Peculiarities of the charged particles distribution near the front of a shock wave in a glow discharge plasma

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Abstract. The charged particles distribution 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 shown that the interaction of the shock wave with the glow-discharge plasma is accompanied by a decrease of charged particles density before the shock wave arrival to the measurement point. This decrease occurs simultaneously through the entire plasma volume. The short-term increase of charged particles density has been revealed. Its appearance caused by interaction of a shock wave with the cathode layer of a glow discharge. These peculiarities of charged particles distribution compared with the case when shock wave propagates through decaying plasma. A significant difference between the distributions of the charged particles in these two cases was revealed.

1. Introduction

The possibilities of plasma influence on supersonic flows in order to aerodynamic characteristics modification are actively investigated [1-4]. The problem of interaction with a shock wave with plasma is part of a fundamental problem directly related to development of modern aeronautics and cosmic technique [5-7], because it reveals a number of unexplained phenomena so far. In particular, the mechanism of decreasing of the charged particles concentration in plasma ahead of the shock wave front in the longitudinal glow discharge is not clear [8-9]. Attempts to explain this effect are made in theoretical works [10-12]. A similar phenomenon is observed in a transverse gas discharge [13-16]. A distinctive feature of the experiments [13-16] is the small linear size of the gas discharge in comparison with the size of the working chamber, which makes it possible to consider the influence of the chamber walls on the discharge to be negligible. This circumstance is important, since in this case self-organization of the discharge occurs in accordance with the conditions in the external gaseous medium.

In this paper, one more feature of the distribution of charged particles near the shock wave front was found, namely, a brief increase in this concentration during the motion of the shock wave through the discharge plasma.
2. Experimental setup and diagnostics
This investigation was carried out on the setup shown at figure 1. It consisted of working chamber of 350 mm in diameter and 400 mm in height and two conical electrodes (2 and 3), which were placed vertically at a distance of 100 mm from each other. Air or argon at a pressure of 4 kPa were used in the working chamber. An external power supply provides the discharge current of 1.1 A with a constant voltage between the electrodes of 650 V. The anode was placed near the bottom of working chamber, and cathode was placed near the top of working chamber and was grounded. This arrangement provided the special stability of axisymmetrical glow discharge with the cross section increasing toward the cathode. The gas temperature in the center of the discharge is ~ 1300 K, electrons ~ 12000 K, the degree of ionization does not exceed $10^{-6}$.

Figure 1 Experimental setup. 1 – electromagnetic shock tube, 2 – cathode, 3 – anode, 4 – double electric probe, 5,6 – laser schlieren systems.

Gas discharge was localized far from the lateral chamber walls, therefore, in the central part of discharge the gas temperature is three times higher than the temperature of ambient gas. It leads to the strong gradients of gasdynamic and electrodynamic parameters and intense convection. The characteristic feature of regarded processes is the shock wave propagation through spatially non-homogeneous media. Gasdynamics peculiarities of this interaction were regarded at the paper [6].

Figure 2 Visible structure of the discharge.
The glow discharge self-organization appears with visually distinguishable areas of the discharge (figure 2): a bright "core" with a diameter of about 20 mm in the center and an outer part with a diameter of the order of 60 mm. 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 (SW) is generated in the electrical shock tube (1) and propagates perpendicularly to the axis of the discharge. Outlet cross-section of the shock tube is located at a distance of 100 mm from the discharge axis. The shock wave velocity at the shock tube outlet is 1,000 m/s, which corresponds to Mach number M=3.

The shock wave was registered by an optical schlieren system consisting of a laser source, a photodiode, and a Foucault knife. When the shock wave crosses the laser beam, the latter deviates from the Foucault knife and thus changes the signal from the photodiode. Optical beam 5 remained fixed and it was placed between electrodes and electrical shock tube outlet at the distance of 60 mm from discharge axis; beam 6 passed through the location point of the electrical probe. The accuracy of shock wave arrival to the measurement point was about 3 μs.

In this study the main facility for discharge plasma diagnostics is the double electric probe. The probe is fixed to the end of the rod 4, which moves in a horizontal plane coaxially with the shock tube. The position of the probe is determined by its distance from the discharge axis. The probe consists of two parallel platinum electrodes with a diameter of 0.5 mm and a length of 10 mm, spaced 8 mm apart.

The probe current meter is an operational amplifier with an input resistance of 1 kOhm. One of the electrodes of the double probe is connected to the common bus of the amplifier. The amplifier input is connected to a circuit consisting of a serial connection of a 38 V source of constant voltage and a second probe electrode. This ensures the operation of the probe in the ion current saturation regime, in which the probe current is determined by the electron temperature and the ion concentration in the vicinity of the negative electrode of the probe [17].

In addition, a double probe was used as a voltmeter. For this, the parameters of the input circuit of the amplifier varied, and, in particular, the 38 V voltage source was eliminated and the input impedance of the operational amplifier was increased. This made it possible to measure the potential difference between the electrodes of a double probe. With this method, the vertical component of the field was measured. It was equal to 30 V/cm at the discharge axis and decreasing by an order of magnitude at a distance of 50 mm from the discharge axis. Thus, the distribution of the vertical component of the electric field in the interelectrode gap and the position of the visible regions of the discharge are in correspondence with each other.

