Using triple Langmuir probe method for study high-speed plasma flow created by a pulsed capillary discharge

A S Pashchina* and R E Karmatsky
Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia

*fgrach@mail.ru

Abstract. The results of triple Langmuir probe method diagnostics of plasma created by a pulsed discharge in a capillary with an ablating wall and injected into a rarefied atmosphere \((p < 1 \text{ Torr})\) are presented. The possibility of obtaining high-speed plasma flows in the wide range of electron density \(n_e = 10^{11} - 10^{15} \text{ cm}^{-3}\) and the temperature \(T_e = 1 - 5 \text{ eV}\) by varying the discharge power input in the range of \(N = 15 - 500 \text{ kW}\) is shown. The effects indicating the violation of approximation of the infinitely thin probe layer while reducing the electron density below \(n_e < 10^{13} \text{ cm}^{-3}\) and requiring account in the theoretical model of a triple probe are found. The results of measurements are in good quantitative agreement with the results of diagnostics of plasma flows similar in parameters.

1. Introduction

A pulsed capillary discharge is known as a relatively simple and efficient method of obtaining plasma over a wide range of pressures, temperatures, and charged particles concentrations [1–3]. It was shown in our previous work [4] that such discharge can be successfully used to produce quasistationary high-speed plasma flows in a rarefied atmosphere that have good prospects in magnetoplasma aerodynamics applications, including problems of laboratory modeling of physico-chemical and gas-dynamic effects and experimental study of bodies interaction processes with hypersonic gas-plasma flows. The problem of plasma diagnostics takes an important place in these studies, which, taking into account the plasma nonequilibrium, high flow rates, and the rapidity of the processes, represent a difficult experimental task. Among the whole variety of diagnostics methods and tools available in the experimental arsenal of plasma physics, the electro-probe methods [5] are the most suitable and convenient under these conditions. Locality of the measurements, as well as the absence of necessity for prior knowledge of the plasma thermodynamic state, are the main advantages of electro-probe methods.

Multi-probe methods offer an advantage over single and double Langmuir probes, allowing simultaneous measurement of plasma parameters without the need for voltage sweeps that can be limited in pulsed plasmas. The triple probe method, first proposed by Chen S.L. and Sekiguchi T. [6,7], is one of such tools, allowing measurement of electron density and temperature in real time. Triple probe method is characterized by high speed, limited by the ion plasma frequency that provides wide opportunities to study fast processes, such as transient processes, low-frequency plasma oscillations and waves, plasma shock waves, etc. Multi-probe methods are successfully used for diagnostics the non-stationary high-speed plasma flows [8,9], obtained in similar conditions considering in this paper.
At the same time, in spite of the relative simplicity, the use of multi-probe methods in plasma-aerodynamic experiments requires certain accuracy when performing measurements. One of the important requirements for conducting such measurements is the spatial uniformity of plasma in the region of probe location, assumed the identity of plasma parameters near each electrode. This requirement can be easily satisfied in a motionless plasma or in a low-speed plasma flows, \( v \ll c \) (\( c \) is the speed of sound). It is much more difficult to fulfill this condition in supersonic flows \( v \geq c \) because the strong perturbation of the flow in the region of probe location. In this case, the collecting electrodes of the probe are located behind the shock wave, where the pressure, density, concentration and temperature of the charged particles, as well as the spatial distribution of these parameters, differ significantly from those in the unperturbed flow. The accuracy and reliability of the obtained results, as well as the very possibility of using multi-probe methods under these conditions, depend largely on how much the flow inhomogeneity influences the plasma parameters near each of the electrodes.

The aim of the work is the experimental study of high-speed plasma flows, created by a pulsed capillary discharge and injected into the atmosphere of rarefied gas, by the triple Langmuir probe method, as well as the assessment of applicability of this method under the experimental conditions, including the estimation of the flux spatial inhomogeneity and its influence on the accuracy of the obtained results.

