Charged particles distribution ahead the shock wave front in the electrode discharge plasma

A S Baryshnikov¹, I V Basargin¹, N O Bezerkhnii¹,², S V Bobashev¹,², N A Monakhov¹,², P A Popov¹, V A Sakharov¹ and M V Chistyakova¹

¹Ioffe Institute, 194021, Saint-Petersburg, Russia.
²Peter the Great Saint-Petersburg Polytechnic University, 195251, Saint-Petersburg, Russia

E-mail: nm1988@mail.ru

Abstract. Experiments on the interaction of a shock wave with a glow discharge were conducted. It was established that the shock wave propagation is accompanied by a change in the potential of the discharge plasma. The varying potential in the glow discharge plasma causes a distortion of the double probe current. A method is proposed for correcting probe measurements, which consists in the joint processing of two signals obtained in separate experiments with different surface areas of the double probe negative electrode and other conditions being equal. Using this method, the ion current and the change in the space potential are determined. The ion current, determined by the concentration of charged particles, remains unchanged until the shock wave arrival to the measurement point.

1. Introduction

High speed flows modification in order to control the flight of high-speed vehicles is an important scientific and technical problem [1-3]. In recent years, the possibility of using a power deposition to a supersonic flow in order to change its parameters has been actively investigated [4-6]. Possible practical applications of plasma energy deposition - reducing the aerodynamic resistance of the body during high-speed flight, active control of the supersonic flow parameters. For these purposes, it is proposed to use various types of gas discharges [7-10]. Despite the large number of experimental and computational studies, the question remains about the mechanisms of discharge plasma influence to the structure of strong gasdynamic discontinuities. So far, there is no generally accepted explanation of the effect of perturbation of the charged particles concentration and the electric field in a gas discharge at a considerable distance ahead of the shock wave front [11-18]. Another interesting effect is the appearance of a narrow peak in the charged particles concentration in a plasma, first discovered and described in [18-20].

One of the methods of measuring local plasma parameters under nonstationary gas-dynamic process is the double electric probe method. When double probe operates in the ion current saturation regime, the double probe current is determined only by the concentration of ions in the vicinity of the negative electrode. This circumstance allows one to study the dynamics of the charged particles concentration in a plasma without measuring the current-voltage characteristic, which is an important advantage in the conditions of an unsteady plasma with a characteristic variation time of its parameters of the order of 1 µs. Measurements in an electrode discharge plasma are complicated by reason of a galvanic coupling between the probe and the electrodes of the discharge gap. When the plasma
potential changes, the measurement results are distorted by the transient process in the measuring circuit. This process can lead to the appearance of features in the charged particles distributions near the shock wave front described in our previous works [16-20]. This work covers the question of whether these features are a manifestation of physical processes in a discharge plasma or are they associated exclusively with the specificity of probe measurements in a plasma during unsteady gas-dynamic processes.

2. Experimental setup and diagnostics

The experiments were carried out on a plasmagasdynamic setup, the scheme of which is shown in figure 1. The stationary glow discharge was created between two 60-degrees conical copper electrodes located vertically at a distance of 100 mm in the working chamber 1 with an internal diameter of 300 mm and a height of 400 mm. A constant discharge discharge is maintained by a voltage source providing a discharge current of 1 A and the discharge gap voltage of 680 V. The working chamber 1 and the cathode 2 have a common zero potential. The anode 4 is located on a non-conductive plate 3, covering the lower end of the working chamber. The mutual arrangement of the electrodes (the anode below, the cathode on top) and their shape are dictated by the need for spatial stabilization of the discharge. The gas temperature in the center of the discharge is ~ 1300 K, electrons ~ 13000 K, the degree of ionization is not exceed $10^{-6}$.

Figure 2 shows the visible structure of a glow discharge. It has the shape of a body of revolution. Visually, the internal structure is discernible in the discharge: a brighter central and external part with a noticeably lower luminous intensity. The radius of the bright central part ("core") of the discharge in the middle section is approximately 20 mm, and the outer part of discharge has the radius of about 60 mm. At the top of the lower cone (anode of the discharge gap) there is a bright spot, where the discharge current contraction occurs. In the immediate vicinity of the cathode surface (upper conical electrode), a bright region is visible, occupying a relatively small part of the cathode surface. The transverse dimension of the cathode luminescence coincides with the diameter of the "core", which allows us to assume that a significant part of the discharge current is concentrated in this region.

