Parameters of an electric discharge in a mixing layer of a supersonic air flow and an injected gas

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Abstract. The data obtained by spectral measurements, high-speed video recording and the current-voltage characteristics acquisition allowed to estimate the parameters (T_e, n_e, σ) of the gas discharge plasma organized in a shear layer formed at injection of carbon-containing gases into supersonic air flow. Injection of ethylene (C_2H_4) into air imitates hydrocarbon fuel; injection of carbon dioxide (CO_2) into the air imitates products of chemical reactions.

1. Introduction
One of the most important tasks of engineering science at 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 operation of the engines requires the achievement of a high completeness of combustion, which is largely limited by an insufficient air/fuel mixing. Preliminary studies [1, 2] have shown that an extended electric pulsed arc discharge introduces significant gas-dynamic perturbations into the flow and can serve as a promising solution to this problem. The appearance of the current channel leads to intense heat generation. Due to the effect on the baroclinic term in the vorticity equation [3], it accelerates the mixing of injected fuel with the incoming air flow. As a result, the completeness of fuel combustion increases. Q-DC discharge can also 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. The joint use of information on the spectral components of the discharge radiation and plasma parameters determined from the analysis of the spectra of diatomic molecules, spatial and current-voltage characteristics, makes it possible to estimate the initial gas composition in the discharge region. As a result a discussed technique represents an important tool for analyzing the location of the discharge at various model gases injected into the air flow. This work is aimed at studying the parameters of the Q-DC discharge located in the shear layer.

2. Measurements
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 = 25-28kPa, gas temperature T = 170 K, tunnel cross-section 72x60 mm. 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 $J = 0.8-2.8$. Following directly injected secondary gases were used: ethylene ($C_2H_4$) representing fuel and carbon dioxide ($CO_2$) representing a product of combustion. The data are compared with one another and with the basic case of air injection into the airflow. The metal 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 $+5$ kV through a ballast resistor that limits the discharge current. The metal wall is grounded. The duration of the discharge is 40 ms, which allows us to consider the average flow in the region of the discharge as steady. The structure of the flow was typical for the case of gas jet injection into the supersonic flow: the oblique shock was located in front of the jet and there was no additional oblique shock caused by discharge operation.

The dynamics of the discharge in the flow were monitored using a Phantom VEO 410 camera (the typical speed in this experiment was 140,000 frames/s). Analysis of this video using OpenCV [5] allowed to obtain the geometric characteristics of the plasma channel. Temperature characteristics were obtained from the plasma emission spectrum. Spectra were recorded with an AvaSpec-UL2048 spectrograph (spectral range $\Delta \lambda = 250-800$ nm, spectral resolution $\delta \lambda = 0.2-0.8$ nm, exposure 2 ms). The actual exposure value was reduced to 400 $\mu$s by turning off the quasi-direct current discharge before the end of the exposure of the spectrograph.

The optical scheme of spectroscopic measurements Figure 1 was organized to provide the image of the emitting zone of the discharge at a reduced scale on a moving screen with an integrated optical fiber of the spectrograph. Moving the screen allows one to select the radiation from different regions of the discharge with a diameter close to the diameter of the visible part of the discharge channel. The actual location of the observed discharge region was controlled by video recording of the screen image.
3. Main results

The discharge occurs between the anode and the metal wall near the nozzle, then it blows off 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 Ref. [6]. The oscillations of voltage and current associated with oscillation of the plasma channel length is in the range of $I = 1.8-3.8A$, $U = 700-2700V$. Instantaneous electrical discharge parameters are measured with high accuracy, not worse than 1%.

Despite significant oscillation of the current – voltage characteristics, the average values of current and voltage, length and diameter of the current channel over a time interval of 1–10 ms remain constant for all injection cases. These values were used to determine the electric field $E$ and current density $J$. A certain error is introduced by the procedure of averaging the channel length $L$ and electric field $E$, which assumes strict linear dependence of the electric voltage $U$ from the length $L$ of the discharge channel. To minimize the error in this work, the value of the electric field strength was calculated as follows. The voltage oscillogram and video recording were precisely synchronized, each frame (i.e., each discharge length) was compared with a fixed voltage value, and the resulting dependence of the discharge voltage on the plasma channel length is shown in Figure 2.

The value $E = \frac{\partial U}{\partial L} = \frac{\partial L}{\partial t}$ was determined as the slope of the linear approximation of the voltage dependence on the discharge length. The procedure for determining the diameter of the plasma channel consisted in calculating the width of the transverse profile of the radiation intensity at half maximum, after which averaging was carried out both over several profiles for one frame, and over several frames. Note that this approach to determining the diameter of the current channel is very approximate.

![Figure 2](image-url)  
**Figure 2.** Dependence of the voltage on the discharge on the length of the plasma channel used to determine the electric field strength.

The temperature characteristics (vibrational temperature $T_v$ and rotational temperature $T_r$) of the discharge plasma were obtained by analyzing the radiation of diatomic molecules. In this work, the assessment was carried out by comparing the experimentally recorded spectra of molecular bands with the artificial spectrum obtained using data presented in Ref. [7, 8].

In the case of $C_2H_4$ injection, the molecular Swan bands ($d^3Π_g-a^3Π_u$ transition) of the $C_2$ radical and the violet CN band system ($B^2Σ^+ - X^2Σ^+$ transition) are available for analysis. The normalized spectra of Swan molecular bands collected from the near-injector zone and in the middle of the discharge region do not present significant difference and corresponds to the best fitting at $T_r = 4500±250K$ and $T_v = 5700±300K$ Figure 3a. The values obtained for the same regions using the violet CN band system also do not differ significantly, though are slightly higher on average: for the sequences $Δν = 0,±1$ $T_r = 5700±300K$ and $T_v = 6100±300K$. 
Figure 3. Comparison of the recorded Swan molecular bands of the C\textsubscript{2} radical with the artificial spectrum (A.S.) at T\textsubscript{v} = 6000K and T\textsubscript{r} = 4500K for the case of C\textsubscript{2}H\textsubscript{4} injection (a) and with the artificial spectrum at T\textsubscript{v} = 8000K and T\textsubscript{r} = 6000K for the case of CO\textsubscript{2} injection (b).