3. Charged particles distribution near the shock wave front in glow discharge plasma

Fig. 3 shows the double probe signals at three different points located at different distances to the axis of the discharge gap: 1 - 0 mm, 2 - 10 mm, 3 - 20 mm. The moments of arrival of the shock wave in the measurement currents are shown by vertical lines. It can be seen from the figure that, firstly, before the shock wave, a decrease in the probe current corresponding to a decrease in the concentration of charged particles is observed, and, secondly, these changes begin simultaneously at all points of measurement. The latter fact suggests that the decrease in local charged particles density is caused not by the shock wave as such, but by a physical mechanism that alters the electrical characteristics of the discharge, for example, as a result of the deformation of the current channel of the gas discharge. In such a case, the propagation of the shock wave can influence on the integral parameters of the gas discharge, such as current and voltage between the electrodes.
Figure 3 Double probe current variation at the shock wave propagation through glow discharge.

Figure 4 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 on the figure. 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 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.

Figure 4 Discharge current and interelectrode voltage variation at a shock wave propagation through glow discharge.
This analysis isn’t a direct evidence of a fact that charged particles decrease is caused by the change of integral discharge parameters. Nevertheless, their influence on plasma parameters is doubtless.

Another feature of the charged particles distributions near the shock wave front the positive current pulse, the temporal position of which remains practically constant irrespective of the double probe position. In other words, this effect is observed simultaneously in the entire cross-section of the discharge plasma. This suggests that the origin of the current pulse is caused by the interaction of the shock wave with either the elements of the internal structure of the discharge (as in the case of a decrease in the current before the front of the shock wave) or with fixed elements of the working chamber, for example, with the cathode of the discharge gap.

![Figure 5](image)

**Figure 5** Comparison of the double probe signal and the cathode emission intensity at the shock wave propagation through the glow discharge.

To verify the last assumption, the time signal of the probe and the radiation intensity of the cathode emission region were compared. A fragment of the image of the luminous cathode was projected onto a photosensitive element whose signal was recorded simultaneously with the probe signal. The axis of the optical Schlieren system was located near the surface of the cathode from the approach side of the shock wave. The results of these measurements are shown in figure 5.

The dashed curve is the double probe signal, the solid curve is the photomultiplier signal, the vertical line marks the moment when the shock wave reaches the cathode. Thus, the moment the shock wave arrives at the cathode coincides with the onset of a change in the intensity of the cathode luminescence and the current of the probe. This allows one to unambiguously associate the appearance of a positive pulse on the probe current signal with the impact of a shock wave on the cathode glow region of a glow discharge.

The size and position of the current pulse caused by the shock wave impact to the cathode layer were studied in dependence on gas pressure in the chamber. Since the pressure in the chamber changes, the shock wave intensity and the size of the glow discharge changes, therefore the measurements were carried out on the discharge axis since this point is common to all regimes.

Experiments have shown that a pressure decrease in the working chamber causes the increase of discharge current. The pressures in the chamber equal to 2; 4; 7 kPa correspond to the following sequence of values of the discharge current - 1.3, 1.1, 1.0 A. When discharge current increases, the region of cathode glow and also diameter of the visible part of the glow discharge increases.

The results of double probe measurements at the discharge axis are shown at figure 6. The time of the shock wave arrival to the point of measurement (the axis of the discharge) is indicated by a vertical line. The double probe current related to the initial current value at a pressure of 4 kPa. The figure
shows that a decrease in pressure in the working chamber causes the shock wave speed and the initial double probe current level increase. Thus, at a pressure of 2 kPa, the double probe current increased by a quarter in comparison to the other two stationary glow regimes.

The goal of this experiment is to show how pulse form depends on shock wave parameters. Times of current pulses caused by the shock wave interaction with the cathode are different because of the different shock wave speed. The magnitudes of the current pulse also significantly differ. Decreasing the pressure in the chamber causes the increase of the pulse magnitude.

4. Charged particles distribution near the shock wave front in decaying plasma
The simultaneity of charged particles density decrease at shock wave entrance to the discharge leads to a conclusion that observed effect may be caused by electric field between the electrodes. This conclusion has determined the further experiments which were carried out with plasma without electric field.

Turning off the discharge was carried out by shunting discharge gap, the voltage across the electrodes and the discharge current decreased to zero within 1 microsecond. One part of this investigation was the study of decaying plasma properties itself. Figure 7 shows the probe currents at the different distances from the discharge axis. Time was counted from the moment when the discharge was turned off. The values of probe current in the area t<0 corresponded to the stationary discharge plasma parameters. After turning off the discharge, the decay of plasma begins and probe current monotonically decreases. Measurements have shown that the conductivity of decaying plasma remains non-zero for 30-40 ms after turning off the discharge. The characteristic time of air plasma decay is about 1 ms.