The shock wave is formed by an electrical shock tube 5 with an inner diameter of 30 mm and a length of 700 mm. The output end of the shock tube is flush with the side wall of the working chamber. The axis of the shock tube passes in the middle of the discharge gap. The initial pressure in the shock tube channel is equal to the pressure in the working chamber. The shock wave propagates perpendicularly to the axis of the discharge and the velocity of the shock wave at the outlet of the shock tube is 1.3 km/s.
The shock wave position registration and the launch of the registration system are carried out using two optical schlieren systems through two windows 7 on the side surface of the working chamber. The beam of one optical system is fixed and located at the left edge of the observation window. It is used to launch the registration system. The beam of the second system moves along with the probe, with the help of which the moment of arrival of the shock wave to the measuring point is recorded. The measurement error of the shock wave position is no more than 3 mm.

The dynamics of plasma parameters variation under the non-stationary gasdynamic process was investigated using a double electric probe. It was mounted on a movable dielectric rod. This rod was inserted into the plasma in the opposite direction to the shock wave. Double electric probe 6 moves in a horizontal plane coaxially with a shock tube. The probe consists of two platinum electrodes with a diameter of 0.5 mm and a length of 10 mm, arranged parallel to each other at a distance of 8 mm. Since the characteristic time of plasma parameters variation during the motion of a shock wave does not exceed 1 μs, the registration of the I – V characteristic of a double probe is difficult. Qualitative analysis of changes in the parameters of the discharge plasma was carried out by applying a constant voltage of 40 V to the electrodes, which ensured the ion current saturation regime of the double probe. In this case, the probe current is determined by the temperature of the electrons and the concentration of ions in the vicinity of the double probe negative electrode [21].

3. Correction method for probe measurements

The propagation of the shock wave influence on the integral parameters of the gas discharge, such as current and voltage between the electrodes. Figure 3 shows the variation of the current I and the voltage U between the electrodes of the discharge gap as the shock wave passes through the discharge. Time is counted from the moment when the shock wave is at a distance of 60 mm to the axis of the discharge, which corresponds to the signal of the first schlieren system. The graph shows that the change in the discharge current and voltage at the electrodes of the discharge gap begins at t = 0 μs, i.e. almost immediately at the moment when shock wave enters the discharge plasma. It can be seen from the figure 3 that by the time the shock wave arrives to the discharge axis (t~50 μs), the discharge current is reduced by 20%, and the voltage is increased by 10% of the initial level. During the time of the shock wave motion over this discharge region (interval 20–120 μs at figure 3), the voltage across the discharge gap increases almost linearly.
An increase in the voltage across the discharge gap under the shock wave propagation is a consequence of changes in the discharge plasma parameters itself and, in particular, of plasma potential. Being a conductive element, the electric probe have a direct to ground capacitance. In the discharge plasma, the probe capacitance is charged to a certain voltage. Due to the presence of a galvanic coupling between the probe and the common electrode of the discharge gap, when the plasma potential changes, a recharge current of this capacitance arises.

The potentials of the probe electrodes differ with respect to the space potential. The potential of the negative electrode is less than the space potential by an amount almost equal to the voltage between the electrodes $E=40\, V$, while the potential of the positive electrode is close to the potential of the plasma. It is for this reason that when the plasma potential in the measurement point changes, the recharge of the electrode capacitances of the probe will occur through the positive electrode. However, only the recharge current of the capacitance of the negative electrode will affect the double probe current. Thus, the measured probe current is determined by the sum of the recharge current of the probe capacitance and the ion current.

