Intensification of mixing of fuel with supersonic air flow when injection and electric discharge are combined

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Abstract. This paper presents the results of experimental investigations of DC discharge influence on mixing intensification of transvers injected gas jet into supersonic airflow. The air was used as injected gas to prevent the influence of chemical reactions on measurements. The data obtained during discharge includes current and voltage acquisition, registration of pressure pulsations in the jet downstream of discharge operation accompanied by correlation and Fourier analysis allowed to conclude that discharge significantly increase the pressure pulsations in a wide frequency range of 1000 Hz to 50kHz. Increase of the oscillations near the jet boundary is assumed to be related to kinematic mixing intensification of the injected gas with the oncoming flow.

1. Introduction

One of the most important tasks in the development of high-speed aerospace vehicle is to design an effective hypersonic ramjet engine that reliably operates in a wide range of velocity, pressure and temperature of the incoming air flow. The organization of energy-efficient engine operation requires the achievement of a high completeness of combustion, which is largely limited by an insufficient air/fuel mixing. Limited flow residence time (at the order of micro-seconds) for mixing of supersonic airstream and fuel in a scramjet combustor calls for the development of techniques for mixing enhancement [1] and it is why jet stability in cross-flow and different approaches to mixing is under active attention and investigations [2-3].

In addition to traditional mechanical and gas-dynamic approaches to mixing, the possibilities of using electrical discharges are also being considered because they widely used within the concept of plasma-assisted combustion in a supersonic airflow [4-5]. Preliminary studies [4, 6-7] have shown that an extended electric pulsed discharge introduces significant gas-dynamic perturbations into the flow and can serve as a promising solution to this problem. Later the possibility of mixing enhancement using short spark discharge was demonstrated [8]. The appearance of the current channel leads to intense heat generation. Due to the effect on the baroclinic term in the vorticity equation, it accelerates the mixing of injected fuel with the incoming air flow. As a result, the completeness of fuel combustion increases.

Q-DC discharge also can generate significant perturbations at the interface between the fuel and the airflow, which could improve the mixing [4]. Thus, an important factor is the area where the electric discharge is localized. Localization of DC discharge in the case of colocation injection point and one...
of discharge electrodes was discussed in work [9]. It was shown that, in a medium with a concentration gradient of the components, the preferred localization of the discharge is based on the balance of processes of molecular dissociation and ionization. It was confirmed that discharge locates in a mixing layer so the next step is quantitative description of discharge influence on the mixing. Q-DC discharge is significantly unsteady even on a flat wall without jet, and geometry and pulsations depends on flow parameters [10]. Flow configuration with Q-DC discharge collocated with cross flow jet in supersonic airflow has a complex structure [4, 11]. Therefore it is important to describe the influence of discharge on the jet flow and mixing.

2. Measurements

General scheme or experiment is presented in figure 1. The experimental study was carried out in a supersonic wind tunnel PWT-50 at JIHT RAS under the following conditions [4]: Mach number $M = 2$ (air flow velocity 500 m/s), static pressure $P_{st} = 26kPa$, gas temperature $T = 170 K$, tunnel cross-section 72x60 mm. Steady state flow duration was 500ms. A ceramic insert was flush mounted with the test section wall and equipped with a secondary gas injection port: profiled nozzle $M = 1.8$, exit diameter of 4 mm. The mass flow rate of the injected gas was $G_f = 2.5-7$ g/s, which corresponds to the jet momentum ratio $J=0.8-2.8$. Jet duration was 300ms and was initiated after 100ms of steady flow operation. Air was used as injected secondary gas to prevent the influence on chemical reactions on results. The metallic nozzle of the injector and the metal wall surrounding the ceramic insert were used as the electrodes for generation of the Q-DC discharge. The injector is connected to the high-voltage power supply of $\pm 5$ kV through a ballast resistor that limits the discharge current. The discharge current was fixed to $6 \pm 0.25$ A, current pulsations were based on oscillations of discharge length (and resistance). Discharge voltage oscillated in a range of 700-1400V. The metal wall was grounded. The duration of the discharge was 80 ms and it was activated after 80ms of jet operation. Such duration of discharge allows us to consider the average flow in the region of the discharge as steady. The structure of the flow in the absence of discharge was typical for the case of transverse gas jet injection into the supersonic flow. The oblique shock was located in front of the jet, with the separation region formed at the leeward side of the jet. From the windward side, vortex rings were shed, merging downstream to form a counter-rotating vortex pair (CVP). Since the discharge is located below the CVP, it was obtained, that no additional oblique shock was caused by discharge operation.

Main part of analysis of discharge influence on mixing was based on processing of stagnation pressure obtained by Pitot probe using Kulite system including pressure sensor XCS-062-15D and amplifier KSC-2. 50kHz low-pas filter was activated on amplifier, pressure data were recorded with 2MHz sampling rate. Pitot sensor was installed at the position 120mm downstream the jet nozzle and could be moved along the channel height.

