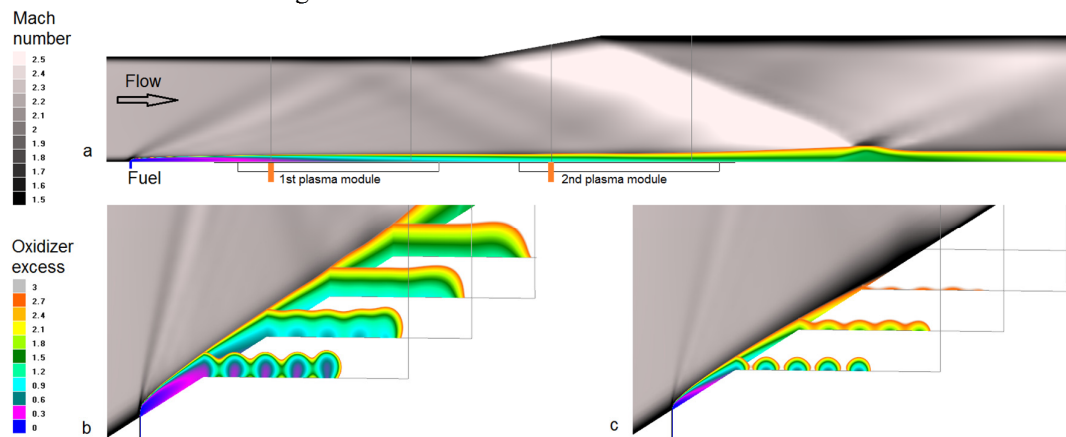


Figure 1. Result of CFD simulation for fuel injection to supersonic flow. a, b – $G_{\text{fuel}}=3$ g/s; c – $G_{\text{fuel}}=1$ g/s. First and third cross-sections corresponds to plasma module locations.

4. Single row plasma system

Distributed tunable plasma system considered in this work consists of two rows of electrodes which were flush mounted onto ceramic wall of supersonic duct downstream of the injectors of gaseous fuel (ethylene). First electrode line was located closer to the injectors (70 mm downstream) and second electrode series was located downstream of the first row on distance 140mm which prevent the electrical breakdown from first row to the second one. Each row of electrodes consists of 4 pairs with 5 mm gap between electrodes in pair and 7 mm gap between the electrodes of neighboring pairs. It was expected that such difference of gaps will protect plasma filaments from interaction with neighbors, and configuration presented in Figure 2(a) should be realized. But actually it was found that in this configuration the plasma filaments share the grounded electrodes, as it is shown in Figure 2(c). Such switching of discharge leads to increase the discharge length and power release (up to 50%) in comparison with expected mode.

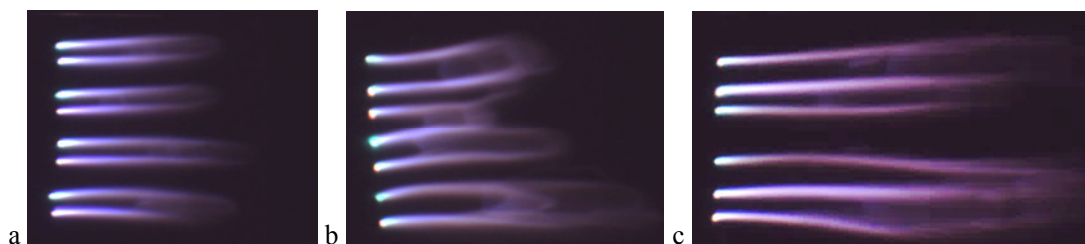


Figure 2. Modes of discharge operation. a – expected mode is realized at discharge initiation; b and c – modes with shared ground electrodes. Flow is from left to right.

Both electrode systems were powered independently via two fast high voltage solid-state switches. Discharge rows were powered by high voltage source with 5kV voltage using ballast resistors for discharge current limitation. Typical current, voltage and power time series for one discharge gap are presented in Figure 3. The length of discharge in flow is not a constant, it is significantly changes in time, and, as a result, it leads to significant fluctuations of plasma resistance which produce voltage and power oscillations. The rise of voltage corresponds to increase of plasma length and sudden voltage drop corresponds to a re-breakdown. Because of such a behavior, this type of discharge is called a Quasi Direct Current (Q-DC) discharge [13, 14].

