Investigation of Q-DC discharge influence on fuel jet mixing with supersonic airflow

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Abstract. This paper presents the results of experimental study of plasma-based actuator for mixing of the fuel with air in a supersonic flow. The long unsteady plasma filament of Q-DC electrical discharge is located along the fuel jet from a wall-arranged supersonic injector with a wall-normal direction of injection. The location of plasma filament over the fuel jet was controlled by using the nozzle of injector as one of discharge electrodes. Three different gases were tested for simulation of fuel injection: air, CO₂ and C₂H₄. It was found that the discharge position in respect of the fuel jet significantly depends on the injected gas. The activation of discharge within all injected gases results in development of fluid instability at fuel-air interface which leads to the mixing enhancement.

Introduction

Ramjet/scramjet efficient operation in a wide range of flow parameters (pressure and temperature) is one of the most challenging technical problems in design of a hypersonic vehicle. A combustion chamber operates, as a rule, in a supersonic flow regime with a Mach number M ~ 2. Key issues in the arrangement of supersonic combustion process are stabilization of the flame front (flameholding) and maintaining of high combustion efficiency. In most schemes, the fuel feeding is organized using wall-mounted injectors or pylons [1–5] that makes the acceleration of the injected fuel mixing with incoming airflow to be a critical task to achieve a high value of combustion completeness. A typical solution employed for mixing enhancement and stabilization of combustion in scramjet is the use of a backward wallstep, wall cavity [6], or a more complex configuration with mechanical elements in the flowpath. For example, in [7], a thin wedge, witch width is substantially less than the height, is used for optimization of injection into a supersonic flow. The injection of a fuel occurs from the combusstor’s wall behind a wedge, which leads to an increase of fuel injection depth into the flow, to stretching of interface between the gases, and, finally, results in increase of the mixing rate. A similar flow pattern is realized when the fuel comes from pylons. Along with high efficiency, such systems have significant weaknesses, which are the loss of total pressure or the need for an active cooling system, especially in the case of a high-enthalpy flow. Due to the a slow diffusion process in comparison with the presence time of mixture components in the zone of chemical reactions, the intensification of mixing in a supersonic flow can only be produced by a kinematic transfer of components in vortex structures formed at the fuel-oxidant boundary. A promising way for the mixing...
acceleration is an extended electric spark that introduces significant gas-dynamic perturbations into the flow [8, 9]. With sufficiently high amplitude of energy deposition to the electric discharge, it is possible not only to introduce initial perturbations into the flow, but also change the increments of their development as a result of flow structure modification in the core airflow [10]. During formation of a localized zone of energy release at shear layer of the fuel jet, the mixing intensification happens as a result of the Richtmyer–Meshkov hydrodynamic instability, which occurs within area of non-collinear gradients of gas density and pressure. This leads to formation of deterministic turbulence and, then, to the appearance of small-scale stochastic perturbations that accelerate the stretching of the boundary and produce the kinematic mixing. Initialization of initial perturbations in the interaction zone may be performed by a pulse-periodic energy deposition in the jet or at some distance from it. Such configurations were considered theoretically in [11], where a significant intensification of mixing in the flow with a Mach number $M = 2.5$ and a relatively weak energy source (0.1 J per pulse) was demonstrated. Quasi-direct current (q-dc) discharge can be used as an alternative to the spark discharge. It was considered as an effective instrument for the fuel ignition and the flame front stabilization in the supersonic flow [4]. In one of the tested configurations of the electric discharge and fuel injection, the injector, flush-mounted on the combustion chamber wall, was combined with one of discharge electrodes [12]. It was found that the plasma filament follows the boundary between the jet and the oxidizer, coming off the wall. In this case, the behavior of the discharge becomes even more unsteady than during its operation near the wall of the combustion chamber. It was suggested that such unsteady behavior should also positively affect the fuel and oxidizer mixing. The current work proceeds those studies and is devoted to explore in details the discharge effect on the fuel jet and supersonic flow mixing in the geometric configuration described in [12]

**Scheme of experiment**

The experiments were performed in supersonic wind tunnel PWT-50 of JIHT RAS. Flow parameters were as follows: Mach number $M = 2$, static pressure $P_{st} = 170$ torr, and stagnation temperature $T_0 = 300$ K. Detailed description of experimental facility can be found in Ref. [12]. As it is shown in figure 1, fuel injector (1) was flush-mounted in the ceramic insertion (2) installed on the metal wall of the test section and supplied with a gaseous fuel. In these experiments, a supersonic injector Ø4 mm was used with Mach number $M_f = 1.8$, at typical mass flow rate of a secondary gas $G_{fuel} = 2–4$ g/s injected perpendicular to a core flow. Three different gases were used for imitation of fuel injection: air, CO$_2$ and C$_2$H$_4$. The conditions of injection and discharge parameters were selected to prevent the ignition of ethylene. The fuel injector was combined with one of discharge electrodes (anode) for generation of q-dc filamentary discharge (3) nearby the air-secondary gas interface. The discharge was powered by 5 kV source connected through fast high-voltage solid-state switch and current limiting resistor.