2. Laboratory installation and research methods
The capillary arrester, whose detailed description and parameters are given in [10], is used to create high-speed plasma flow. Perspex is used as a capillary wall material (chemical formula \( \text{C}_2\text{H}_2\text{O}_2 \)). The depth and the initial diameter of a capillary are respectively \( h = 5 \text{ mm} \) and \( d = 1 \text{ mm} \). A capacitive storage device with series-connected inductor is used as the discharge power supply. The algorithm of power supply approximately corresponds to the sine half-wave. The following parameters and conditions are typical for our experiments: the stored energy of a power supply \( Q = 90 - 640 \text{ J} \), the peak discharge current \( I_m = 200 - 2500 \text{ A} \), the discharge pulse duration \( \tau_d = 2 \text{ ms} \) (a “short-pulse” mode of discharge) and \( \tau_d = 18 \text{ ms} \) (a “long-pulse” mode of discharge).

Experimental investigations were carried out in a vacuum chamber 1, inside which a capillary arrester 2 and a triple probe 3 were placed (figure 1). The residual pressure in the chamber is \( p_{\infty} \approx 0.1 \) Torr. The probe is placed in the central zone of the plasma jet at a distance of about 10 cm from the capillary outlet. The probe consists of three identical electrodes made of tungsten wire with a diameter of \( 2r_p = 0.23 \text{ mm} \). The length of each electrode is \( l_p = 5 \text{ mm} \), and the distance between their axes is \( s = 1 \text{ mm} \). Inside the vacuum chamber, the probe is placed in such a way that the electrodes axes would be oriented along the direction of the plasma flow.

The so-called “current-mode” operation of triple probe [8,9] is used in experiments (figure 2) that makes it possible to minimize the influence of electromagnetic interference on the measured signal. One of the electrodes in the probe circuit \( (P_1) \) is selected as the reference one, and the negative bias voltage is applied to the other two electrodes \( (P_2, P_3) \). The bias voltages (their values are equal to \( V_{12} = -8.5 \text{V} \) and \( V_{13} = -40 \text{V} \) in our experiments, see also figure 1) is chosen from the condition of location of the operating points of both probes on ion saturation branch of probe characteristic. Each circuit probe contains low-inductance metal film resistors \( R1, R2 \) and \( R3 \), which are used as shunts to measure the probe currents \( I_1, I_2, I_3 \).

The use of conductive-type shunts to measure probe currents leads to the necessity of grounding the reference electrode \( P_1 \). In this case, to ensure galvanic isolation between the probe and the arrester’s power supply, the electrodes of the latter one are not grounded. It is obvious that such circuit modification leads to the fact that the probe system ceases to be isolated, since the potential difference between the plasma and the probe electrodes causes the additional leakage of ion current to the ground. This circumstance, in general, leads to a change of the probe layer parameters and, as a consequence of the probe characteristic, and must be taken into account in calculating the plasma parameters (electron temperature and density).
Figure 1 Principal scheme of laboratory installation: (1) vacuum chamber, (2) capillary arrester, (3) triple Langmuir probe, (4) probe measurement unit, (5) discharge power supply.

Figure 2 Electric diagram of a triple (P₁, P₂, P₃) Langmuir probe in a “current-mode” operation.

All elements of the probe measurement unit (see figure 1) are mounted inside the metal casing, and shielded cable is used to enter the probe into a vacuum chamber. The measures taken, in conjunction with “current-mode” operation of the probe circuit, made it possible to minimize the influence of electrical interference on the measuring equipment. The probe currents and voltages between the reference and negative electrodes recorded during the experiments were used for calculation the electron density and temperature.

3. Calculation of plasma parameters
The multi-probe methods are based on the theory of the Langmuir probe in collisionless plasma [11], which completely determines the requirements for the range of the pressure, concentration of charged
particles, and also probe dimensions in accordance with the limits of applicability of the theory. To estimate the applicability of the Langmuir probe theory with respect to the gas pressure, we will proceed from the fact that the characteristic radius of the probe is \( r_p \approx 0.1 \text{ mm} \), the mean free paths of electrons and ions are of the order of \( \lambda_e \approx 10^{-1}/p \text{ [cm]} \) and \( \lambda_i \approx 10^{-2}/p \text{ [cm]} \) (the pressure \( p \) is expressed in Torr). Then the conditions \( r_p \ll \lambda_e, \lambda_i \) and \( r_p \ll \lambda_e, \lambda_i \) are satisfied for \( p < 1 \text{ Torr} \) (\( r_D = \sqrt{e_0 k T_e/e^2 n_i} = \text{Debye length} \)).