Hereby, the recharge capacitance current of the probe passes through its positive electrode, and the ion current is determined by the plasma parameters in the vicinity of the negative electrode of the double probe. If other conditions are equal, changing the surface area of the negative electrode of the probe leads to the ion current magnitude variation in proportion to electrode area change. In this case, the recharge current will remain constant. Performing two measurements with different surface areas of the negative electrode, we obtain a system of two linear equations:

$$
\begin{align*}
I_t + I_c &= I_1, \\
\alpha I_t + I_c &= I_2.
\end{align*}
$$

At this point, $I_t, I_c$ – ion current and capacitance recharge current, $I_1, I_2$ – double probe currents, measured with different surface areas of the negative electrode, $\alpha$ – electrode surface area relative change. The solution of system (1) is:

$$
\begin{align*}
I_t &= \frac{I_1 - I_2}{1 - \alpha}, \\
I_c &= \frac{I_2 - \alpha I_1}{1 - \alpha}.
\end{align*}
$$

The values included in (2) are functions of time except for constant $\alpha$. Its value can be calculated, taking into account that in stationary mode, the capacity recharge current is equal to zero $I_c = 0$. In this case, the solution (1) gives the value $\alpha = I_{t2}/I_{t1}$, which is equal to the ratio of currents with different surface areas of the negative electrode in the stationary mode of discharge.
4. Results of probe measurements correction

A typical double probe signal obtained while shock wave propagates through the discharge plasma is shown in figure 4 (a). The red line shows the change in the current of the probe with an open electrode, the green line shows the change in the current with a reduced surface area of the negative electrode of the probe. The change in the surface area of the negative electrode of the probe was carried out by donning a short quartz capillary on it. In this case, \( \alpha = \frac{I_{o2}}{I_{o1}} \approx 0.38 \) The time of the shock wave arrival at the measurement point is marked by vertical line.

As mentioned above, a feature of the double probe signal is a decrease in current before the arrival of a shock wave. In the figure, this feature is observed after 35 µs from the start of registration. In some cases, the current decrease is more than half the initial level. Another feature of the probe signal is the appearance of a short-term current increase in the vicinity of time point 55 µs. Special studies have shown that this increase in current corresponds to the shock wave passage through the central part of the discharge, and in the authors' opinion, it is caused by the interaction of a shock wave with a discharge cathode glow region [19].

Figure 4(a) shows that the current values do not change at the beginning of the registration. They can be considered equal to the values of the stationary double probe currents and they can be used to determine the value of \( \alpha \). Estimates have shown that the value of \( \alpha \) corresponds to the magnitude of the relative change in the negative electrode surface area.

The results of the calculation of the ion current and the recharge current of the double probe capacitance, obtained using relations (2), are shown in figure 4(b). The brown line indicates the change in the ion current, the blue line indicates the probe capacitance recharge current. It shows that the ion current remains unchanged before the shock wave arrival to the measurement point. The ion current variations which are observed in the vicinity of the moment 55 µs should be considered as the calculation error caused by the insufficiently accurate reproduction of the experimental conditions in different experiments. An almost linear increase in the charged particles density is observed behind the shock wave for about 70 µs. Such a change in the charged component concentration differs from an abrupt change in the gasdynamic parameters at the shock wave front [18].

![Figure 4](image)

**Figure 4.** (a) Double probe currents with an open (red line) and partially closed (green line) negative electrode under the shock wave propagation through the discharge plasma. (b) Calculated values of ion current (brown line) and recharge current (blue line) under a shock wave propagation through the discharge.

The double probe capacitance recharge current (blue line in figure 4(b)) noticeably differs from zero after about 35 µs from the start of registration which corresponds approximately with the time
when the discharge voltage change begins (see figure 3). Attention should be paid to this coincidence, since the temporal correlation of the two parameters obtained by independent methods indicates the validity of the assumptions incorporated in the method of processing the measurement results.

The capacitance value of the probe $C$ allows us to calculate the change in voltage on the probe:

$$\Delta U(t) = \frac{1}{C} \int_0^t I_c(\tau) d\tau$$  \hspace{1cm} (3)

Since the cause of the double probe capacitance recharge current is a change in the space potential, it is natural to associate it with the dependence (3). The result of integration is shown in figure 5. The calculation used the measured value of the probe capacitance of $40 \text{ pF}$.

Figure 5 shows that by the time of the shock wave arrival (vertical line), the change in potential is a fraction of a volt. A significant change in the space potential occurs behind the shock wave front after approximately $150 \mu\text{s}$.