The interaction between shock wave and decaying plasma was realized at the time about 1 ms after turning off the discharge when the recombination rate of charged particles became small and their concentration remained nearly constant during the observation time. The level of that concentration is about 5 times smaller in comparison with stationary discharge plasma. Figure 8 shows the probe currents at the discharge axis for two different cases: dotted curve— shock wave interaction with the decaying plasma, solid curve— shock wave interaction with the discharge plasma. Time was counted from the moment of the shock wave arrival to point X=-60 mm. The probe measurements have shown that there is no charged particles density decrease before the shock wave front in the decaying plasma.
Figure 7 Temporal evolution of decaying plasma at different distances from discharge axis.

Figure 8 Probe signals at the shock wave interaction with the decaying plasma (dotted curve) and with the discharge (solid curve)

5. Charged particles distribution behind the shock wave front in glow discharge and decaying plasma

As it was shown at figures 3 and 8, the probe current, which corresponds to charged particles concentration, increases monotonically at shock wave front. This peculiarity of probe current oscillogram allows us to raise a question about shock wave existence in the discharge plasma. Per contra, in our previous works [15-16] we measured the pressure distribution at a shock wave propagation through the discharge plasma and that results had shown the existence of shock wave at the discharge plasma. An increase in the gas density at the shock wave front, calculated according to the measured shock wave velocity, did not exceed 2. The relative increase in the concentration of the charged component compared with the unperturbed value differs for different measurement points, while the maximum concentration of the charged component behind the shock front remains approximately constant (figure 3). The time delay between the shock wave arrival to the measurement point and the attainment of the maximum concentration of charged particles increases when the distance between discharge axis and measurement point increases. Such a character of variation of the charged particles distribution variation behind the shock wave front is determined by the...
inhomogeneity of the charged particles distribution in the unperturbed plasma, and the instant of reaching the maximum on the oscillogram of the probe current corresponds to the arrival of a compressed plasma from the central region of the discharge to the double probe.

6. Conclusion
We have experimentally confirmed the effect of local conductivity decrease before the shock wave arrival. We manifest that this decrease simultaneously at the entire volume of gas discharge plasma. The probable reason of this phenomenon is the decrease of electrical power which was put in the discharge region. In a decaying plasma, the concentration of charged particles remains constant until the shock wave arrival.

A short-term increase in the current of the double probe observed before the front of the shock wave is apparently caused by the interaction of the shock wave with the cathode of the discharge gap. Thus, the shock wave interaction with the cathode glow region of a glow discharge affects the plasma parameters of the positive column of the glow discharge. This influence is determined, in particular, by the gas-dynamic interaction of the shock wave with the cathode surface, i.e. depends on the shape of the cathode, the state of the medium near its surface, the intensity of the shock wave and the angle of its approach to the cathode.

At the shock front, the charged particles concentration varies continuously, in contrast to the stepwise variation of the neutral component concentration. The charged particles concentration maximum arises at the noticeable distance from the front. The complex nature of the variation of the charged particles concentration behind the shock wave front is determined by the inhomogeneity of the distribution of charged particles in the unperturbed plasma.

References
[1] Georgievsky P Yu, Levin V A 2003 Fluid Dynamics 38 794
[2] Zheltovodov A A, Pimonov E A, Knight D D 2007 AIAA Pap. 2007–1230
[3] Adamovich I V 2010 Encyclopedia of Aerospace Engineering (John Wiley & Sons Ltd)
[4] Starikovskiy A, Aleksandrov N 2011 Nonequilibrium Plasma Aerodynamics Aeronautics and Astronautics, Ed. By M. Mulder (InTech)
[5] Bletzinger P, Ganguy B N, Van Wie D, and Garscadden A. 2005 J. Phys. D: Appl. Phys. 38 R33
[6] Baryshnikov A S, Basargin I V, Bobashev S V, Monakhov N A, Popov P A, Sakharov V A and Chistyakova M. V. 2015 Tech. Phys. Lett. 41 753
[7] Lapushkina T A and Erofeev A V 2017 Tech. Phys. Lett. 43 17
[8] Gorskhov N, Klimov A, Mishin G, Fedotov A, Yavor I. 1987 Sov. Phys. —Tech. Phys. 57 1893
[9] Ershov P, Klishin S V, Kuzovnikov A A, Ponomareva S E, and Pyt'ev Y P 1989 Sov. Phys. —Tech. Phys. 34 936
[10] Avramenko R F, Ruhadze A and Teselkin S F 1981 JETP Lett. 34 463
[11] Naidis G V 1991 High Temp. 29 15
[12] Teselkin S F 1991 Sov. Phys. —Tech. Phys.Lett. 17 50
[13] 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.Thermophysics. 89 565
[14] Bobashev S V, Basargin I V, Baryshnikov A S, Monahov N A, Popov P A, Sakharov V A and Chistyakova M V 2016 Abstracts of 15th International Workshop on Magneto-Plasma Aerodynamics, Moscow, April 19-21, 2016 112
[15] 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
[16] Baryshnikov A S, Basargin I V, Bezverkhni N O, Bobashev S V, Monakhov N A, Popov P A, Sakharov V A and Chistyakova M V 2018 Tech. Phys. 63 180
[17] Kotelnikov V A and Kotelnikov M V 2017 High Temp. 55 477