![Figure 1. General scheme or experiment.](image1)

Flow is from left to right. On the scheme: 1 – jet nozzle combined with HV electrode, 2 – ceramic insertion, 3 – metal wall, 4 – discharge, 5 – air jet, 6 – oblique shock, 7 – Pitot (stagnation) pressure probe.
3. Main results

After the supersonic flow become steady, the jet starts after 100ms delay. It results in change of the average stagnation pressure and significant intensification of pressure pulsations figure 2(a). Activation of discharge additionally changes the mean and amplitude of stagnation pressure. Detailed inspection of the average stagnation pressure and pulsations profiles was performed in the symmetry plane normal to the wall. It can be seen in figure 3(a) that jet injection causes the formation of disturbed region at the position y=6mm from the wall (y/d~1.5). Activation of discharge significantly (at least two times) increases the pressure pulsations and moves the disturbed region from the wall to the core flow, as it is shown in figure 3(b).

The discharge occurs between the anode and the metal wall of the test section. Then the discharge is blown downstream, and the long (~ 80 mm) current channel located 5-15 mm away from the wall is formed. A detailed video of the process, synchronized with the voltage oscillogram, is presented in supplementary materials for [9]. The short fragment of voltage oscillations due to discharge operation is presented in figure 2(b). During operation of discharge it has regular re-breakdowns closer to its contact with grounded electrode that results in voltage oscillations with amplitude of 100-200V at frequency range 10-40 kHz. If the length of discharge is high the conditions could appear for re-breakdown in the middle part of discharge to the region of metal plate close to the end of ceramic insertion. These reconnections are assumed to be due to filament distortion, caused by local turbulence. Reconnections are accompanied by significant decrease of discharge voltage amplitude of 500-700V at frequency range 1-5 kHz.

Figure 2. Stagnation pressure during experiment at 7.6mm height (a) and typical time dependence of the voltage on the discharge (b).

Figure 3. Wall-normal profiles of average stagnation pressure (a) and its standard deviation (b).
To analyze the frequency content of the pulsation, Fourier transform was applied to the pressure data for cases of jet with and without discharge figure 4. Spectra were calculated across of the intervals 8ms long with 50% overlap. 20-25 individual realizations were used to obtain an average spectrum. It was found that discharge operation results in increase of pulsation amplitude in all frequency bands by 15dB. The signal decay at high frequency limit, 50000Hz, is attributed to the filtering of the signal by sensor electronics.

![Fourier spectra of stagnation pressure.](image)

Figure 4. Fourier spectra of stagnation pressure.

It can be assumed, that the discharge not only changes the mean flow structure, but also performed excitation of the jet. The mechanism for this effect can be associated with the self-sustained current oscillations in the discharge. Correlation function between discharge voltage and pressure signal was calculated for all available sensor heights. It was obtained that the average shift between two signals was 85ms. It means that the main source of disturbances is located near the end of ceramic insertion. It can be speculated that breakdowns with big voltage drop introduce the main impact to the correlation of two signals, because the distance between that area and Pitot probe corresponds to obtained flow passing time.

4. Conclusion

The results of experimental investigations of DC discharge influence on mixing intensification of transvers injected gas jet into supersonic airflow were presented. Due to the high complexity of direct determination of the mixing degree in the experiment the analysis of pressure pulsations was performed. Baroclinic term in the vorticity equation (responsible for kinematic mixing) includes the density gradient, which is provided by local heat release in discharge, and pressure gradient. This is why it is so important to describe and analyze the influence of discharge on pressure pulsation. The data obtained during discharge current-voltage characteristics acquisition provide the information about two frequency ranges of discharge re-breakdown, and the total frequency range of discharge pulsations spectra in presented configuration is wide – 1-40kHz. Analysis of pressure pulsations shows that jet injection causes the formation of disturbed region at the distance y=6mm from the wall (y/d~1.5). Activation of discharge significantly (at least two times) increases the pressure pulsations and moves the disturbed region 5-7mm from the wall. Based on spectrum of stagnation pressure with and without discharge we can conclude that discharge operation results in increase of pulsation amplitude in all frequency bands by 15dB. By means of correlation function estimation between discharge voltage and pressure signal it was obtained that the average shift between two signals was 85ms. This time corresponds to flow passing time between positions of breakdowns with big voltage drop and Pitot probe.

This study implicitly supports an idea of significant advantages of a longitudinal extended Q-DC electrical discharge for the fuel mixing, ignition, and flameholding in a high-speed airflow.
Acknowledgments
This work was supported by the RFBR grant No. 18-08-01452 and by the Ministry of Science and Higher Education of the Russian Federation (State Assignment No. 075-00460-21-00)

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