Abstract. The application of electrical probes for measurement of plasma parameters of pulse discharges in supersonic air and air-propane flows was investigated. Experiments were carried out in case of pulse discharge, feeding from the generator of current, in supersonic jet with Mach number \( M = 2 \) at the static ambient pressure \( p = 50 \pm 30 \) Torr and the discharge current \( I = 1 \pm 30 \) A. A double probe and PC-controlled probe measurement circuit with an opto-galvanic isolation was used. The circuit was based upon the transformation of measured analogue signal to digital sequence, the transmission of the said sequence via optic fiber line for the required distance and the inverse transformation of the digit code to the analogue signal. Computer simulations of one-dimensional probe diagnostic problems in a wide range of parameters of plasma flows were carried out to interpretation of the measured probe characteristics. Results of charged particle measurements in the transversal discharge obtained by probes and by Stark-effect method show that the concentration quickly increases at small currents and then its rising slows down. Absolute concentration values at \( p \approx 10^2 \) Torr and currents up to \( 10^1 \) A do not exceed \( 10^{14} \) cm\(^{-3}\).

Introduction

The study of characteristics of the gas discharges in supersonic flows is of interest at the solution of the problem of fuel ignition in hypersonic vehicle ramjet with supersonic combustion. Electric discharges in supersonic high-pressure gas flows are characterized by inhomogeneous and unsteady parameters. Under these conditions, the main advantage of the probe method (a possibility of local measurements with a high temporal resolution) becomes important. However, an application of the standard schemes and methods of processing of probe characteristics for such discharges is very difficult due to a combination of several extreme conditions: high plasma potential (\( V \approx 1 \) kV) and large modulation of the discharge current and voltage [1]. The unsteady character of plasma parameters suggests a necessity of development of an automated scheme of probe measurements, which provides the necessary temporary resolution and allows one to measure the probe voltage-current characteristic with a condition of sufficiently weak changes of plasma parameters. As a rule, the characteristic frequencies of oscillations of discharge current and voltage are about 3...30 kHz [1]. The available temporary resolution of a probe itself is sufficiently higher (better than 1 \( \mu \)s). Thus, the available temporary resolution of a probe method is defined by a probe measurement circuit.

Probe measurements

The experimental setup for development and testing of probe diagnostic methods is built around a stainless steel cylindrical gas/vacuum chamber [1]. It consists of two sections that can form a vacuum-tight junction with help of a lever-operated gate. The experiments were carried out for the direct current discharge with current up to 5 A., pulse-periodic discharge with current up to 40 A and pulse plasma jets with current up to 20 kA.

The electrical probes were used for a measurement of a plasma density, floating potential and electric field in plasma. A PC-controlled probe measurement circuit with an opto-galvanic isolation was developed performed and tested.

It is based upon the transformation of measured analogue signal to digital sequence, the transmission of the said sequence via optic fiber line for the required distance and the inverse transformation of the digit code to the analogue signal.

The block diagram of the device is presented in Fig.1. Timing and controlling of the device are governed by the computer (13) via unit (11) and (12). At the time moment \( t_0 \) (start point of measurement of the probe voltage-current characteristic) the module (11) forms a start pulse, which is transmitted to the generator (12) of a current of injection and management of an emitter (14). The emitter (14) will transform an injection current pulse to a light pulse. A laser diode \( \text{Ɉɉɇ-301-1} \) with average power 300 mW and wavelength 790-820 nm is used as an emitter. The 0.1 mcs long optical pulse is transmitted through a fibre-optical line (15) on a photosensitive site of the photoreceiver (16), which transforms the light beam to an electric current. A laser diode \( \text{Ɉɉɇ-301-1} \) with average power 300 mW and wavelength 790-820 nm is used as a photoreceiver. The electric current signal is further transmitted to the block of amplification (17). The block of amplification (17)
consists of a transimpedance amplifier, an amplifier - proofer and a threshold element. Transimpedance amplifier transforms a signal current of the photodiode to an integrated voltage. The amplifier - proofer is intended for amplification and restoring of the form of a signal. The threshold element forms a digital signal in levels of TTL (transistor-transistor logic) on an output of the block (17), and also allows to reduce modification of on-off time ratio of an output signal in a dynamic range. The threshold element is based on a comparator, which is connected in accord with the Schmitt trigger circuit design.