Registration area: near the injector (T1).

In the case of CO\textsubscript{2} injection, the rotational and vibrational temperatures measured from the C\textsubscript{2} spectra near the injector have values of T\textsubscript{r} = 6000±300K and T\textsubscript{v} = 8000±300K respectively, which is noticeably higher than in the case of C\textsubscript{2}H\textsubscript{4} injection Figure 3b. At a distance from the injector, Swan molecular bands are not reliably detected, but a second positive system of N\textsubscript{2} bands appears (C\textsuperscript{2}Π\textsubscript{u}−B\textsuperscript{2}Π\textsubscript{g}, transition, Δν=0). Estimation of the rotational temperature from these N\textsubscript{2} bands leads to the same result T\textsubscript{r} ~ 6000 K as in the case of C\textsubscript{2} bands near the injector. An estimate of the temperatures in different regions of the discharge using the violet CN band system (sequences Δν = 0, ± 1) did not reveal significant differences in major parameters. The approximately constant values along the discharge measured by CN were T\textsubscript{r} = 6700±300K, T\textsubscript{v} = 8000±300K, which is quite close to the values of C\textsubscript{2} temperatures obtained for the region near the injector.

In the case of air to air injection, the temperature T\textsubscript{r} = 6000±300K was measured using a second positive system of molecular nitrogen (Δν=0).

The experimentally determined values of the current density J, the reduced field E/N, and the gas temperature T\textsubscript{e} were used to obtain the values of the concentration n\textsubscript{e} and temperature T\textsubscript{e} of electrons and plasma conductivity σ table 1. The method for calculating the characteristics of the plasma was as follows. The average density of electrons in the plasma channel is calculated through the current density [9],

\[ j = I / S = e \cdot n_\text{e} \cdot V_{de}, \]

where S is the cross-sectional area of the plasma channel, V\textsubscript{de} is the electron drift velocity, which is calculated from the known electric field strength and the frequency of collisions of electrons with neutral particles ν\textsubscript{en}, or through the electron mobility in the electric field μ\textsubscript{e}:

\[ V_{de} = \frac{e \cdot E}{m_\text{e} \cdot ν_{en}} = μ_\text{e} \cdot E = (μ_\text{e} \cdot N) \cdot \frac{E}{N}, \]

where the collision frequency is calculated from the known gas composition

\[ ν_{en} = ν_\text{e} \cdot \sum_i N_i \cdot σ_i, \]

where \( N_i = \frac{P_i}{kT} \) is the concentration of particles i, P\textsubscript{i} is the partial pressure of component i, k is the Boltzmann constant, T is the gas temperature. The experimentally measured T value was used as the gas temperature. The values \( μ_\text{e} \cdot N \) and T\textsubscript{e} were calculated in the Boltzig program [10,11] for a mixture of components corresponding to the approximate model [12] based on the gas temperature. Additional information devoted to the processing and calculating the obtained values shown in Table 1 is presented in Ref. [6].
Table 1. Average plasma parameters measured and calculated

|       | \( U_{av} \), V | \( I_{av} \), A | \( R \), \( \Omega \) | \( d \), mm | \( L \), mm | \( \sigma \), \( \Omega m^{-1} \) | \( T_e= T_{in}, \) K | \( E/N \), \( 10^{21} V m^2 \) | \( T_e \), eV | \( n_e \), cm\(^{-3} \) |
|-------|----------------|--------------|---------------|--------|--------|----------------|----------------|----------------|--------|---------------|
| \( \text{C}_2\text{H}_4 \) | 1870 | 2.7 | 693 | 0.65 | 89 | 390 | 4500 | 50 | 1.1 | 0.95·10\(^{15} \) |
| \( \text{CO}_2 \) | 1620 | 3.0 | 540 | 0.65 | 105 | 580 | 6000 | 50 | 1.6 | 0.87·10\(^{15} \) |
| \( \text{Air} \) | 1970 | 2.5 | 788 | 0.65 | 136 | 530 | 6000 | 45 | 1.7 | 0.65·10\(^{15} \) |

4. Conclusion

The experimental values of plasma conductivity in all three cases are significantly higher than the range of values \( \sigma = 3.5-150 \) S/m [13], which is typical for pure, thermally ionized air with parameters \( P = 200 \) Torr and \( T = 4500-6000 \) K. They are also higher than the values given in [14] for arcs in air, \( \sigma = 80 \) S/m at \( T = 6000\)K. The conductivity \( \sigma > 300 \) S/m is achieved in air and \( \text{CO}_2 \) at \( T > 7000\)K. Such a significant difference in the electrical conductivity of the plasma can be explained by the significant role of the mechanism of nonequilibrium ionization by direct electron impact at the reduced field \( E/N = 45-50 \) Td. Based on the measured values, the total resistance of the plasma channel has maximum in air, implicitly indicating a preferred localization of the discharge in carbon-containing gases. However, the result of interaction and the mechanisms governing the electric discharge behavior in two described cases, \( \text{C}_2\text{H}_4+\text{air} \) and \( \text{CO}_2+\text{air} \), are different: a lower gas temperature in \( \text{C}_2\text{H}_4+\text{air} \) vs pure air in the first case, and a higher electrical conductivity in \( \text{CO}_2+\text{air} \) mixture vs air in the second case.

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.

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