Distributed plasma-assisted combustion system in supersonic flow

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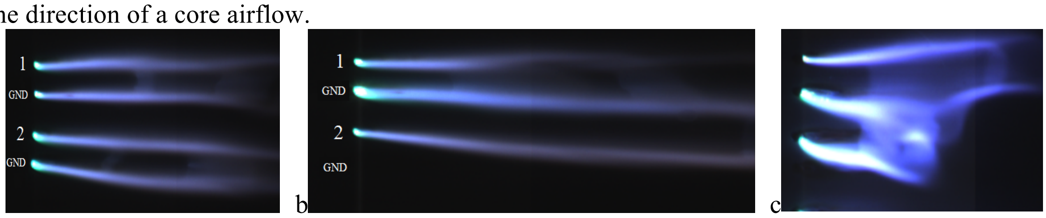
The plasma-based technique was studied for ignition and flameholding in a supersonic airflow in different laboratories for a long time. It was shown that flameholding of gaseous and liquid hydrocarbon fuel is feasible by means of surface DC discharge without employing mechanical flameholders in a supersonic combustion chamber. However, 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. 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 [1], and control of the flow structure to improve the conditions for a flame stabilization (flameholding) [2].

In general, this study is based on concept of two-stage mechanism of fuel ignition in supersonic flow described in Ref. [3]. 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 [4] 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.

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 Fig.1(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 Fig.1(b). Such switching of discharge leads to increase of discharge length, because the gap between electrodes is higher in this case and this allows the discharge to stretch more along the flow. As a result an increase of voltage and power release (because of constant current mode) up to 60% was obtained in comparison with expected mode.

The fuel combustion leads to modification of flow structure: 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 Fig. 1(c). In some cases, the resulting reverse motion led to a movement of the discharge opposite the direction of a core airflow.



a b c

Figure 1. Modes of discharge operation. a – expected mode is realized at discharge initiation; b - mode with shared ground electrode. Flow is from left to right. Switching of 2nd discharge to another ground leads to voltage and power increase; c – discharge at combustion

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, Gfuel=2.5-3 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.

Comparison of static pressure distribution for the described cases is presented in Figure 2. It was found that plasma modules, working separately, cannot ignite such lean mixture at fuel mass flow rate Gfuel=2.5-3 g/s. Operation of the first plasma module results in an insignificant pressure increase at location near x=200 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.

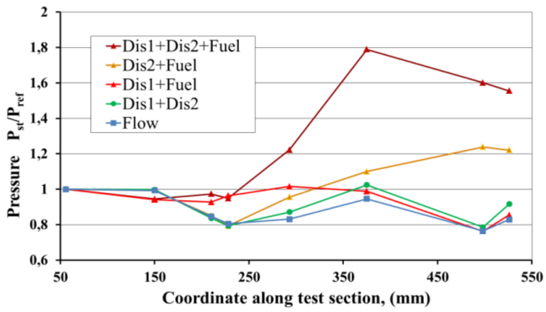


Figure 2. Pressure distribution: comparison of independent discharge systems cases with distributed plasma system which consist of two actuators working simultaneously.

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