Parameters of electron component in a pulsating discharge in a supersonic airflow

Shibkova L.V., Shibkov V.M., Logunov A.A., Andrienko A.A., Kornev K.N., Dolbnya D.S.
Moscow State University, 119991 Moscow, Russia

shibkov@phys.msu.ru

Abstract. The plasma parameters of an unsteady pulsating transverse-longitudinal discharge created in subsonic and supersonic air flows are determined. It was shown that in the anode part of the plasma loop, the longitudinal electric field, as well as the electron density and temperature exceed the corresponding values in the cathode part of the loop. The effect of gas flow rate and discharge current on the temperature of electrons in plasma of a pulsating discharge in air and propane-air mixture is also shown.

1. Introduction
For efficient operation of a high-speed ramjet engine, the air-fuel mixture flow should have a supersonic velocity in all areas of its path. The high gas velocity makes it difficult to control the flow inside the combustion chamber. The air-fuel mixture passing with supersonic speed through the direct-flow chamber should have enough time for complete combustion in order to generate maximum thrust. In order to increase the efficiency of a ramjet engine with a supersonic flow rate in the combustion chamber, new methods are actively being developed to increase the burning rate and ensure complete combustion of fuel inside the engine without the use of various mechanical stabilizers. One of such methods is the use of various types of electric discharges [1-19]. In the works presented above, as well as in many other studies, it was shown that the use of gas-discharge plasma in most cases leads to ignition of the fuel.

The induction period varies from a microsecond time scale under condition of high-voltage nanosecond high-current discharges, freely localized and surface microwave discharges to a millisecond range for direct current discharges. Application of nanosecond and microsecond discharge with pulse repetition frequency up to several kilohertz cannot ensure constant mode of fuel combustion in supersonic flow. To stabilize fuel combustion, it is proposed in [10, 19-23] to use quasi-stationary pulsating transverse, longitudinal and transverse-longitudinal discharges produced in high-speed multicomponent chemically active gas flows. For the effective use of a transverse-longitudinal discharge as a fast ignition and combustion stabilization of air-hydrocarbon mixtures, it is necessary to know the main parameters of a low-temperature plasma.

The parameters of freely localized microwave discharges used to ignite hydrocarbon fuels in supersonic air flows are presented in [2, 3, 21, 24, 25]. The main properties and plasma parameters of a surface microwave discharge are given in [2, 3, 26-28]. This article is devoted to determining the parameters of the electronic component in plasma of a non-stationary transverse-longitudinal
discharge created in subsonic and supersonic air flows, as well as in chemically active propane-air mixtures.

2. Experimental setup

The experiments were carried out on an installation consisting of a vacuum pressure chamber, a system for creating a supersonic air flow, a high-pressure air receiver, a high-pressure propane receiver, aerodynamic tunnels of rectangular cross section with attached air ducts, a high-voltage power supply for creating a pulsating discharge, a synchronization system and diagnostic equipment. The experimental setup and diagnostic methods are described in detail in [3, 8, 10, 19].

The diagnostic complex consists of spectrographs with digital recording of the spectrum; a probe diagnostics block with digital recording of the volt–ampere characteristics; pressure sensors; photo cameras; a high-speed video camera; oscilloscopes and computers. The discharge was produced using a power source with an output voltage of up to 4.5 kV and a discharge current of up to 16 A, the pulse duration being of up to 2 s. Propane-air mixtures were used as fuel. The second mass air flow rate in the experiment could vary from 25 g/s to 150 g/s, the second mass flow rate of propane varied from 3 g/s to 6 g/s. Aerodynamic channels were located inside a metal pressure chamber with a volume of 3 m³, the air pressure in which could vary from 10 to 760 Torr.

A pulsed discharge was excited between two well streamlined electrodes [8, 10, 19]. In the experiments an electrode system with the shortest distance between the anode and cathode \( d = 0.2 \text{ mm} \) was used. The electrodes were mounted inside the diverging wind tunnel. The air flow velocities varied from 150 to 550 m/s. For synchronizing the operation of electromechanical valves and discharge, a special scheme is used, which provides a time delay between the opening of the valves in the air ducts, which supply air and propane gas, and the start of the discharge.