Fig. 1. The device for probe measurements in plasma of electric discharges in supersonic flow.

A 0.1-μs long electric switching pulse is formed in the unit (17) and is transmitted to the unit of formation of linearly growing bias voltage (18). This unit is designed as a voltage integrator on base of a powerful operational amplifier. The electric circuit of measuring of the double probe voltage current characteristic is comprised of the unit (18), the plasma under investigation, the probes (1) and (2), and a 15-Ohm resistor (3).

The voltage bias \( U(t) \) in the probe circuit changes linearly from a minimal voltage of \(-25 \text{ V}\) to a maximal voltage of \(+25 \text{ V}\) during 10 μs. The resulting probe current \( i(t) \) in this circuit is continuously transformed by a unit (4) into a frequency of pulse repetition. This unit is a voltage-to-frequency transformer on base of the chip VFC110. The mean transformation frequency is 3.0 MHz. In a moment of time \( t_0 \) a unit (11) also starts a sequence of 100 transformations, which are carried out by a unit (10) in fixed intervals of 0.1 μs. The unit (10) is a 12-bit 3-ns analog-to-digit converter. As the temporary dependence of the bias voltage is also pre-determined, an array of 100 pairs of values \( \{ U(t_i), i(t_i) \} \) is formed in a memory of the computer (13), that is the measured voltage-current characteristic.

The parameters of the device are shown in the Table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of single I-V probe</td>
<td>10 μs</td>
</tr>
<tr>
<td>characteristic measurement</td>
<td></td>
</tr>
<tr>
<td>Probe bias limits</td>
<td>±25 V</td>
</tr>
<tr>
<td>Probe current limits</td>
<td>±50 mA</td>
</tr>
<tr>
<td>Bandwidth (–3 dB level)</td>
<td>350 kHz</td>
</tr>
<tr>
<td>ADC</td>
<td>12 bit</td>
</tr>
<tr>
<td>Fiber optic line</td>
<td>&lt; 300 m</td>
</tr>
<tr>
<td>High voltage isolation</td>
<td>not limited</td>
</tr>
</tbody>
</table>

The oscillograms of a probe current and sawtooth bias voltage with the help of this circuit were measured. I-V probe characteristic was determined with the help of special developed program. The program allows looking through the measured oscillograms of bias voltage and probing current, selecting a desirable recording area and constructing I-V probe characteristic.

Typical view of the probe voltage - current characteristic was shown in Fig. 2 for a pulsed transversal discharge.

Fig. 2. The double probe voltage - current characteristic in plasma of pulse transversal discharge in supersonic airflow.

Cylindrical probe \( \phi = 0.3 \text{ mm} \), axial position \( z = 4 \text{ cm} \). \( P_0 = 1 \text{ atm} \), \( p = 40 \text{ Torr} \), \( I = 11 \text{ A} \).

Modes of probe operation in dense weakly ionized plasma flows under conditions of significant processes in the Debye layer have been studied primarily analytically on base of asymptotic analysis in extreme cases [2]. The modes of probe
operation in the range of plasma parameters of igniting discharges are intermediate from the point of view of the analytical approach. For an interpretation of the measured probe characteristics, an analytical approach has been developed for different cases of diffusion, drift and intermediate modes, its results agree with experimental data for these modes.

Computer simulations

To studies of probe voltage current characteristics under realistic conditions to occur in plasma flows, we have carried out a cycle of computer simulations of one-dimensional probe diagnostic problems in a wide range of parameters of plasma flows. Both cases of the steady plasma and the plasma flow with the Blausius gas dynamical profile have been considered. The corresponding semi-analytical study for equal electron and ion temperatures and a well-developed diffusion layer is reported in [3].

Characteristic parameters of the experiments are: probe radius \( R \sim 0.2 \text{ mm} \), length \( L \sim 10 \text{ mm} \), flow speed \( v \sim 600 \text{ m/s} \), gas temperature \( T_g \sim 1000-3000 \text{ K} \), probe potential \( \Phi_p \sim 1 - 30 \text{ V} \), electron temperature \( T_e \sim 0.5-3 \text{ eV} \), electron density \( n_e \sim 10^{18}-10^{21} \text{ m}^{-3} \), gas density \( n_g \sim (1-3) \times 10^{24} \text{ m}^{-3} \).