![Figure 1. Scheme of experiment. 1 – injector Ø4mm combined with electrode; 2 - ceramic insertion; 3 - Q-DC electrical discharge; 4 - fuel jet; 5 - Pitot probe, arrow shows the direction of M = 2 air flow](image)

**Experimental results**

Typical electrical characteristics of discharge are presented in figure 2. The averaged discharge current was 3 A and averaged voltage of discharge was 1.5 kV. The discharge behavior is highly transient: instant values of current and voltage significantly varies in time with frequency 3–15 kHz. Such a behavior is resulted from the discharge interaction with secondary gas jet which carries the discharge away from wall and leads to significant increase in discharge length. Typical realizations of
discharge shape at ethylene injection taken with high-speed camera are shown in figure 3. In these experiments, the discharge length was 60–70 mm that is controlled mostly by dimensions of the ceramic insert. It is shown that the plasma filament can have a significant variation in length and degree of curvature. Note, the plasma filament has a complex three-dimensional curved shape in both xy and xz planes of view (in figure 3, c-d), that may significantly affect the air-fuel mixing.

High-speed schlieren visualization of flow structure at jet injection was performed using high power pulsed laser diode as a light source and Basler camera. Pulse duration of laser was 100 ns that limits the exposure of schlieren image. The discharge image obtained by schlieren system has an exposure of 10 µs based on the camera shutter. Schlieren visualization of the fuel jet injection in supersonic flow allows demonstrating the influence of discharge on the character of flow. As it is shown in figure 4, activation of discharge makes the flow downstream the injector significantly unstable with increased gradient of the gas density on the boundary of jet, which is corresponded to the discharge curvature. To confirm the discharge effect on the flow of injected gas the Pitot probe was installed 100 mm downstream of injection port on the boundary between the jet and the core flow. Activation of the jet injection to the supersonic flow results in pressure decrease measured by the probe. It was found that after activation of discharge the character of pressure measured by the probe changes: oscillations of pressure are observed, which correlate with change in discharge shape and electrical characteristics, as it is shown in figure 2 with arrows.

To visualize the central plane of the jet simultaneously with the discharge operation, the particle visualization method (PIV) was applied. The width of the laser sheet was about 0.5 mm, the duration of the laser pulse was 15 ns, and the frame exposure was 1 µs. The jet was seeded with oil droplets with a diameter of about 2 µm, and the oncoming supersonic flow was seeded with a natural condensate of water vapor. The measurement system used made it possible to obtain instant images of the discharge and the simultaneous distribution of oil droplets visualizing the shape of the jet. Such visualization in the case of CO₂ injection is shown in figure 5. It can be seen that the discharge is localized along the jet below its lower boundary. Averaging the PIV measurements over 50 starts with identical parameters showed that the discharge activation causes deeper penetration of the jet into the main flow and the increase of angle of oblique shock wave caused by jet. The interface between the fuel and the oxidizer increases due to the use of a discharge.

![Figure 2. Electrical characteristics of discharge and its impact on Pitot pressure.](image-url)
Summary

From previous studies [12], it was known that the electric discharge prefers localization in the region with high gradients of gas density or species concentration, especially if the initiation of the discharge is geometrically associated with the injection of a secondary gas. In the latter case, the discharge is localized in the mixing layer of the fuel jet in a supersonic incoming flow. In the current work, the analysis of experimental data, including high-speed schlieren visualization, high-speed video recording, electrical measurements, and pressure measurements using a Pitot probe, demonstrates that the $q - dc$ discharge operation significantly affects the flowfield in the region of jet injection into a supersonic flow, creating high gradient of gas density and pressure oscillations in the wake of the jet. For all considered injected gases, an increase in the unsteadiness of jet was observed. In the case of ethylene injection, the plasma filament dynamics was observed to be especially unstable comparing to the air or CO$_2$ jets. This fact is explained by the discharge specific localization during the injection of ethylene. It was shown by PIV visualization that the discharge activation causes deeper penetration of the jet into the main flow. The interface between the fuel and the oxidizer increases due to the use of a discharge. Further efforts are planned to obtain a quantitative data on the mixing dynamics and enhancement by means of the electric discharge generated within the shear layer.

Acknowledgments

This work is supported by RFBR grant No. 18-08-01452. The work of Efimov AV on discharge visualization are also supported by President grant №075-15-2019-633 (MK -2610.2019.8).

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