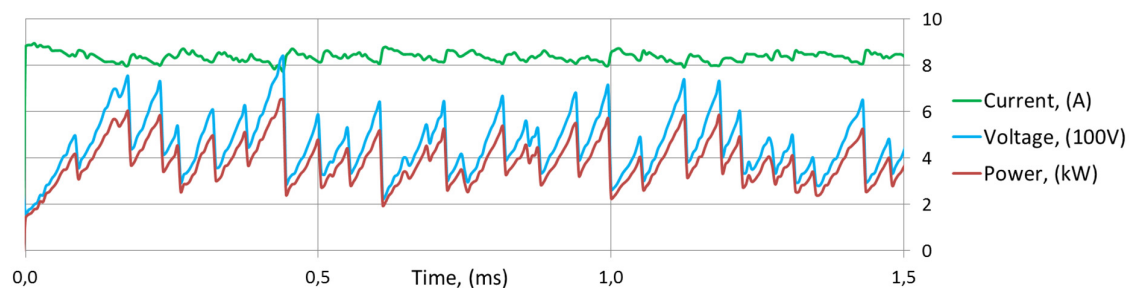


Figure 3. Typical electrical characteristics of Q-DC-discharge in supersonic flow for one gap. Increase of discharge filament length leads to increase the power release.

Influence of discharge operation mode on ignition of lean mixture was tested using second plasma module. In first case two non-interacting plasma loops (4 filaments case in Figure 4a) were used for ignition. In the second case electrical configuration with shared ground electrode were used (3 filaments case in Figure 4a). In this case a weak combustion was realized, as it is demonstrated in pressure distribution in Figure 4b. No combustion was observed in first case. This situation could be explained by increase of total power in the second case and significant local power increase caused by double current in the area of middle discharge filament. Thus, a special configuration with a shared ground could be preferable comparing to the standard electrode circuit shown in Figure 2a.

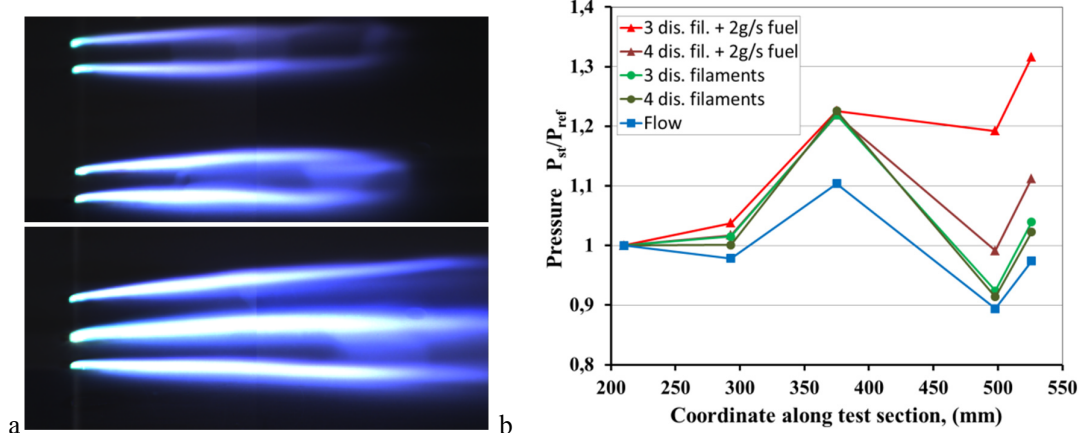


Figure 4. Influence of discharge operation mode on ignition: a – photos of discharge in case of non-interacting plasma loops (top) and shared ground electrode (bottom), b – pressure distribution;

5. Distributed plasma pattern

The test was performed with a distributed plasma pattern in a supersonic flow to confirm the concept of two-stage mechanism of fuel ignition. Fuel-air mixture, $G_{\text{fuel}}=2.5\text{--}3\text{ g/s}$, was affected by each actuator separately and the results were compared to the ignition data by distributed plasma system which contains two plasma modules working together. In these experiments the plasma power of the first module was about 8kW, and the plasma power of the second module was about 14kW.

All experiments were supported by schlieren visualization. Typical schlieren images are presented in Figure 5 for three cases: second discharge row only, second discharge plus fuel injection, and two discharge rows plus fuel injection. In all images upper wall demonstrates an undisturbed boundary layer. Flow disturbances near the bottom wall were caused by discharge in images (a) and (b), and by combustion in image (c). In the latter case, the wedge of the perturbations has a much larger size due to the expansion caused by flow pressure increase at combustion.

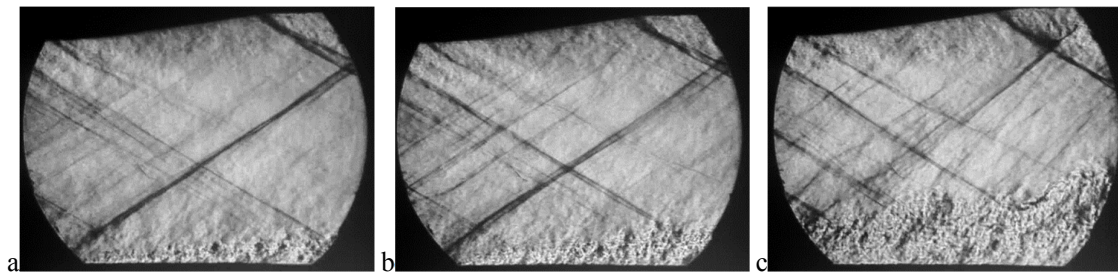


Figure 5. Schlieren visualisation: a - Dis02 only, b - Dis02+fuel 3 g/s, c - Dis01+Dis02+fuel 3 g/s. Flow is from left to right.