The main dimensionless parameters of the problem are [2]:

- the Reynolds number \( Re=\nu R/D \) (\( D \approx 10^{-14}(2n_i)^{-1}\{k_BT_e/(2m_e)\}^{0.5} \) is the ion diffusion coefficient, \( k_B \) is the Boltzmann constant, \( m_e \) is the mass of a neutral particle),
- \( \nu = k_B T_e \phi_e/(n_e e R^2) \) (\( \phi_e \) is the dielectric constant, \( e \) is the electron charge, \( R \) is the probe radius),
- the dimensionless probe potential \( \Phi_{p0} = e \Phi_p/(k_B T_e) \).

Under experimental conditions of interest, \( Re \approx (0.6-1) \times 10^5 \), \( \varepsilon \approx (1-3) \times 10^{-4} \) at \( n_e=10^{18} \text{ m}^{-3} \), \( \varepsilon \approx (1-3) \times 10^{-7} \) at \( n_e=10^{21} \text{ m}^{-3} \).

The mathematical model is steady, it neglects chemical reactions and temperature changes near a probe. Its dimensionless formulation is

\[
\nabla (n_i \nu_i) = 0, \quad \nu_i = \frac{1}{n_i} \nabla (T_i n_i) + \nu_i \nabla E, \\
E = -\nabla \Phi, \\
\nabla (n_e \nu_e) = 0, \quad \nu_e = \frac{1}{n_e} \nabla (T_e n_e) + \nu_e \nabla E, \\
\varepsilon_0 \nabla \cdot \nabla \Phi = (n_e-n_i), \quad T_e = T_i = 1, \quad \mu_e = \mu_i = 1.
\]

Here

\[
\Phi^M = \Phi^M/L, \quad E^M = \frac{\Phi^M}{L}, \quad n_e^M = n_i^M = n_{\infty}, \\
\nu^M = \nu_{x\infty}, \\
\varepsilon^M = \frac{k_B T_e^M}{e} \mu_e^M, \quad \chi = \frac{e \Phi^M}{k_B T_e^M}, \\
\varepsilon_i^M = \frac{k_B T_i^M}{e} \mu_i^M, \quad \tau = \frac{T_e^M}{T_i^M} \left( \frac{\mu_i^M}{\mu_e^M} \right)^2 \frac{T_e^M}{2T_i^M} \frac{m_e}{m_i}, \\
\varepsilon_\phi = \frac{\varepsilon_0 k_B T_e^M}{e^2 n_{\infty}} = \chi \left( \frac{\lambda_D}{L} \right)^2, \quad \lambda_D^M = \frac{\varepsilon_0 k_B T_e^M}{e^2 n_{\infty}}.
\]

There are three small parameters in the system: two diffusion parameters \( \varepsilon_e \), \( \varepsilon_i \) and the Debye parameter \( \varepsilon_\phi \). The ion diffusion parameter can be much less than the electron one:

\[
\left( \frac{\varepsilon_i}{\varepsilon_i} \right)^2 \approx 2 \left( \frac{T_i^M}{T_e^M} \right) \left( \frac{m_e}{m_i} \right)^2 \approx 10^{-4}, \quad \frac{T_i^M}{T_e^M} \approx 10^{-1}
\]

Assume [3] that the densities depend on a variable \( \eta = y/\sqrt{U/v_x} \) only, here \( x, y \) are the longitudinal and transversal special coordinates, \( r = r^*+r_0, \ r_0 \) is the probe radius. Then in a one-dimensional case the system of model equations looks like

\[
\nabla (n_e \nu_e - \varepsilon_e \nu_i \nabla (\nabla (T_i n_i) + \chi n_i E) \nabla \Phi) = 0, \\
E = -\nabla \Phi, \\
\nabla (n_e \nu_e - \varepsilon_i \nu_e \nabla (T_e n_e) + \chi n_e E) = 0, \\
\nu_e \nabla \cdot \nabla \Phi = (n_e-n_i), \\
T_e = T_i = 1, \quad \mu_e = \mu_i = 1.
\]

