Space potential and charged particles density variation in a glow discharge plasma during shock wave propagation

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Abstract. The plasma parameters in a glow discharge plasma near the front of shock wave moving perpendicularly to the discharge axis has been investigated using a double electrical probe. It has been discovered that the shock wave propagation is accompanied by an increase in the potential of discharge plasma. A relatively small change in the potential is observed before the shock wave arrival and a significant one behind shock wave front. The varying potential in the glow discharge plasma distorts the current of the double probe. A method of its correction is proposed, which consists in the joint processing of two signals obtained in separate experiments with different surface areas of the negative probe electrode. The method allows us determine the ionic current and the change in the potential of space. The magnitude of ion current corresponding to the charged particles concentration remains unperturbed before the shock wave arrival to the measurement point. A gradual increase in the ionic current is observed behind the shock wave front in contrast with the abrupt change in gas-dynamic parameters on the shock wave front.

1. Introduction
Modification of shock-wave structures around high-speed aircraft in order to improve their aerodynamic characteristics and reduce mechanical and thermal loads on their structural elements is an actual scientific and technological task [1]. The possibility of using a power deposition to the supersonic flow in order to change its parameters has been actively investigated [2-4]. For these purposes, various types of gas discharges can be used [5-8]. Despite the large history of experimental and computational studies, some questions remain about the mechanisms of low-temperature plasma influence to the structure of strong gasdynamic discontinuities. There are many investigations in which some peculiarities of charged particles distribution near the shock front were obtained [9-14], for instance, perturbation of the charged particles concentration and the electric field in a gas discharge at a considerable distance ahead of the shock wave front [9-14] or the appearance of a narrow peak in the charged particles concentration in a plasma [15-17].

When a shock wave propagates in a plasma, plasma parameters, including electric ones, such as plasma potential or charged particles concentration, change with a characteristic time of 1 μs. The necessity for their local measurement is associated with a number of technical difficulties. Our experience in the experimental study of such fast processes in plasma indicates that the most suitable
method for this is the double electric probe method operating in the ion current saturation mode. In this case, the probe current is determined by the plasma parameters near it. However, measurements in the plasma of an electrode discharge can be complicated by the presence of a galvanic coupling between the probe electrodes and the electrodes of the discharge gap. In this case, it is necessary to take into account the appearance of the probe recharge current and its effect on the measurement results. This work is devoted to the development of a technique for correcting the results of double probe measurements of plasma parameters during the shock wave and the application of this technique to the study of the temporal dynamics of local plasma parameters near the shock wave front.

2. Experimental setup

The experiments were conducted by using the plasmagasdynamic setup, the scheme of which is shown in Fig. 1. The discharge burned between two conical electrodes located at a distance of 100 mm from each other in the working chamber 1 in air at a pressure of 4 kPa. 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 discharge current was 1 A at a voltage between the electrodes of 680 V. The small transverse size of the gas discharge 8 (~ 60 mm) compared with the size of the working chamber 1 (300 mm) allows us to consider the effect of the chamber walls on the discharge to be insignificant. The gas temperature in the center of the discharge is ~ 1300 K, electron temperature is ~ 12000 K, the degree of ionization does not exceed $10^{-6}$.

![Figure 1. Experimental setup. 1 – working chamber, 2 – cathode, 3 – non-conducting plate, 4 – anode, 5 – electrical shock tube, 6 – double electric probe, 7 – observation window, 8 - discharge.](image)

The shock wave (SW) was generated by means of electrical discharge shock tube 5 with an inner diameter of 30 mm and a length of 700 mm. The shock wave propagates perpendicularly to the axis of the discharge. The SW velocity at the entrance to the plasma was 1000 m/s, which corresponded to the Mach number $M = 3$.

To determine the plasma parameters in an unsteady gas-dynamic process, a double electrical probe was used. It consisted of two parallel platinum electrodes with a diameter of 0.5 mm and a length of 10 mm, spaced apart in a horizontal plane by a distance of 8 mm. The probe electrodes are oriented
parallel to the discharge axis. Since the characteristic time of plasma parameter changes during the
movement of the shock wave is of the order of 1 μs, the registration of the I – V characteristic presents
certain technical difficulties. A qualitative analysis of the dynamics of the parameters of the discharge
plasma is possible without measuring the I – V characteristics. For this purpose, a constant voltage of
38 V was applied to the probe electrodes. This ensured that the probe operates in the ion current
saturation mode, at which the probe current is determined by the electron temperature and ion
concentration in the vicinity of the probe’s negative electrode.

As it was shown at [15, 16, 18], the shock wave propagation affects the integral parameters of glow
discharge. The results of [18] shows that discharge current and voltage variation starts almost
immediately when SW arrives the borders of the discharge plasma. When SW arrives to the discharge
axis, the discharge current is reduced by 20%, and the voltage is increased by 10% of their stationary
levels. These plasma parameters variations lead to the change in the space potential which induces a
current associated with the recharge of the probe capacitor through the grounded electrode of the
discharge gap. Therefore, the results of probe measurements can be distorted upon a change in
discharge parameters in electrode discharge plasma. If the recharge current passes through elements of
the measuring circuit, the results of measurements will contain an error.