5. Conclusion
The peculiarity of probe measurements in the electrode discharge plasma is associated with the presence of a galvanic coupling between the probe and the electrodes of the discharge gap. When the space potential changes, the measurement results are distorted by the double probe capacitance recharge current along the circuit including the elements of ion current registration.

The method for correcting the probe measurement results proposed. This method consists in the joint processing of two signals obtained in separate experiments with different probe negative electrode surface areas. The method allows to determine the ion current and probe capacitance recharge current.

In the present study, it was established that the shock wave motion through the glow discharge plasma is accompanied by an increase in the space potential. The beginning of this process corresponds with the shock wave position near the boundary of the luminous region of the glow discharge. Before the shock wave arrival to the measuring point, the change in potential is relatively small. A significant increase in the space potential occurs behind the front of the shock wave.

The shock wave motion through the central part of the discharge causes a reverse change in the space potential of space, namely, its short-term decrease. This decrease occurs apparently due to the shock wave impact to the cathode glow region.

It was established that the probe current variation ahead of the shock wave front, as noted in previously published papers [16-20], is caused by the distortion of the probe current due to a change in
the space potential. The ion current, determined by the concentration of charged particles, remains constant until the shock wave arrives at the measurement point.

References

[1] Bletzinger P, Ganguly B N, Van Wie D and Garscadden A. 2005 J. Phys. D: Appl. Phys. 38 R33
[2] Adamovich I V 2010 Encyclopedia of Aerospace Engineering (John Wiley & Sons Ltd) p 5810
[3] Starikovskiy A and Aleksandrov N 2011 Nonequilibrium Plasma Aerodynamics Aeronautics and Astronautics, Ed. By M. Mulder (InTech) p 55-96
[4] Georgievsky P Yu and Levin V A 2003 Fluid Dynamics 38 794
[5] Zheltovodov A A, Pimonov E A and Knight D D 2007 AIAA Paper 2007–1230
[6] Knight D, Kolesnichenko Y, Brovkin V, Khmara D, Lashkov V and Mashek I. 2009 AIAA J. 47 2996
[7] Jin J, Znamenskaya I and Sysoev N 2013 Tech.Phys. Lett. 39 418
[8] Koroteeva E, Znamenskaya I, Orlov D and Sysoev N 2017 J. Phys. D: Appl. Phys. 50 085204
[9] Lapushkina T A and Erofeev A V 2017 Aerosp. Sci. Tech. 69 313
[10] Gutierrez D R and Poggie J 2018 AIAA J. 56 2911
[11] Gorshkov N, Klimov A, Mishin G, Fedotov A and Yavor I. 1987 Sov. Phys. —Tech. Phys. 57 1893
[12] Ershov A P, Klishin S V, Kuzovnikov A A, Ponomareva S E and Pyt'ev Y P 1989 Sov. Phys. —Tech. Phys. 34 936
[13] Avramenko R F, Ruhadze A and Teselkin S F 1981 JETP Lett. 34 463
[14] Naidis G V 1991 High Temp. 29 15
[15] Teselkin S F 1991 Sov. Phys. —Tech. Phys.Lett. 17 50
[16] Baryshnikov A S, Basargin I V, Bobashev S V, Monakhov N A, Popov P A, Sakharov V A and Chistyakova M V 2016 Journ. Eng. Phys.Thermophys. 89 565
[17] Baryshnikov A S, Basargin I V, Bezverkhii N O, Bobashev S V, Monakhov N A, Popov P A, Sakharov V A and Chistyakova M V 2018 J.Phys.: Conf. Series 1112 012007
[18] Baryshnikov A S, Basargin I V, Bezverkhii N O, Bobashev S V, Monakhov N A, Popov P A, Sakharov V A and Chistyakova M V 2018 Tech. Phys. 63 180
[19] Baryshnikov A S, Basargin I V, Bezverkhii N O, Bobashev S V, Monakhov N A, Popov P A, Sakharov V A and Chistyakova M V 2018 AIAA J. 56 3782
[20] Baryshnikov A S, Basargin I V, Bobashev S V, Monakhov N A, Popov P A, Sakharov V A and Chistyakova M V 2017 Tech. Phys. Lett. 43 511
[21] Kotelnikov V A and Kotelnikov M V 2017 High Temp. 55 477