In the range of electron density \( n_e = 10^{13} - 10^{15} \text{ cm}^{-3} \) and temperature \( T_e = 0.5 - 10 \text{ eV} \), the ratio of the probe radius to the Debye length is \( r_p/r_D > 100 \), so the case of an infinitely thin layer is realized. This makes it possible to simplify the procedure for calculating the plasma parameters by using the approximation of the independence of the ion saturation current density from the probe potential, i.e. \( J_i(\phi_{s1}) \approx J_i(\phi_{s2}) \approx J_i(\phi_{s3}) = J_i \) (here \( \phi_{sn} \) – the potential of \( n \)-th probe electrode relative to the plasma potential). The ion current density to the probe in this case is determined by the Bohm relation [6]:

\[
J_i = \exp \left(-\frac{1}{2}\right) en_e \sqrt{\frac{k T_e}{M}}.
\]

If \( n_e < 10^{13} \text{ cm}^{-3} \), then the size of the probe layer increases, and the condition of an infinitely thin layer ceases to be satisfied. The violation of this condition can also be caused by the leakage of the ion current to the ground. In this case, to calculate the density of the ion saturation current, that depend on the probe potential, it is necessary to use the modified relations, for example, obtained by Peterson and Talbot [12] on the basis of Laframboise data [13], which are valid in the range of moderate values of the probe layer thickness \( 5 < r_p/r_D < 100 \). In this paper, in order to simplify the calculation procedure, we used the assumption of an infinitely thin layer.

An important condition for the applicability of the Langmuir theory is the small thickness of the probe layer in comparison with the distance between the probes, i.e. \( (r_5 - r_p) \ll r \). It can be seen that this condition is satisfied throughout the whole range of expected values of electron temperatures and densities.

Taking into account above approximations, the initial system of equations for the probe currents can be written in the form

\[
I_1 = -S J_0 e_0 \exp(-\phi_{s1}) + S J_i,
I_2 = -S J_0 e_0 \exp(-\phi_{s2}) + S J_i,
I_3 = -S J_0 e_0 \exp(-\phi_{s3}) + S J_i.
\]

The solution of the system, taking into account the leakage of the ion current by introducing into the Kirchhoff law the corresponding term \( I_0 \) (i.e., \( I_0 + I_1 + I_2 + I_3 = 0 \)), leads to the relations for determining the electron temperature

\[
\frac{-I_1 + I_2}{-I_1 + I_3} = \frac{1 - \exp(-\phi_{s1})}{1 - \exp(-\phi_{s2})},
\]

the ion saturation current density

\[
J_i = \frac{1}{S} \frac{I_3 - I_2 \exp(-\phi_{s2})}{1 - \exp(-\phi_{s2})},
\]

and the electron density

\[
n_e = \frac{1}{0.66} \sqrt{\frac{k T_e}{M}}.
\]

Here \( M = \mu m_p \) – the ion mass, \( m_p = 1.6726219 \times 10^{-27} \text{ kg} \) – the proton mass, \( \mu \) – the effective molecular weight of plasma (\( \mu = 6.67 \) for Perspex), \( S = \pi dl \) – the surface area of the probe electrode.