The fuel combustion leads to modification of flow structure: in the case of airflow without fuel injection an elongated discharge located along streamlines is realized, see Figure 6(a), and in the case of fuel combustion the discharge still follow the flow and the plasma filaments visualize the vortex structures which takes place in the combustion area. The discharge retreats from the wall, and its length is decreased, see Figure 6(b). In some cases, the resulting reverse motion led to a movement of the discharge opposite the direction of a core airflow.

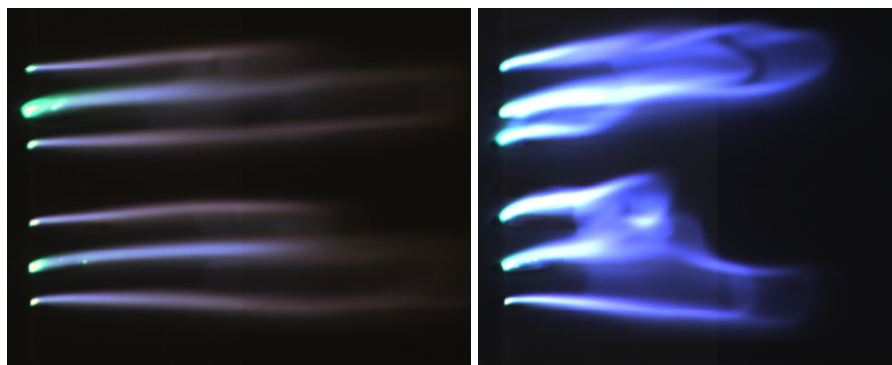


Figure 6. Photo of QDC-discharge (2nd actuator) in supersonic flow without fuel (a) and with 3g/s fuel (b).

Comparison of static pressure distribution for the described cases is presented in Figure 7. It was found that plasma modules (1st and 2nd in Figure 1(a)), working separately, cannot ignite such lean mixture at fuel mass flow rate $G_{\text{fuel}}=2.5\text{--}3\text{ g/s}$. Operation of the first plasma module results in an insignificant pressure increase at location near $x=200\text{ mm}$ in the test section, but there is no active

combustion downstream. Such behavior could be explained by means of occurrence of a partial fuel oxidation that did not develop to the “hot” combustion. Second plasma module results in weak combustion. It looks like that there is not enough length of the test section for a further increase of the combustion intensity and pressure. A fixed length of combustion chamber is one of limiting factors for development of scramjet: from this point of view the result at using two plasma modules at the same time looks to be the most interesting. In this case, a low pressure increase corresponds to the area between two plasma modules, whilst a rapid increase of pressure is observed in the region of the second plasma generator. The second plasma generator does not allow the flame to be blown out, and the preliminary processing performed by the first generator helps to accelerate the combustion process in the area of the second plasma generator. This test may be an implicit verification of a two-stage ignition mechanism. A more subtle use of this effect could allow reducing the power required for the plasma-assisted combustion in a high-speed flow.

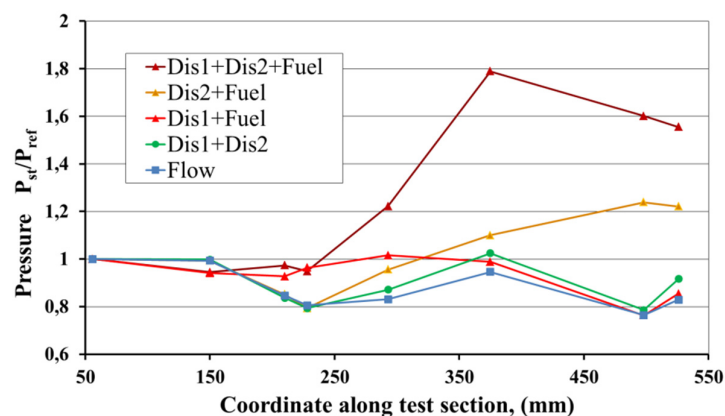


Figure 7. Pressure distribution: comparison of independent discharge systems cases with distributed plasma system which consist of two actuators working simultaneously.

Conclusions

Experimental study of distributed plasma system for ignition and flameholding for lean mixtures in supersonic flow was performed. The numerical simulation helped to improve a geometrical configuration of the test cell. It was found that the tested electrical scheme with shared ground electrode has some advantages in comparison with non-interacted plasma loops. Also it was shown that distributed plasma system, consisting of two plasma modules, accelerates the combustion process comparing to a single plasma module. These test series, at some extent, verify the two-stage mechanism of plasma-assisted ignition/flameholding.

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