\[
r^{-\alpha} \frac{d}{dr} \left( r^\alpha n_e \left[ \frac{v_y - y}{2x} \right] + \left[ 1 + \frac{\alpha y}{r} \right] n_x v_x \right) - \varepsilon_e r^{-\alpha} \frac{d}{dr} \left[ \mu_e r^\alpha \left( \frac{d}{dr} (T_e n_e) + \chi n_e E \right) \right] = 0
\]

\[
r^{-\alpha} \frac{d}{dr} \left( r^\alpha n_i \left[ \frac{v_y - y}{2x} \right] + \left[ 1 + \frac{\alpha y}{r} \right] n_x v_x \right) - \varepsilon_i r^{-\alpha} \frac{d}{dr} \left[ \mu_i r^\alpha \left( \frac{d}{dr} (T_i n_i) + \chi n_i E \right) \right] = 0
\]

\[
\varepsilon_\phi r^{-\alpha} \frac{d}{dr} \left( r^\alpha \frac{d}{dr} \phi \right) = n_e - n_i
\]

\[
T_e = T_i = 1, \quad \mu_e = \mu_i = 1, \quad E = -\frac{d}{dr} \phi
\]
\( a = 0, 1 \) for planar and cylindrical symmetry, correspondingly. The values of \( v_x, v_y \) are tabulated from the Blasius problem solution. In case of \( a = 1 \) the value of \( v_y \) is divided by \( r \) to conserve the gas mass. The boundary conditions are:

\[
n_{i,c}(1) = 0, n_{i,c}(\infty) = 1, \quad \phi(1) = \phi(t), \quad \phi(\infty) = 0
\]  

(2)

Assume \( r_0 = x_1 = 1 \).

The problem (1), (2) has been solved at various conditions.

**Results of computation**

**Steady plasma**

The only small parameter is \( \zeta_0 \) it was varied in a wide range \((10^{-14} \leq \zeta_0 \leq 10^{-2})\) for methodic purposes. The results are in a good agreement with the analytic estimates [4]. Typical view of the voltage-current characteristic for very small value of \( \zeta_0 \) is shown in Fig.3.

\[
\varepsilon_0 = 10^{-12}, \quad \varepsilon_i = \sqrt{500r}.
\]

**Plasma flow**

The computations were carried out for \( a = 1 \) (cylindrical symmetry), at \( \text{Re} = \varepsilon_i^{-1}, \quad \varepsilon_i = \sqrt{500r} \). The plasma perturbation zone around an electric probe can be divided into three main regions [4]. The space - charge region (Debye sheath) adjoins to a probe directly. In this region it is impossible to neglect separation of charges, i.e. the solution of the Poisson equation is necessary. The sheath width depends on the value of Debye radius \( r_d \) and also the value of applied voltage.

The quasineutral layer is located further (diffusion region), in which charge separation is small, the Poisson equation is superfluous, and charge transfer by ambipolar diffusion is essential. The thickness of this region depends on the magnitude of electrical Reynold's number.

Behind diffusion region there is the layer of quasineutral nonviscous flow (drift region) with the thickness about a probe radius, in which drift of charge particles in electrical field is main process of current collection.

**Saturation mode**

The spatial profiles of parameters and the voltage-current characteristic for the classical [4] case of small Debye layer (as compared to the diffusion layer), which corresponds to current saturation, is shown in Fig.4. One can see that the voltage drop in the quasi-neutral zone amounts here to 30...50%. Note that earlier estimates [4] yielded a complete domination of the Debye layer drop under these conditions \((\varepsilon \text{Re}^2 = 10^{-6} < 1)\).
Intermediate mode

Computations for intermediate $\varepsilon \Re^2=100$ with two sets of $\varepsilon$, $\Re$ values ($\varepsilon=10^{-8}$, $\Re=10^5$ and $\varepsilon=10^{-4}$, $\Re=10^3$) have shown that the situations are different. The first case the Debye layer size amounts to 10% of the diffusion layer, i.e. the situation is close to the current saturation mode, but the diffusion layer becomes shorter with voltage growth (due to the growth of the Debye layer size), which gives a slowly rising voltage current characteristic at saturation (Fig.5). Note that the probe current depend on $\tau$: at $\tau=1$ it is about twice as less than that at $\tau=3$.