4. Results of experiments

The oscillograms of currents \( I_1, I_2, I_3 \) onto the probe electrodes and also of the leakage current \( I_0 \) for the two discharge modes ("long-pulse" and "short-pulse") are shown in figure 3. The change in currents starts synchronously for all electrodes with a certain time delay relative to the beginning of the discharge. The delay time is determined by the speed of the front of the plasma jet and depends on the discharge power. The velocity of the jet front, calculated from the delay time, is approximately of
300-400 m/s for the "short pulse" and of 40-60 m/s for the "long-pulse" discharge mode. We did not find explicit signs of the plasma homogeneity violation in the region of the probe location: the floating potentials measured for this purpose showed the same values for all three electrodes regardless of the discharge power. The change in the discharge power is accompanied by a corresponding change in the ion current density to the electrodes, whose magnitude varies from 0.1 mA/mm² to 10 A/mm² for the "long-pulse" and "short-pulse" discharge modes, respectively. It is noteworthy that in the "short-pulse" discharge mode (the discharge power \( N > 100 \) kW and electron density \( n_e > 10^{14} \) cm\(^{-3}\)), the condition of an isolated system for a triple probe is performed with good accuracy: the leakage current does not exceed 10% of the probes currents. This condition violates in the "long-pulse" discharge mode (the discharge power and electron density are less than \( N < 20 \) kW and \( n_e < 10^{12} \) cm\(^{-3}\), respectively), in which the leakage current becomes comparable with probes currents.

The results of calculating the electron densities and temperatures are presented in figure 4. The time course of the electron density in both modes monitors the discharge power algorithm and reaches the maximum approximately in the middle of the discharge pulse. Thus, if the electron density in the "short-pulse" and "long-pulse" modes differs by more than three orders of magnitude (its typical value in the "short-pulse" mode is \( n_e \sim 10^{14} - 10^{15} \) cm\(^{-3}\), and in the "long-pulse" mode - \( n_e \sim 10^{11} - 10^{12} \) cm\(^{-3}\)), then the discharge power in these modes changes only by an order of magnitude (from \( N = 150 \) kW in "short pulse" mode to \( N = 15 \) kW in "long-pulse" mode). The observed feature is related to the Joule heating of a section of a plasma jet by remote currents. These currents travel far beyond the capillary and heat a sufficiently long section of the plasma jet (up to some hundred calibers relatively to the capillary diameter). The size of the zone of remote currents and, correspondingly, the length of the heated section is the greater, the higher the discharge power. Therefore, in the "short-pulse" discharge mode, the remote currents heat up a substantially longer section of the plasma jet than in the "long-pulse" mode. So, in the "short-pulse" mode, the spatial position of the probe corresponds to the section of the jet heated by the remote currents, and in the "long-pulse" mode - to the section of relaxed plasma. This conclusion is indirectly confirmed by the results of the electron temperature estimates, which value in the "short-pulse" mode (\( T_e = 4 - 6 \) eV) more than twice exceeds that for the "long-pulse" mode (\( T_e = 1.5 - 3 \) eV).

The results of calculating the electron densities and temperatures are presented in figure 4. The time course of the electron density in both modes monitors the discharge power algorithm and reaches the maximum approximately in the middle of the discharge pulse. Thus, if the electron density in the "short-pulse" and "long-pulse" modes differs by more than three orders of magnitude (its typical value in the "short-pulse" mode is \( n_e \sim 10^{14} - 10^{15} \) cm\(^{-3}\), and in the "long-pulse" mode - \( n_e \sim 10^{11} - 10^{12} \) cm\(^{-3}\)), then the discharge power in these modes changes only by an order of magnitude (from \( N = 150 \) kW in "short pulse" mode to \( N = 15 \) kW in "long-pulse" mode). The observed feature is related to the Joule heating of a section of a plasma jet by remote currents. These currents travel far beyond the capillary and heat a sufficiently long section of the plasma jet (up to some hundred calibers relatively to the capillary diameter). The size of the zone of remote currents and, correspondingly, the length of the heated section is the greater, the higher the discharge power. Therefore, in the "short-pulse" discharge mode, the remote currents heat up a substantially longer section of the plasma jet than in the "long-pulse" mode. So, in the "short-pulse" mode, the spatial position of the probe corresponds to the section of the jet heated by the remote currents, and in the "long-pulse" mode - to the section of relaxed plasma. This conclusion is indirectly confirmed by the results of the electron temperature estimates, which value in the "short-pulse" mode (\( T_e = 4 - 6 \) eV) more than twice exceeds that for the "long-pulse" mode (\( T_e = 1.5 - 3 \) eV).