The emission spectrum of the gas-discharge plasma was recorded using an AvaSpec-2048-2-DT dual-channel spectrograph with an inverse linear dispersion of 0.05 nm/mm for the first channel and 0.32 nm/mm for the second channel.

A distinctive feature of the spectrum is the presence of an intense continuum, which may electron bremsstrahlung from ions or atoms and/or recombination emission. Estimates show that, under these experimental conditions, the intensity of bremsstrahlung caused by electron–ion collisions exceeds the intensity of bremsstrahlung caused by electron-neutral collisions. The electron temperature in the plasma channel was determined by comparing the measured spectrum with the theoretical bremsstrahlung spectrum calculated for different electron temperatures.

To this, it was necessary to correct the measured spectrum with allowance for the spectral sensitivity of the spectrograph. The absolute sensitivity of the spectrograph was calibrated using a tungsten incandescent lamp, whose emission intensity is determined by the temperature of the tungsten ribbon, which depends on the heating current.

The electron density was determined from the Stark broadening of the H\(_{\alpha}\) and H\(_{\beta}\) spectral lines of the hydrogen Balmer series.

One of the main characteristics of the discharge is the electric field strength in the plasma. In previous studies [15, 19], it was shown that the average electric field along the length of the plasma loop increases with increasing air velocity. Moreover, at any air flow rate, an increase in the discharge current leads to a decrease in the electric field in the plasma.

In the present investigation, the distributions of floating potentials along the anode and cathode parts of the plasma loop were measured by the probe method. The measurements were carried out using a single unit of two probes, the distance between which is 0.7 cm. In our case, the electron energy distribution function in a pulsed discharge plasma is close to the Maxwell function with a temperature of the order of 1 eV. In this case, the difference between the floating potential and the potential of a space of the order of several \( kT_e = 1 \text{ eV} \). Therefore, the electric field strength was determined as the difference of floating potentials divided by the distance between the probes.
3. Experimental results

Investigations of the plasma parameters of a pulsating transverse-longitudinal discharge were performed at changing the gas flow velocity from 200 to 500 m/s and the discharge current from 5.5 to 15.5 A.

The dependences of the longitudinal electric field strength in the anode and cathode parts of the plasma loop are shown in Figure 1.

![Figure 1. The longitudinal distribution of the electric field strength in the anode (1) and cathode (2) parts of the plasma loop.](image)

It can be seen that in the anode part of the loop, the electric field has a maximum value near the anode \( E_a = 210 \text{ V/cm} \) and decreases slightly with increasing of distance \( z \) from the anode, while the electric field has a minimum value near the cathode \( E_c = 77 \text{ V/cm} \) and increases slightly with increasing distance \( z \) from the cathode. The excess of the electric field \( E_a \) over \( E_c \) reaches 60 \% near the electrodes and 20 \% on distance \( z = 6 \text{ cm} \). Different values of the electric field strengths \( E_a \) and \( E_c \) lead to different values of the electron concentration and temperature in the anode and cathode parts of the plasma channel. It was too shown that in the anode part of the plasma loop the electron density systematically exceeds \( n_e \) at the same distances \( z \) in the cathode part of the plasma loop by about 15 \%. Similar results were obtained when measuring the longitudinal distribution of electron temperature. It was shown that the electron temperature decreases along the plasma channel downstream as well as the electron concentration, when the distance \( z \) from the electrodes increases. In this case, the excess of the measured electron temperature in the plasma channel near the anode over \( T_e \) near the cathode reaches 30\%.

The dependences of the electron temperature in the plasma on the air flow velocity were shown in Figure 2 at various values of the discharge current. It can be seen that with increasing air flow velocity, the average electron temperature decreases both at a discharge current of 5.5 A and at \( i = 15.5 \text{ A} \). Moreover, at any value of the flow velocity the electron temperature increases with increasing discharge current.