In the second case the sizes of the Debye and diffusion layers (Fig.6) are close to each other; no quasi-neutral diffusion layer is formed.

The ion probe current grows with growth of the probe voltage due to growth of the Debye layer. Instead of saturation one can observe a fall of the voltage current characteristic slope for 3...5 times.

Note that from the viewpoint of the earlier analytical works [2,3] these two cases are the same. Fig.7 shows a case ($\varepsilon=10^{-4}$, $\Re=10^4$) of a complete absence of the quasi-neutral diffusion layer. About a half of voltage falls in the zone of unperturbed flow. The change of the voltage current characteristic slope is still less.
**Plasma parameters**

The values of gas temperature and gas density are necessary for definition of ion density. The gas temperature was measured by spectral methods over relative intensities of lines of the rotational structure of the band (0;2) with the quantum wave length $\lambda = 380.5$ nm of the second positive system of nitrogen molecule and of the band (0;0) with quantum wave length $\lambda = 388.3$ nm of the CN molecule.

It was shown earlier [5] and confirmed now that the gas temperature in transversal discharge is slowly decreasing along a flow. Thus, we can operate the mean gas temperature of main part of discharge. The correlation between this mean gas temperature and discharge current is shown in Fig.8.

Determined charged particle concentration – discharge current dependence is shown at Fig.9. Data obtained both by the probe method and based on Stark effect were shown. Absolute concentration values at $p \sim 10^2$ Torr and currents up to $10^5$ A do not exceed $10^{14}$ cm$^{-3}$.

**Modeling of the Double Probe in the Air-Fuel Plasma**

A direct computer simulation of the double probe in the plasma of the air-fuel mixture has been carried out on base of the model similar to that developed in [6] for plasmas of air.

The neutral gas dynamics was simulated in the 2D planar approximation with the apparent boundary conditions, which are traditional for computations of flow over a body: zero velocity on the probe surface, ambient plasma flow parameters on the input boundary, and a free exit on the opposite side. The ion mobility was taken 4 times as high as that of the air plasma, and all the other plasma properties were the same as in the case of air plasma [6]. The plasma boundary conditions were analogous to [6]: on the boundary near the probe the mean normal component of the total ion velocity was computed as [5] $v_{bn} = v_{in} + v_{iT}/2 \exp(-2 [v_{in}/v_{iT}]^2)$, here $v_{iT}$ is the arithmetic mean thermal ion velocity, $v_{in}$ is the drift velocity; the ‘probe’ boundary potential in computations $\phi_b$ was taken $C_b$ times less than the probe voltage $V_p$, $C_b = \ln(L/R) / \ln(R_0/R)$, $R_b$ is the maximal radial
coordinate of the mesh (in order to account for the finite size of the computational region). At \( r = R_b \), the potential was a zero, and the ion velocity was equal to the gas flow velocity.

![Fig.10. Plasma density spatial distributions for air-fuel (a) and air (b) plasmas](image)

The computer simulation of the gas dynamics of flow over the probe was carried out with use of the implicit free-LaGrange method and an irregular triangular mesh bound with the gas. The mesh had a characteristic cell size that quickly decreased at approaching the probe surface; the mesh had about 200 cells along the probe surface, and about 20,000 cells total. The plasma part of the problem was solved with use of a fixed mesh, which had resulted from the solution of the gas dynamical part of the problem, and with the corresponding distributions of gas temperature, density and velocity.

Characteristic results of computations for air and air-fuel plasmas under similar conditions are presented in Fig. 10-11. The differences in distributions of plasma density, electric field etc. are considerable. The computed ion probe current is 2…4 times as high as in the air plasma (Fig. 11).

![Fig. 11. The probe ion current density over the probe voltage bias for air-fuel (dashed lines) and air (solid lines) plasmas: computations with constant \( T_e \) (thin lines) and with direct computation of electron energy (thick lines)](image)

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References