3. Double probe measurements correction
In this investigation, we use method for correcting the double probe signal during measurements in
non-stationary plasma. The method 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. This method can be used since the recharge current of the double probe
passes through its positive electrode, and the ion current is determined by the plasma parameters
in the vicinity of the probe negative electrode. This assumption is valid due to the difference
between the potentials of the double probe electrodes – the potential of positive electrode is about
plasma potential whereas the potential of the negative electrode is less by an order of magnitude of
the voltage applied between the electrodes (~40 V). This circumstance allows us to change the ion
current by changing the surface of the negative electrode while the recharge current remains constant.

Having two measured current values \( I_1, I_2 \) corresponding to different negative electrode surface we
obtain a system of two linear equations:

\[
\begin{align*}
I_1 + I_R &= I_1 \\
I_1 \frac{S_2}{S_1} + I_R &= I_2
\end{align*}
\]

(1)

Here \( I_1, I_R \) – ion current and capacitance recharge current, \( S_1, S_2 \) – electrode surface areas in two
experiments. The solution of system (1) is:

\[
\begin{align*}
I_i &= \frac{I_1 - I_2}{1 - \frac{S_2}{S_1}}, \\
I_c &= \frac{I_2 - \frac{S_2}{S_1} I_1}{1 - \frac{S_2}{S_1}}.
\end{align*}
\]

(2)
The values included in (2) are functions of time except of constant $S_2 / S_1$. Its value can be calculated using stationary mode data when the capacity recharge current $I_c = 0$. In this case, the solution of (1) gives the value $S_2 / S_1 = I_2(t = 0) / I_1(t = 0)$.

The solution of associated system of equations allows one to calculate time dependences of double probe recharge current and ionic current which corresponds with charged particles concentration near the probe. If the probe capacitance $C$ is known, the probe voltage variation can be easily calculated:

$$\Delta U(t) = \frac{1}{C} \int_0^t I_R(\tau) d\tau$$

(3)

Since the appearance of the recharge current is due to the space potential variation, it is natural to associate it with dependence (3).

4. Results

Fig. 2 shows the result of integration of equation (3). The calculation used the measured value of the probe capacitance of 40 pF. It is established that the shock wave motion through a transverse glow discharge plasma is accompanied by a change in the discharge plasma potential. The potential variation is relatively small before the shock wave arrival to the discharge axis, while there is a significant increase behind the shock wave front. Such a change in the plasma potential is the cause of the previously observed [14-18] decrease in the current of the double probe in front of the shock wave due to the presence of galvanic coupling between the probe and the electrodes of the discharge gap.

Figure 2. The probe potential variation during the shock wave propagation through the discharge.

The vertical line indicates the moment of the shock wave arrival to the measurement point.

Another feature of the probe potential dependence on time is the appearance of a short-term decrease in the vicinity of 55 μs. Matching this peculiarity with the earlier studies [17] we have concluded that it corresponds to the shock wave passage through the central part of the discharge, and it is caused by the shock wave interaction with a near-cathode glow region [17].

The technique was tested in experiments on the interaction of a shock wave with a transverse glow discharge in the stationary mode and with decaying plasma. The variation in the surface area of the
negative electrode of the probe was carried out by putting a short quartz capillary on it. In this case, \( S_2 / S_1 = I_2(t = 0) / I_1(t = 0) \approx 0.38 \). The time of the shock wave arrival at the measurement point is marked by vertical line.

Figure 3 shows the results of the calculation of the ion current and the recharge current of the double probe capacitance using relations (2). In contrast to our previous studies [14-18], it is clearly seen that all peculiarities of ion current variation before the shock wave arrival are due to capacitance recharge current variation whereas the ion current determined by the charged particles concentration remains undisturbed until the shock wave arrival to the measurement point. The double probe capacitance recharge current noticeably differs from zero after about 40 µs from the start of registration which corresponds approximately with the time of the discharge voltage variation beginning in our previous studies [18]. Attention should be paid to this coincidence, This temporal correlation of the two parameters obtained by independent methods gives the additional proof to the validity of the assumptions used in the method of processing the measurement results.

A smooth increase in the ion current is observed behind the shock wave front (\( t > 55 \) µs), in contrast to the abrupt change in the gas-dynamic parameters at the shock wave front. An increase in the gas density at the shock wave front, calculated according to the measured shock wave velocity, did not exceed 2 [18], which corresponds with the ion current relative variation by the shock wave propagation. As it was obtained in the same investigation for the shock wave interaction with the decaying plasma [19], the gas-dynamic compression of plasma is the same for the propagation of a shock wave through glow discharge plasma and through decaying plasma and profiles of ion currents in these two cases are of the same shape.

![Figure 3](image_url)

**Figure 3.** Calculated values of the ion current and capacitance recharge current during the shock wave propagation through the discharge. The vertical line indicates the moment of the shock wave arrival to the measurement point.

5. Conclusion

The peculiarity of probe measurements in the electrode discharge plasma is associated with the presence of a galvanic coupling between the probe electrodes 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 is 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.

It was established that the shock wave propagation through the discharge plasma is accompanied by an increase in the space potential. The beginning of this process corresponds with the shock wave enters the luminous region of the glow discharge. The potential variation is relatively small before the shock wave arrival to the measuring point. A significant increase in the space potential occurs behind the shock wave front. The shock wave propagation through the central part of the discharge causes the short-term decrease of the space potential. This decrease occurs due to the shock wave interaction with the cathode glow region.

It was found that the double probe current variation before the shock wave arrival to the measurement point is caused by the distortion of the double probe current due to a change in the space potential. The ion current, determined by the concentration of charged particles, remains unperturbed until the shock wave arrives at the measurement point.

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