![Figure 3](image_url) Figure 3 Typical oscillograms of currents in triple probe circuit for (a) the “short-pulse” and (b) “long-pulse” discharge modes. The voltage and energy of the power supply are \( U = 600 \) V and \( Q = 360 \) J, respectively.
Figure 4 Temporal dependences for the electron densities and temperatures for (a) the “short-pulse” and (b) “long-pulse” discharge modes. The discharge parameters are the same as in figure 3.

Attention is drawn to the different temporal trend of electron temperature observed in two discharge modes: in-phase with the discharge power in the "short-pulse" mode, and the antiphase one in the "long-pulse" mode. In our opinion, the main reason for this difference is the violation of the approximation of an infinitely thin probe layer because the low electron density \( n_e < 10^{13} \) cm\(^{-3}\) and the significant leakage of the ion current observed in the "long-pulse" discharge mode. These factors, obviously, should be taken into account in the theoretical model of the triple probe, which is planned in the future.

5. Conclusion

Thus, even the first experiments showed the principal possibility of using the triple Langmuir probe method for diagnostics the high-speed plasma flows created by a pulsed capillary discharge and injected into a rarefied atmosphere. It was shown experimentally that such plasma flows can be obtained in the range of electron densities \( n_e = 10^{11} - 10^{15} \) cm\(^{-3}\) and temperatures \( T_e \sim 1 - 5 \) eV by varying the discharge power in the range \( N = 15 - 500 \) kW. A change in the temporal trend of electron temperature is observed when the electron density decreases below \( n_e < 10^{13} \) cm\(^{-3}\), which is caused by a violation of the approximation of an infinitely thin probe layer, as well as by the increasing role of leakage of ion current under these conditions. The role of these factors must be accounted in developing the theoretical models of triple probe.

In general, the results of probe measurements are in good quantitative agreement with the results obtained by various authors who used the triple Langmuir probe method to study plasma with close parameters. This fact, as well as the absence of obvious signs of the spatial uniformity violation of the plasma in the probe localization region, is the encouraging arguments of the reliability of obtained results and the applicability of this method for diagnostics the capillary discharge plasma injected into a low-pressure atmosphere. In the future, it would be advisable to perform measurements and compare the results of diagnostics obtained in open and isolated probe systems, which will help to determine the influence of ion leakage current on the accuracy of the measurements. The preparation and approval of the quadruple Langmuir probe method [14], which will expand the set of measured parameters by including such important parameter as the plasma flow velocity, should be the important step in future research.

References

[1] Min'ko L Ya 1970 Obtaining and study the pulsed plasma flows (Minsk: Nauka i tekhnika) (in Russian)
[2] Ogurtsova N N, Podmoshensky I V and Shelemina V M 1974 Teplofiz. Vys. Temp. 6 48–53 (in Russian)
[3] Pashchina A S, Efimov A V and Chinnov V F 2017 Optical investigations of multicomponent plasma of capillary discharge. Supersonic outflow regime High Temp. 55 650–64
[4] Pashchina A S, Karmatsky R E and Klimov A I 2017 Tech. Phys. Lett. 43 1033–6
[5] Lochte-Holtgreven W 1968 Plasma Diagnostics Ed. North-Holland (Amsterdam; New York:Wiley–Interscience)
[6] Chen S L and Sekiguchi T 1965 J. Appl. Phys. 36 2363–75
[7] Chen S L 1971 J. Appl. Phys. 42 406–12
[8] Tilley D L, Kelly A J and Jahn R G 1990 The Application of the Triple Probe Method to MPD Thruster Plumes (AIAA-90-2667) 21st International Electric Propulsion Conference (Orlando, Florida, USA)
[9] Eckman R, Byrne L, Gatsonis N a. and Pencil E J 2001 J. Propuls. Power 17 762–71
[10] Pashchina A S, Efimov A V and Chinnov V F 2016 High Temp. 54 488–502
[11] Mott-Smith H M and Langmuir I 1926 Phys. Rev. 28 727–63
[12] Peterson E W and Talbot L 1970 AIAA J. 8 2215–9
[13] Laframboise J G 1966 Theory of Spherical and Cylindrical Langmuir Probes in a Collisionless, Maxwellian Plasma at Rest (UTIAS REPORT NO. 100)
[14] Johnson B H and Murphree D L 1969 AIAA J. 7 2028–31