Studies have also been fulfilled on the effect of propane injection into a high-speed air flow on the electron temperature in pulsating transverse-longitudinal discharge plasma. It was experimentally obtained that when propane is added to the air flow, the electron temperature decreases. This is due to the fact that the addition of propane to the air flow leads to an increase in the fraction of electron energy losses due to dissociation, excitation and ionization of impurity molecules. In the case of a propane-air mixture, the dependence of the average electron temperature on the velocity does not
qualitatively change as compared to the air flow, i.e. an increase in velocity leads to a decrease in the electron temperature (Figure 2, line 3).

Figure 2. Dependence of the electron temperature on the air (1 and 2) and the air-propane (3) flow velocity at various values of the discharge current 5.5 A (1); 12.5 A (3); 15.5 A (2).

Mathematical modeling of the electron energy distribution function in a non-equilibrium pulsed plasma was performed to justification of the experimentally obtained results on measuring the temperature of electrons. The electron energy distribution function was calculated based on the solution of the Boltzmann equation for the spherically symmetric component of the EEDF.

\[
\frac{1}{n_e n_0^2} \frac{d(n_e f(\varepsilon, t))}{dt} = \frac{\partial}{\partial \varepsilon} \left( \frac{1}{3} \frac{(eE)^2}{\sigma_c} + \delta kT_0 \varepsilon^2 \sigma_c \right) \frac{\partial f}{\partial \varepsilon} + \\
+ \frac{\partial}{\partial \varepsilon} \left( (\delta \varepsilon^2 \sigma_c + 4 \varepsilon B_0 \sigma_{re}) f \right) - \begin{cases} 
\sum_{\varepsilon_i} g_i^+ \varepsilon \sigma_i(\varepsilon) f(\varepsilon), & \varepsilon \geq \varepsilon_i^{nop} \\
0, & \varepsilon < \varepsilon_i^{nop}
\end{cases}
+ \sum_{\varepsilon_i} g_i^- \varepsilon \sigma_i(\varepsilon) f(\varepsilon - \varepsilon_i^{nop}), & \varepsilon \geq \varepsilon_i^{nop} \\
+ \sum_{\varepsilon_i} g_i^+ \varepsilon \sigma_i(\varepsilon) f(\varepsilon + \varepsilon_i^{nop}), & \varepsilon \geq \varepsilon_i^{nop}
\]
Here \( f(\varepsilon, t)e^{\varepsilon/2} \) is the spherically symmetric component of the electron energy distribution function, \( \alpha_{e,i}(\varepsilon) \) is transport cross-section of the \( i \)-th component of the mixture, \( \alpha_{t}(\varepsilon, t) \) is total transport section of the mixture, \( \gamma_i \) is mole fraction of the corresponding component, \( N \) – total concentration (mol/cm\(^3\)), \( E \) is the electric field (V/cm), \( C_{p,i} \) – the molar heat capacity of the \( i \)-th component at constant pressure, \( \alpha_{tq} \) and \( \alpha_{q}^+ \) – stoichiometric coefficients, \( \ln \Lambda \) – Coulomb logarithm.

It was found that a close to Maxwell electron energy distribution function with an effective electron temperature of the order of one electron-volt is formed at high degrees of plasma ionization, which is realized under conditions of an unsteady transverse-longitudinal discharge in a gas stream (Figure 3, dash line 2).

For the same value of the reduced electric field \( E/n= 30 \) Td, but in a weakly ionized plasma with an ionization degree of \( 10^{-6} \), a non-equilibrium electron energy distribution function is realized, the form of which strongly depends on the degree of vibrational excitation of air molecules (Figure 3, curve 1).

4. Conclusions

The spatial distributions of the plasma parameters of a pulsating discharge as a function of air velocity and discharge current are obtained. Significant excess of the longitudinal electric field in the anode part of the plasma loop of the pulsating transverse-longitudinal discharge over the field in the cathode part of the loop was revealed.

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